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Hearing loss rehabilitation and higher-order auditory and cognitive processing

Edited by
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and Aaron Moberly

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Hearing loss rehabilitation and higher-order auditory and cognitive processing

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Editorial: Hearing loss rehabilitation and higher-order auditory and cognitive processing

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Editorial on the Research Topic
Hearing loss rehabilitation and higher-order auditory and cognitive processing

The associations between hearing loss and cognition are complex. Over the last decade, our understanding of some of the underlying mechanisms that contribute to this association have emerged. Additionally, more recent research has focused on the role of auditory rehabilitation on cognitive function. It is an exciting time to be a part of the interface of otologic medicine and surgery and cognitive hearing science research because of the rate at which knowledge is amassing in these disciplines. Each new idea represents a step forward and builds upon prior work. The breadth of this research is vast and involves a number of different research and clinical specialists that not only brings readers from the bench to the bedside, but also introduces them to ideas from surgeons to psychologists. With the range of specialists active in research of the associations of hearing loss and cognition, the field will likely continue to expand and evolve in a positive way. In this article collection we aim to highlight some of the ongoing research by demonstrating the breadth of the work.

With fifteen articles in the Research Topic and ninety-five authors, the included authors represent multiple countries spanning the globe. Beyond the diversity of our authors, the topics being researched are just as diverse, as are the types of research reported, from basic experimental research to applied science studies of patient and public involvement. Our authors present work that studies the association of hearing loss and cognition across the life span. Jamsek et al. and Zhou et al. start by presenting research that explores the associations between executive function and cortical responses in children with hearing loss. van Wieringen et al. studied how sensorimotor and cognitive functions are coupled in mid- to late-adulthood. Jiang et al. evaluate the associations of audiometric hearing and speech-in-noise performance with cognitive decline in the aging population (>60 years old), and Burleson et al. explore the cognitive-linguistic abilities that contribute to perceptual restoration of degraded speech. Slade et al. present a meta-analysis of the impact of age-related hearing loss on structural neuroanatomy.

In addition to the impact of age on the association of hearing and cognition, the type of hearing loss and mode of intervention were explored in research for this article collection. Qiao et al. demonstrated central reorganization patterns in patients with single-sided deafness, while others explore bilateral hearing loss patterns. The impact of hearing aids (Moradi et al.) and cochlear implants (Völter, Götze et al.; Beckers et al.) are assessed in various studies as well, along with the potential impact of cognition on device programming (Windle et al.). Evolving forms of assessment of hearing loss and cognition in clinical populations are reported by Tarawneh et al. and Völter, Fricke et al.. Mathias et al. offer research that introduces the notion of genetic factors influencing the associations between cognition and hearing loss. Finally, Broome et al. explore patient perceptions of cognitive testing within the adult hearing service model.

This article collection covers incredible breadth and depth in the field of cognitive hearing science. As the fields of otology and cognitive hearing science continue to evolve and expand, so too will the collaborations that exist among clinicians and researchers. While our article collection brings clarity to a number of complicated questions related to hearing loss and cognition, it simultaneously blurs the distinction between surgeon, psychologist, and scientist. Similarly, the once clear-cut roles of the ear and the brain are becoming cloudy. The work we present to readers in this article collection represents a solid foundation on which future research can be established. We are fortunate to be involved in contributing to this foundation, and we are eager to see how this future evolves.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

AM has served as a paid consultant for Cochlear Americas and Advanced Bionics and serves as CMO for Otologic Technologies.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Comparison of Auditory Steady-State Responses With Conventional Audiometry in Older Adults

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Behavioral measures, such as pure-tone audiometry (PTA), are commonly used to determine hearing thresholds, however, PTA does not always provide reliable hearing information in difficult to test individuals. Therefore, objective measures of hearing sensitivity that require little-to-no active participation from an individual are needed to facilitate the detection and treatment of hearing loss in difficult to test people. Investigation of the reliability of the auditory steady-state response (ASSR) for measuring hearing thresholds in older adults is limited. This study aimed to investigate if ASSR can be a reliable, objective measure of frequency specific hearing thresholds in older adults. Hearing thresholds were tested at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz in 50 participants aged between 60 and 85 years old, using automated PTA and ASSR. Hearing thresholds obtained from PTA and ASSR were found to be significantly correlated ($p<.001$) in a cohort consisting of participants with normal hearing or mild hearing loss. ASSR thresholds were significantly higher as compared to PTA thresholds, but for the majority of cases the difference remained within the clinically acceptable range (15 dB). This study provides some evidence to suggest that ASSR can be a valuable tool for estimating objective frequency-specific hearing thresholds in older adults and indicate that ASSR could be useful in creating hearing treatment plans for older adults who are unable to complete behavioral PTA. Further research on older adults is required to improve the methodological features of ASSR to increase consistency and reliability, as well as minimize some of the limitations associated with this technique.

Keywords: auditory steady-state response (ASSR), pure-tone audiometry (PTA), hearing, older adult, objective audiometry

INTRODUCTION

Sensory processing declines across adulthood, with one third of those over the age of 65 being affected by disabling hearing loss (HL) (1). It is estimated that around 466 million people worldwide have disabling HL, accounting for over 5% of the world's population (1). The World Health Organization estimates that untreated hearing loss has an annual global cost of approximately US$750 billion. The identification of and addressing HL can be cost-effective and beneficial at an individual and societal level. Hearing loss can have great impact on quality of daily living and on communication (2–4). In addition, untreated HL is associated with multiple co-morbidities, including anxiety (5), depression (6), social isolation (7), loneliness (8) and poor physical health (9).

Assessing auditory acuity is frequently obtained using pure-tone audiometry (PTA), the gold standard for evaluating hearing threshold status, however, PTA does not always provide reliable hearing information in difficult to test individuals (10). This can be due to lack of cooperation during the assessment, inability to maintain attention and focus or limited understanding of test instructions (11). Older adults with cognitive impairment, particularly at moderate-to-severe levels, can have difficulties in performing behavioral hearing assessments, due to their diminished ability to maintain attention and understand test instructions (12). However, detecting and treating HL in those with cognitive impairment can have positive implications on their cognitive performance (13–16), social interaction (15) and overall quality of life (2). Therefore, being able to objectively measure hearing function in older adults who are unable to complete behavioral PTA is of great interest.

The auditory brainstem response (ABR), a far-field auditory electrophysiological test conducted using surface electrodes, provides an objective alternative method for measuring hearing function and is used particularly in infants and children not suited for behavioral PTA. ABR includes auditory evoked potentials from the eighth cranial nerve (auditory nerve) and neurons along the brainstem auditory pathway after presentation of an acoustic stimulus (17). ABR evoked using click stimuli provides a high degree of information regarding the integrity of the central and peripheral auditory pathways, particularly due to the reproducibility and stability of the waveform (18, 19).

However, a major limitation of the click-evoked ABR for assessing hearing sensitivity is its inability to determine frequency-specific hearing thresholds (20). As click-evoked ABR collects whole basilar membrane responses, it is difficult to accurately determine participating frequency ranges, which limits its effectiveness in providing accurate information for hearing loss intervention and rehabilitation. Commonly, ABR recordings are also dependent on the subjective interpretation of a recorded waveform by the examiner in order to evaluate if a response is present or not, and therefore, ABR results can be influenced by the examiner's experience and expertise (21, 22). Additionally, research has suggested that ABR testing cannot be used to evaluate severe-to-profound hearing loss, as it provides inadequate measures at thresholds >90 dB eHL (23, 24).

Tone-evoked (tone-burst) ABR can be used to assess responses in one ear to one frequency at a time, however, this is time consuming and, like click-evoked ABR, does not provide responses in cases of severe and profound hearing loss (21). Recently, a new ABR testing paradigm, parallel ABR (pABR), has been proposed to provide frequency-specific hearing threshold measures for multiple octave frequencies in both ears simultaneously (25). This new ABR technique uses independently randomized sequences of tone-burst stimuli to acquire ABR waveforms. pABR has been suggested to acquire waveforms with similar morphology of traditional ABR in a fraction of the recording time (25, 26). However, pABR technique still requires examiners to subjectively interpret recorded waveforms and its performance in assessing participants with HL or from different age groups has not been established yet.

Auditory steady-state responses (ASSR) has been suggested to be another objective audiometry test that can overcome some of the limitations associated with ABR (27). Similar to ABR, ASSR is a scalp-recorded auditory evoked potential (28). ASSR is a periodic electrical response evoked by periodically modulated tones, which is used to assess hearing sensitivity in patients of all ages and various degrees of sensorineural hearing loss without the need for patient participation (29, 30). Unlike ABR, which is evoked by a short stimuli at a relatively low repetition rate, ASSR is evoked using repeated pure tones at high repetition rates. ASSR uses amplitudes and phases in a spectral domain and is dependent on peak detection across a spectrum, meaning that the response is periodic and phase-locked to a modulation envelope (28). ASSR can be detected using frequency, time or spectral based analyses (28, 31). The neural generators of ASSR are dependent on the modulation frequencies used in the testing. Higher cortical and subcortical structures are suggested to generate responses to slower modulation rates (<50 Hz), while the auditory nerve and brainstem are suggested to respond to faster modulation rates (>80 Hz) (32, 33).

ASSR can be used to evaluate hearing sensitivity at a range of frequencies similar to behavioral PTA, using simultaneous stimulation and evaluation of multiple frequencies binaurally (33). ASSR results are presented as an electrophysiological audiogram, allowing for easy interpretation of hearing quality and for the preparation of medical reports (34). ASSR has also been suggested to provide better hearing data in comparison to ABR, in cases with severe-to-profound sensorineural hearing loss of 90 dB HL or greater (22, 35). Moreover, ASSR thresholds (spectrum of the response) are predicted by the stimulus spectrum and do not require subjective interpretations of the recorded responses, therefore overcoming some of the common limitations associated with other clinical audiometric tests, e.g., ABR.

Previous research suggests that ASSR can be a reliable predictor of hearing thresholds when compared to PTA in both children and adults (10, 11, 30, 35–37). However, there is no research comparing hearing threshold measures between PTA and ASSR in a cohort consisting of only older adults (aged 60 years and over), to date, research has only included older adults as part of a mixed aged (ranging from children to older adults) cohort when comparing PTA and ASSR thresholds (11, 30, 37).

TABLE 1 | Demographical characteristics of participants.

	Sample (*n*)	Age (years)	Education (years)	MoCA score	Depression score	Anxiety score	Stress score
Combined	50	72.1 ± 5.4	14.8 ± 2.5	26.9 ± 2.7	2.2 ± 2.1	2.2 ± 2.2	4.3 ± 2.9
Females	36	71.6 ± 5.1	14.9 ± 2.4	27.3 ± 2.9	2.1 ± 2	2 ± 1.9	4.5 ± 2.9
Males	14	72.9 ± 6	14.6 ± 2.7	26.2 ± 2.2	2.5 ± 2.3	2.6 ± 2.8	3.8 ± 2.8

There is evidence to suggest that age-related changes in neural envelope processing and phase-locking may result in decreased ASSR responses in older adults compared to young adults or children (38–41). Therefore, the reliability of ASSR as a measure of hearing acuity specifically for older adults remains unclear. The aim of this study is to investigate if ASSR can be a reliable objective measure of frequency-specific hearing thresholds in older adults.

METHODS

Participants

Community-dwelling (i.e., from the general population) older adults (aged 60 years and over) were recruited from an ongoing longitudinal research project known as the Western Australia Memory Study (WAMS). All procedures undertaken in this study were conducted in accordance with ethical approval (HPH-139) from the Ramsay Health Care WA| SA Human Research Ethics Committee (previously, the Hollywood Private Hospital Ethics Committee, Western Australia). As part of the WAMS, participants underwent comprehensive neuropsychological assessments, using self-reports and informant-reports questionnaires and surveys. All participants completed a demographic questionnaire and provided informed consent. Participants with current or previous diagnosis of a neurodegenerative disease, stroke or psychotic disorders were excluded from this study. Only older adults who performed within the normal range on cognitive measures were included in this study. More information on the neuropsychological and psychological assessments used in the WAMS can be found in Sohrabi et al. (42). Participants with unilateral deafness or already wearing hearing aids were excluded from this study. All participants underwent an otoscopic examination, a PTA and an ASSR, in the order given, in the same session/day. Only participants with normal otoscopic findings were included in the study.

PTA Recording

Pure tone audiometry was conducted (air-conduction) bilaterally at 500, 1000, 2000, 4000, 8000 Hz using the KUDUwave 5000 system, Type 2 clinical audiometer (Emoyo, Johannesburg, South Africa). Tones were presented via insert earphones which were inserted in the ear canals with circumaural headphones placed over the ears. An automated threshold-seeking paradigm was used to establish hearing threshold. At each frequency, threshold levels were determined using the Hughson-Westlake (43) procedure, by increasing increments of 10 dB followed by decreasing increments of 5 dB. Participants were required to press a button in response to any tones they heard during the assessment. Degree of HL was classified based on the American Speech-Language-Hearing Association (ASHA) classification system adapted from Clark 1981 (44).

ASSR Recording Parameters

ASSR was performed in an electrically shielded and sound attenuated room. Participants were tested while awake and in a relaxed Fowler's position (45). Air-conducted stimuli were presented to the left and right ear simultaneously via ER-3A insert earphones. Acoustic stimuli were generated and presented by the Chartr EP system (Version 5.3, GN Otometrics). Four carrier frequencies: 500, 1000, 2000, and 4000 Hz, were tested using an automated multiple ASSR technique that utilizes an algorithm that uses a Fourier Linear Combiner with an adaptive filter and circular statistical analysis (46). This means that the four carrier frequencies were tested simultaneously in both ears at each modulation frequency. 100% amplitude modulation and 20% frequency modulation were used for all carrier frequencies, with the response confidence set at 95% as predefined by the system manufacturer. The modulation frequency varied for each carrier frequency: modulation rates were 88, 80, 96, and 92 Hz for the right and 90, 82, 98, and 94 Hz for the left ear, for 500, 1000, 2000, and 4000 Hz carrier frequencies, respectively. A gain of 200 k, a low-pass filter at 105 Hz and a high-pass filter at 65 Hz were used.

ASSR recordings were obtained using four Ag/AgCl disc electrodes which were placed according to the International Electrode System (IES) 10-20; two inverting (reference) electrodes on each mastoid (one behind left ear and one behind right ear) behind the ear, non-inverting (active/recording) electrode at vertex (Cz) and ground electrode on the lower forehead. Prior to recording, the skin was prepared for electrode placement with a mild abrasive to obtain electrode impedances under 5 KΩ. ASSR measurements were performed using a descending procedure, by recording electrical responses while reducing the intensity of the acoustic signal in 10 dB steps until the threshold. The threshold was defined as the minimum intensity of detected responses, with a maximum of 7 min search time for each frequency allowed. Participants were not required to actively participate during ASSR recordings. Default correction factors (500 Hz−20 dB HL, 1000 Hz−10 dB HL, 2000 Hz−10 dB HL, 4000 Hz– 10 dB HL) on the Chartr EP system were applied to all final audiograms obtained from ASSR. To minimize artifacts and noise interference as a result of body movement, participants were instructed to stay still during the recording.

TABLE 2 | Mean (± SD) pure tone audiometry (PTA) and auditory steady-state response (ASSR) hearing threshold values (in decibels dBHL) in normal hearing older adults.

Frequency (Hz)	**500**			**1000**			**2000**			**4000**		
Ear	**R (*n* = 34)**	**L (*n* = 32)**	**Combined (*n* = 66)**	**R (*n* = 45)**	**L (*n* = 45)**	**Combined (*n* = 90)**	**R (*n* = 50)**	**L (*n* = 49)**	**Combined (*n* = 99)**	**R (*n* = 35)**	**L (*n* = 36)**	**Combined (*n* = 71)**
PTA	13.9 ± 8.2	13.2 ± 7.2	13.6 ± 7.7	17.1 ± 8	16.6 ± 8.6	16.8 ± 8.2	15.5 ± 11.2	15.5 ± 11.7	15.5 ± 11.4	23.7 ± 16.3	24.5 ± 16.6	24.1 ± 16.3
ASSR	21.7 ± 12.4	20.6 ± 11.6	21.2 ± 11.9	22.8 ± 12.7	22.8 ± 11	22.8 ± 11.8	20.6 ± 12.1	21.8 ± 10.5	21.2 ± 11.3	30 ± 15.7	27.7 ± 16.7	28.8 ± 16.1
Difference	7.7 ± 11.6	7.3 ± 10.8	7.5 ± 11.2	5.7 ± 10.2	6.2 ± 10.2	6 ± 10.2	5.1 ± 8.3	6.3 ± 8.2	5.7 ± 8.2	6.2 ± 9.1	3.1 ± 9.2	4.7 ± 9.2
P-value	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P = 0.046$	$P < 0.001$

R, right ear, L, left ear.

Statistical Analysis

After the PTA and ASSR measurements, statistical analysis was performed using IBM SPSS Statistics, version 25.0 (IBM Corp, Armonk, NY). Continuous variables were presented as a mean with standard deviation, and categorical variables were presented as absolute numbers and percentages. A Student *t*-test was used to compare normally distributed continuous variables between PTA and ASSR measures. PTA and ASSR threshold measures were also compared with an assessment of the correlation using Pearson's correlation analysis. Frequencies in which ASSR testing did not elicit a response were excluded from the final statistical analysis. A *p*-value of <0.05 was considered statistically significant.

RESULTS

A total of 50 (100 ears) community-dwelling older adults (14 male and 36 female) took part in this study (**Table 1**). Participants were aged between 61–84 years, average age for males was 72.9 ± 6 years and for females 71.6 ± 5.1 years (combined mean age 72.1 ± 5.4 years). On average, participant depression, anxiety, and stress scores were within normal levels (depression: 0–4, anxiety: 0–3, and stress: 0–7) according to the DASS 21 (47) severity scale: 2.2 ± 2.1, 2.2 ± 2.2 and 4.3 ± 2.9, respectively (**Table 1**). There was no significant correlation between psychological status (depression, anxiety, and stress) and participant age or gender (Pearson's correlation).

Behavioral PTA

Behavioral hearing thresholds using PTA were obtained for the whole sample. In this study, hearing range between 0–25 dB HL was considered normal hearing, 26–40 dB HL was considered mild HL, 41–55 dB HL was considered moderate HL, 56–70 dB HL was moderately severe HL, 71–90 was considered severe HL and 91 dB HL and above was considered profound HL. According to average 4-point PTA threshold measures, 78% (39/50) of participants had normal hearing thresholds (0–25 dB HL) and 22% (11/50) had mild hearing loss (26–40 dB HL). There was no significant correlation between PTA threshold measures and participants' depression, anxiety, or stress scores (Pearson's correlation). On average, males (24.6 dB ± 10.3, $n = 14$) had significantly higher hearing thresholds ($p < 0.05$) when compared to females (16.3 dB ± 7.2, $n = 36$), $t_{(48)} = 3.26$; $p = 0.002$. There was a low, however significant, correlation between PTA thresholds and participant age, $r_{(49)} = 0.28$; $p < 0.05$, showing increased thresholds with age.

ASSR

ASSR thresholds could not be measured in 34%, 10%, 1% and 27% of ears for 500, 1000, 2000, and 4000 Hz frequencies, respectively. These cases were excluded from further statistical analysis for the frequency in which no response was measured; hence the number of data points differs between frequencies. ASSR testing took on average 20 min to complete, with the shortest time recorded to achieve threshold measures at all tested carrier frequencies being 3.5 min and the longest time being 30.5 min. Threshold measures for all four carrier frequencies were obtained in 36% (18/50) of participants. Of those participants the average 4-point hearing thresholds indicate 72.2% (13/18) had normal hearing, 22.2% (4/18) had mild hearing loss and 5.5% (1/18) had moderate hearing loss. There was no significant correlation between ASSR thresholds and participants' gender, depression, anxiety, and stress scores (Pearson's correlation). There was a moderate, and significant, linear positive correlation between ASSR thresholds and participant age $r_{(17)} = 0.48$; $p < 0.05$.

Comparison of ASSR and PTA in Older Adults

Table 2 and **Figure 1** provide a summary of the mean thresholds for each carrier frequency for both PTA and ASSR. ASSR thresholds were significantly higher as compared to PTA thresholds based on the paired sample *t*-test analyses. The significant difference between the two procedures (i.e., PTA and ASSR) was seen at all frequencies, 500 Hz (7.5 dB ± 11.2, $t_{(65)} = 5.49$; $p < 0.001$), 1000 Hz (6 dB ± 10.2, $t_{(89)} = 5.58$; $p < 0.001$), 2000 Hz (5.7 dB ± 8.2, $t_{(98)} = 6.87$; $p < 0.001$) and 4000 Hz (4.7 dB ± 9.2, $t_{(70)} = 4.28$; $p < 0.001$), in order from highest to lowest threshold difference (**Table 2**). Mean PTA and ASSR hearing threshold values and differences were similar for each carrier frequency when analyzed for left and right ears separately, as noted in **Table 2** and **Figure 1**.

The majority of all thresholds measured using ASSR were higher than thresholds measured using PTA for the same ear. Overall, 59% of ASSR thresholds overestimated (were higher than) PTA thresholds, 18% underestimated PTA thresholds and 23% were the same as the PTA thresholds. A similar trend can be seen when looking at each carrier frequency separately, with the majority of ASSR thresholds overestimating the PTA threshold (**Figure 2**). Over 80% of hearing thresholds measured using ASSR were within ± 15 dB from thresholds measured using PTA at 500 (80.3%), 1000 (85.5%), 2000 (90.9%) and 4000 (88.7%) Hz. In total, 63.6% of thresholds measured using ASSR were within ±10 dB from PTA thresholds at 500 Hz, 72.2% at 1000 Hz, 79.8% at 2000 Hz and 78.9% at 4000 Hz. Distribution of ASSR and PTA threshold differences (dB HL) for each carrier frequency are presented in **Figure 3**.

Correlation analysis, as presented in **Figure 4**, revealed strong significant ($p < 0.001$) linear correlations between hearing threshold measures from ASSR and PTA at 1000 Hz, 2000 Hz and 4000 Hz at $r_{(89)} = 0.53$, $r_{(98)} = 0.74$, and $r_{(70)} = 0.84$, respectively. A moderate, yet significant, correlation between thresholds for ASSR and PTA was seen for the 500 Hz carrier frequency ($r_{(65)} = 0.42$; $p < 0.001$). Similarly, correlation analysis of each ear separately resulted in strong correlations for threshold measures between ASSR and PTA at 1000 Hz (right ear only), 2000 Hz and 4000 Hz and moderate correlations at 500 Hz and 1000 Hz (left ear only). See **Supplementary Figures S1, S2** and **Supplementary Table S1**.

DISCUSSION

Hearing thresholds obtained from PTA and ASSR in the current study were found to be significantly correlated in a cohort consisting of elderly participants with normal hearing or mild hearing loss. This is in agreement with other studies that also reported a significant correlation between hearing thresholds obtained using PTA and ASSR (10, 37, 48). However, in the present study, there was a statistically significant increase in thresholds measured with ASSR as compared to PTA at all tested carrier frequencies. Mean threshold differences between PTA and ASSR were largest at 500 Hz with a difference of 7.5 dB HL and lowest at 4000 Hz with a difference of 4.7 dB HL. Nonetheless, we showed that the majority (varying between 64 and 79% dependent on carrier frequency) of threshold differences between ASSR and PTA were within 10 dB of each other and over 80% of ASSR thresholds were within 15 dB of PTA thresholds. Ten to fifteen dB differences in threshold measures are considered to be clinically acceptable and are tolerable when making hearing intervention plans (37, 49). Therefore, the results of this study indicate that threshold measures recorded using ASSR have the potential to provide useful objective estimations of hearing thresholds in "difficult to test" older adults for the timely detection and treatment of hearing loss. It should be noted that the present cohort of older adults presented with normal cognitive function and psychological status (i.e., depression, anxiety and stress), therefore, these factors would have no influence on test outcomes. Additionally, there was no statistical correlation between cognitive, psychological or gender status and hearing acuity.

In most cases, ASSR over estimated PTA thresholds. Over estimation of hearing thresholds could lead to an increased risk of false positives (identifying someone with HL even if hearing is normal) as well as over estimation of HL severity. Variations in the analysis algorithm and application of correction factors used to obtain ASSR and PTA thresholds could be contributing factors to the variation in threshold measures between the two techniques (49). In commercial acquisition systems, to counteract differences between ASSR and PTA, correction factors are applied based on the carrier frequency. Correction factors are set based on the difference between PTA and ASSR thresholds in subjects with varied hearing and age range (50). These correction factors can differ from one system manufacturer to another and are set as standard for most groups (i.e., adults, children, those with and without HL), which can result in variations in the threshold measures from one commercial system to another for the same subject (50). It may be that the correction factors applied to other age ranges may be suboptimal for older adults as used in the present study. Indeed, it has previously been suggested that ASSR can be a more useful technique in children, adults and older adults if the correction factors applied are defined specifically for each age group (50).

One factor that may influence the observed variations is the modulation rate used. In this study, for ASSR, default modulation rates were set for each carrier frequency according to manufacturer [Chartr EP (44)] recommendations. Modulation rates ranged from 80–98 Hz across the carrier frequencies. These

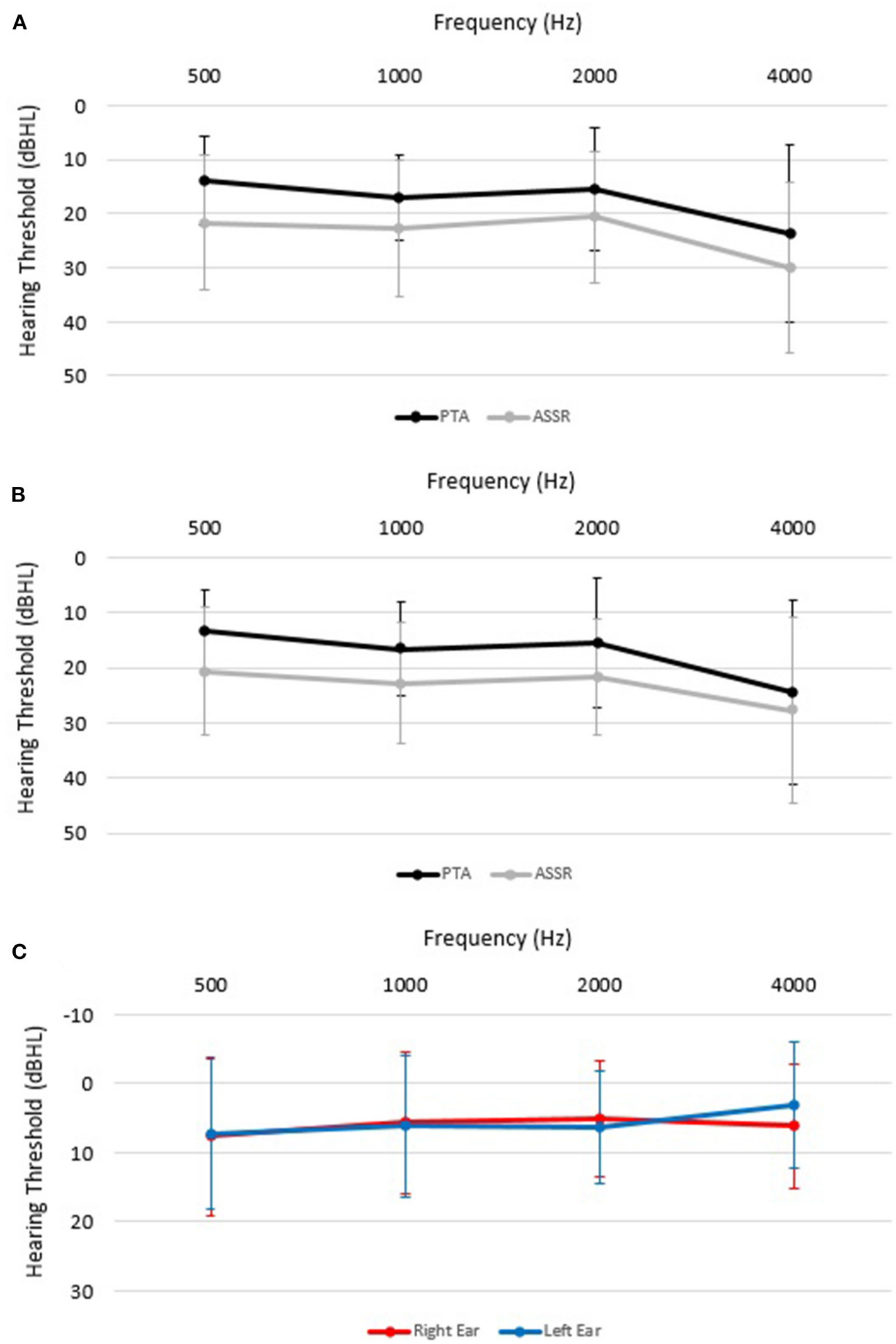

FIGURE 1 | Mean (± SD) pure tone audiometry (PTA; black lines **A, B**) and auditory steady-state response (ASSR; gray lines **A, B**) hearing thresholds (in decibels dBHL) for each carrier frequency in the right ear **(A)**, left ear **(B)**. **(C)** shows threshold differences between PTA and ASSR in left and right ears.

modulation rates are considered fast modulations as they are over 50 Hz. Previous research that has informed acquisition system manufacturers, has been on participants in other age ranges [i.e., infants (35), adults under 35 (48), or a combination of children and adults (10, 11, 30, 36)] and this has yielded inconsistent ASSR protocols/recommendations. Previous research revealed that ASSRs are difficult to record in infants at low modulation frequencies (∼40 Hz), therefore, high modulation frequencies have become a standard for ASSR testing regardless of the age of the subject (51). However, there is evidence to suggest that age-related changes in neural envelope processing may result in decreased ASSR responses for faster modulation rates in older

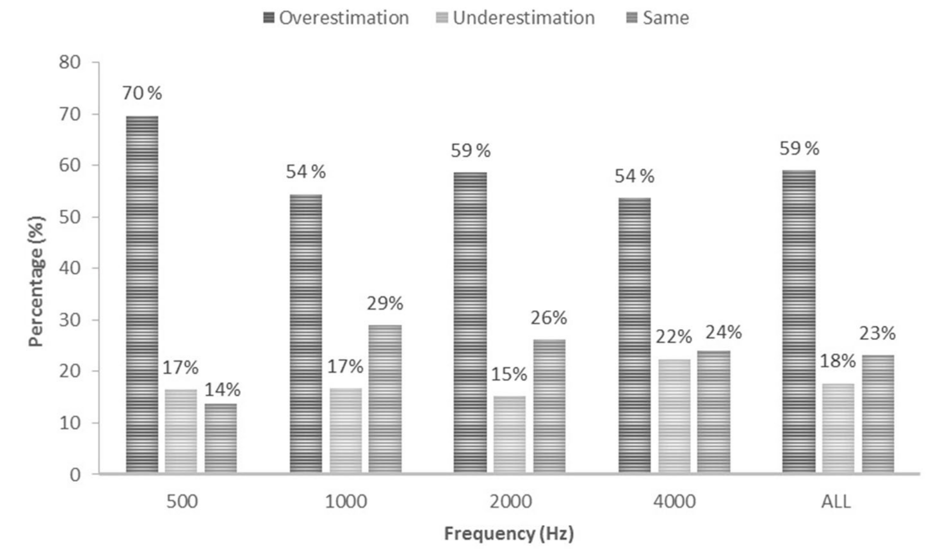

FIGURE 2 | Accuracy of ASSR estimations in percentage (%) presented for each frequency and for all frequencies combined.

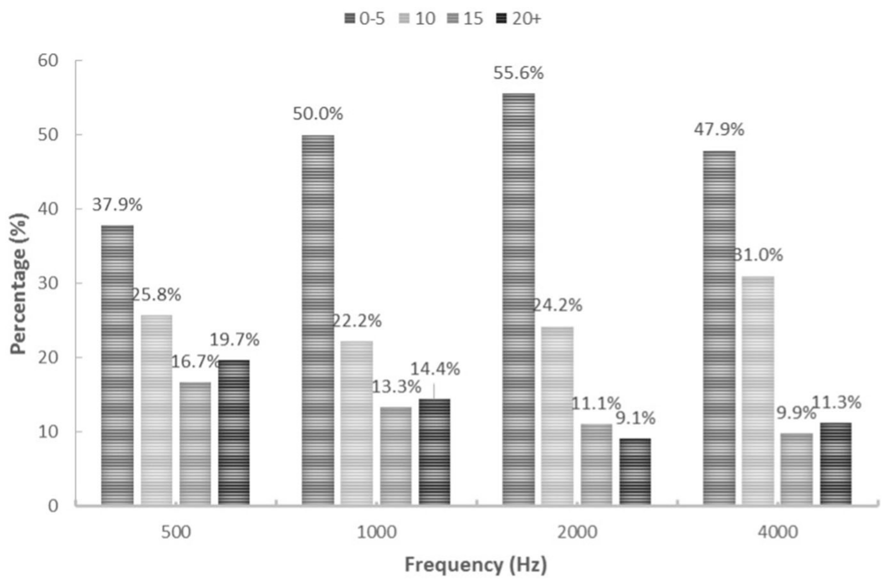

FIGURE 3 | Distribution of ASSR and PTA differences for each frequency. Percentages presented for 0–5 dB, 10 dB, 15 dB and 20 dB+ (and over) threshold differences.

adults compared to young adults or children (39, 40). Specifically, for high gamma frequencies ($\geq$ 80 Hz) ASSRs decrease with age, which in turn suggests age-related decline in synchronized activity of high gamma oscillations (52–54). Therefore, this could contribute to the significant increase in thresholds seen when using ASSR compared to PTA in the present study.

Additionally, phase-locking of ASSR is suggested to be lower at high modulation rates in middle-aged and older adults in comparison to young adults (39). This has also been demonstrated by a number of animal studies, which show decline in phase-locking in fast modulations in both near- and far-field recordings with aging (55–57). The effect of aging on phase-locking is not reported for slow modulation frequencies (<50 Hz) (39). Reduced ASSR strength and lower phase-locking to fast modulation frequencies with aging is in line with reports of reduced temporal precision in encoding rapidly modulated

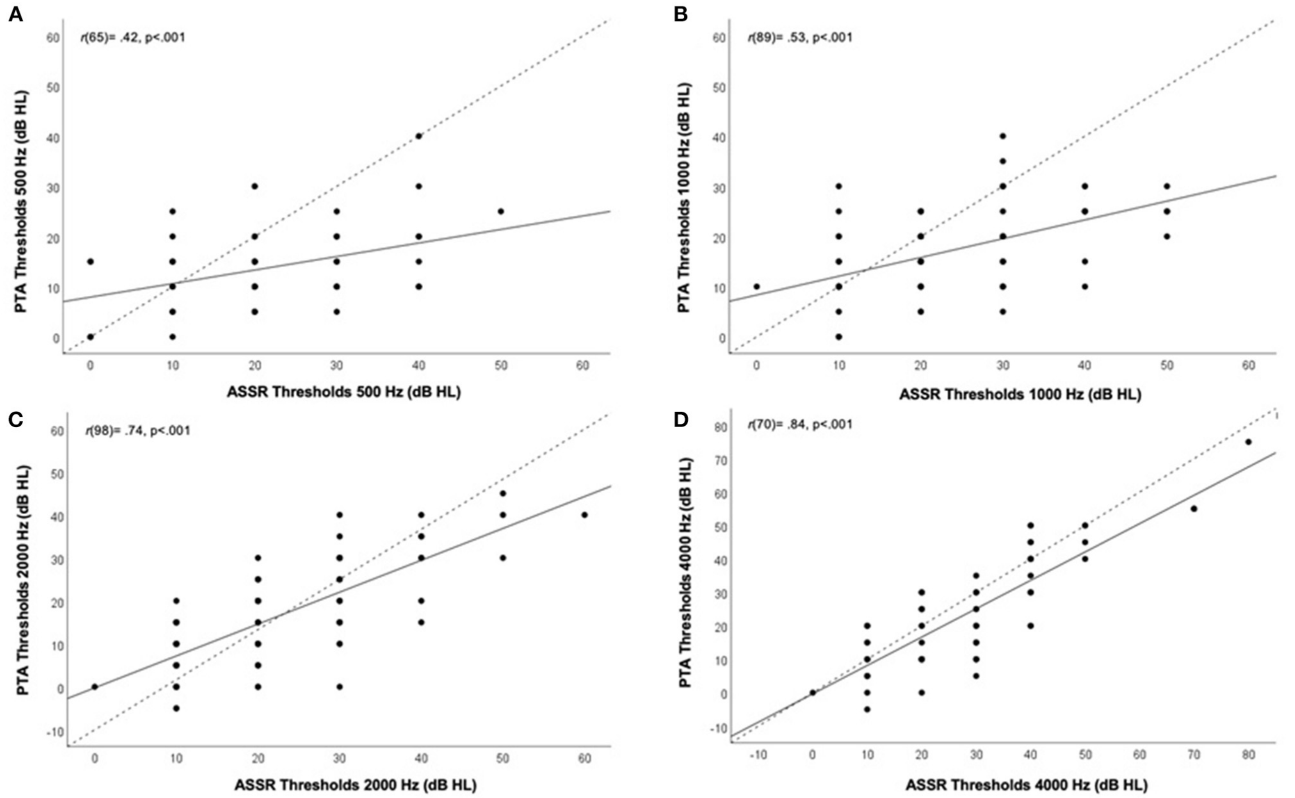

FIGURE 4 | Correlation between hearing thresholds (both ears combined) obtained from auditory steady-state response (ASSR) (x-axis) and pure-tone audiometry (PTA) (y-axis) in dB HL according to carrier frequency. Different panels show different frequencies. **(A)** 500Hz, **(B)** 1000 Hz, **(C)** 2000 Hz, and **(D)** 4000 Hz. Correlation coefficients (r) and p-value are presented on the top left corner of each panel for all tested frequencies. Black line indicates line of best fit, dotted line indicates 1:1 ratio line.

stimuli as a result of loss of functional inhibition across the central auditory pathway with aging (38, 39, 41). Therefore, the use of high modulation rates for older adults may have resulted in no thresholds being established through ASSR in some cases and larger variations (less accuracy) in threshold differences between PTA and ASSR.

In this study ASSR thresholds were obtained for all tested carrier frequencies in only 36% of the participant sample ($n = 50$). Similarly, a study conducted on children ($n = 20$) found that ASSR thresholds were obtained for all frequencies tested (500, 1000, 2000, and 4000 Hz) in only 45% of the sample (35). Although, ASSR provides an objective measure of hearing thresholds without the need for active participation of the subject, it can be affected by patient movement, behavioral status (e.g., awake vs. asleep) and patient preparation (electrode impedance). Therefore, variations in these factors can result in inaccurate measures or no thresholds being established (11, 30). Additionally, a number of studies suggest that ASSR threshold measures at 500 Hz should be interpreted with caution (10, 30, 58). Similar to previous research, in the present study ASSR threshold measures at 500 Hz were the most variable among all carrier frequencies and also had the highest percentage of thresholds that were not established during the testing time limits (36, 59). This has been suggested to be due to the higher EEG noise and internal jittering as a result of neurologic asynchronicity (60). More research is required to establish strategies to overcome patient and equipment factors than may have negative impact on test results and accuracy.

Study Limitations

One experimental protocol limitation that could have contributed to larger variations in threshold differences between ASSR and PTA is the difference in step sizes used for establishing thresholds in the two tests. For PTA in this study threshold levels were determined by increasing increments of 10 dB followed by decreasing increments of 5 dB, and for ASSR, measurements were performed using a descending procedure, by reducing the intensity of the acoustic signal in 10 dB steps until the threshold. The differences in step size and protocols used in PTA and ASSR can easily result in at least 5 dB difference in thresholds between the two tests. Additionally, this study used an automated KUDUwave audiometer to establish PTA and compared them to ASSR. There is a ± 5–10 dB difference between KUDUwave and clinician obtained (in an audiological clinical setting) hearing thresholds in frequencies between 1000 and 4000 Hz and more than 10 dB difference for 500 Hz (47). Therefore future research should compare ASSR thresholds with KUDUwave PTA and clinician obtained PTA.

In this study, a maximum threshold search time of 7 min was set for ASSR due to testing time constraints. However, in some participants no thresholds were establish during this 7 min time frame and ASSR thresholds were obtained at all four carrier frequencies for only 36% of the participant sample. For ASSR, it is unknown how much search time should be allowed for thresholds to be established, highlighting another ASSR protocol element that requires refining and further research to improve methodological quality and clinical application.

Furthermore, this study only included participants with normal hearing or mild hearing loss, which does not provide full insight into the use of ASSR for testing hearing acuity in older adults. Previous reports indicate that ASSR thresholds are closer to PTA thresholds in participants with sensorineural hearing loss in comparison to normal hearing participants (30, 36, 61). It has been suggested that such smaller threshold differences between ASSR and PTA in HL participants could be due to abnormal increase in the response amplitude as a result of recruitment for damage to outer hair cells (36, 61). Therefore, generalizing ASSR findings to normal hearing and HL groups could result in incorrect threshold estimation. Due to the limited sample size in this study and difficulties obtaining ASSR thresholds in some participants, exploring the reliability of ASSR threshold measures in participants based on hearing thresholds (those with normal hearing and those with mild HL) was not suitable. Future research would benefit from investigating ASSR threshold measures in older adults with different degrees of HL.

CONCLUSION

The findings of the present study provide evidence to indicate that ASSR may be a valuable tool in estimating objective frequency-specific hearing thresholds in older adults. Though there is increased risk of false positive, due to over estimation of HL, ASSR is still reliable in assessing HL. Threshold differences between ASSR and the gold standard PTA were, for the majority of participants, within clinically acceptable ranges, thus ASSR can be useful in identifying HL in order to create hearing treatment plans for older adults who are unable to complete behavioral PTA. However, additional research is required to determine optimal parameters of ASSR for threshold estimation in older adults in order to increase its consistency and reliability, as well as eliminate some of the limitations associated with this technique. More research is also required to define modulation frequencies that are more suitable for older adults, which could provide valuable information to inform ASSR testing protocols for them as well as acquisition system manufacturers. Defining specific correction factors that take into account the patient's age, degree of HL and are specific for the carrier frequency can also help improve the methodological quality of ASSR.

AUTHOR CONTRIBUTIONS

HT, DJ, WM, HS, and RM conceived the idea for this study. HT collected hearing data with the supervision of DJ. HT prepared the initial draft with input from DJ, WM, and HS. All authors contributed to the development of the idea of this manuscript, as well as contributed to the revision of the manuscript. All authors approved for the manuscript to be submitted.

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The impact of age-related hearing loss on structural neuroanatomy: A meta-analysis

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This meta-analysis investigated the association between age-related hearing loss and structural neuroanatomy, specifically changes to gray matter volume. Hearing loss is associated with increased risk of cognitive decline. Hence, understanding the effects of hearing loss in older age on brain health is essential. We reviewed studies which compared older participants with hearing loss (age-related hearing loss: ARHL) to older adults without clinical hearing loss (no-ARHL), on neuroanatomical outcomes, specifically gray matter (GM) volume as measured by magnetic resonance imaging. A total of five studies met the inclusion criteria, three of which were included in an analysis of whole-brain gray matter volume (ARHL group $n = 113$; no-ARHL group $n = 138$), and three were included in analyses of lobe-wise gray matter volume (ARHL group $n = 139$; no-ARHL group $n = 162$). Effect-size seed-based d mapping software was employed for whole-brain and lobe-wise analysis of gray matter volume. The analysis indicated there was no significant difference between adults with ARHL compared to those with no-ARHL in whole-brain gray matter volume. Due to lacking stereotactic coordinates, the level of gray matter in specific neuroanatomical locations could only be observed at lobe-level. These data indicate that adults with ARHL show increased gray matter atrophy in the temporal lobe only (not in occipital, parietal, or frontal), compared to adults with no-ARHL. The implications for theoretical frameworks of the hearing loss and cognitive decline relationship are discussed in relation to the results. This meta-analysis was pre-registered on PROSPERO (CRD42021265375).

Systematic Review Registration: https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=265375, PROSPERO CRD42021265375.

KEYWORDS

age-related hearing loss (ARHL), gray matter (GM), structural MRI, brain volume, hearing loss, meta-analysis

Introduction

The population is aging, meaning that health issues which affect older adults become more prevalent (1), impacting on the older population's quality of life and placing increasing pressure on health care services. Two such health concerns are hearing loss and dementia. In the UK around 70% of people aged 70+ experience hearing loss (2), and around 7.1% of over 65's, rising to 14% of those over 80, are living with dementia (3). Critically, there is evidence that these health concerns may be associated. Hearing loss has been identified as the largest potentially modifiable risk factor for dementia (4). Hearing loss could account for as much as 8% of global dementia cases (5). It is likely that many risk factors are associated, and exacerbate one another leading to increased risk of dementia in certain individuals. Considering this, understanding the neural mechanisms of hearing loss, and how they may contribute to the association between hearing loss and dementia, is a priority.

Age-related hearing loss (ARHL) is often caused by degeneration of the inner and outer hair cells within the cochlea. These cells are responsible for the transduction of sound, and their atrophy can manifest in high-frequency hearing loss (6). Age-related atrophies in the peripheral auditory system can also be observed in the stria vascularis, a cochlea structure responsible for maintaining metabolic processes (7), or in degeneration of spiral ganglion cells, the initial neurons in the pathway from the ear to the brain (8). Importantly, evidence suggests that changes and atrophies in people with ARHL do not end at the peripheral auditory system, but are also evident in the auditory pathway and auditory cortex (9, 10). Understanding the cortical changes, in auditory areas and beyond, would provide valuable insights into how the brain changes in people with ARHL, and provide evidence for the mechanisms that underpin the association between hearing loss and cognitive decline.

A number of potential explanations for the relation between hearing loss and dementia have been proposed. These include non-causal hypotheses such as: (1) The common cause hypothesis, which suggests that rather than hearing loss leading to dementia, there is a common neuro-degenerative pathology which underlies both conditions such as general aging or vascular disease (11, 12); or (2) The hearing bias in cognitive assessment hypothesis, which suggests that there may be an overestimation of the link between hearing loss and dementia, because untreated hearing loss could be a significant confound in clinical cognitive assessments that rely on auditory presentation (13, 14). However, the relation between hearing loss and cognitive decline remains after controlling for age and vascular factors (15, 16), and hearing loss has been found to be associated with poorer cognitive functioning even when the cognitive assessments do not rely on verbal communication (17). As such, a causal mechanism may be more likely. Causal hypotheses include: (1) The cognitive load (or information degradation) hypothesis, which theorizes that people with ARHL are required to use more cognitive resources for speech perception leaving fewer available for general cognitive processes, which could lead to the symptoms of dementia (18); and (2) The sensory deprivation hypothesis, which postulates that reduced sensory input from the ear leads to reduced neural activation, cortical re-organization, and atrophy across brain areas involved with speech perception (10, 19). Both these causal hypotheses make suggestions with regards to functional or structural neuro-cognitive changes that might accompany ARHL, including upregulation or reorganization of neural resources (20) or atrophy across speech perception networks [see (21) for a discussion of cortical changes]. As such, a comprehensive review of the current literature on the neural consequences of ARHL is required to generate evidence to refute or support these causal hypotheses.

The first step in the systematic examination of neural consequences of ARHL is to assess the evidence for tangible neuroanatomical changes, in both auditory and wider cortices. There is evidence from longitudinal studies that individuals with ARHL display accelerated gray matter (GM) atrophy in auditory cortex compared to individuals without ARHL (22), however these group differences have not always reached statistical significance (23). In cross-sectional studies, there is also evidence for decreases in whole brain volume in those with ARHL compared to those without (10), and in specific brain areas associated with speech perception including the anterior cingulate cortex (24). The mechanism by which ARHL leads to wider brain atrophy is unclear. One potential explanation is that over-reliance on wider brain networks involved in speech perception due to impaired auditory processing contributes to neural degeneration of these areas. There is evidence that individuals with ARHL, compared to those without, display increased functional connectivity across auditory and visual sensory cortices (25), and between auditory cortex and the cingulo-opercular network after controlling for both age and cognitive function (26). The over-reliance on these additional brain networks to support speech perception in individuals with ARHL could enable neural degeneration due to glutamate excitotoxicity (24). Through this mechanism, the neurons across the up-regulated brain networks may die due to prolonged activation of glutamate receptors beyond their natural capacity (27).

Despite evidence for potential up-regulation and cortical atrophy, it is still unclear as to whether or not ARHL exacerbates the cortical changes observed in aging. Heterogeneity in research methods, such as differences in participant age ranges, imaging techniques, or clinical definitions of hearing loss, as well as small sample sizes, can lead to ambiguity in interpretation of the results. This meta-analysis will deliver a systematic and specific analysis of the existing literature on neuroanatomical changes in ARHL, controlling for some of these confounds through appropriate inclusion criteria, and study quality assessment. We sought to investigate across cross-sectional and longitudinal evidence whether GM volume, as measured by MRI, differs in adults aged ≥60 years with ARHL compared to those without ARHL. In this paper, ARHL is defined by hearing thresholds above 25 dB HL for frequencies between 500 and 2,000 Hz in adults aged 60+, whereas "without ARHL" is defined by hearing thresholds below 25 dB HL for frequencies between 500 and 2,000 Hz in adults aged 60+, representing age-appropriate hearing function. It was hypothesized that we would observe (1) decreased whole brain GM volume, as well as (2) decreases in GM volume in the temporal lobe, in individuals with ARHL compared to those without ARHL.

Methods

This meta-analysis was pre-registered on PROSPERO (PROSPERO 2021, CRD42021265375), available from: https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42021265375) Additionally, all materials including: search strings; references obtained at all screening stages; screening manuals and inter-rater consistency data; extracted data; and analysis files can be found in the project's repository on the Open Science Framework (OSF): https://osf.io/g5qcb/.

Literature search

An initial pilot search was conducted on PubMed and Prospero according to best practice guidance (28, 29), in order to: (1) confirm whether systematic reviews and meta-analyses on this topic already existed; (2) estimate the feasibility of the meta-analysis and availability of data; and (3) identify key papers to inform the selection of appropriate key words and criteria for the final search string. Unlike the full literature search, the pilot search was characterized by iterative searching without pre-defined search strings. In-depth engagement with the literature might introduce potential bias in the construction of the full literature search. Hence, engagement with the pilot search was limited to 2 h.

Subsequently, the full literature search was conducted following PRISMA guidelines (30) and best practice guidelines from the "Cochrane Highly Sensitive Search Strategy" (31). Nine databases were searched (Table 1). To maximize effective retrieval of relevant papers, the research question was approached, inter alia, from medical (PubMed), nursing (CINAHL), and psychological (PsycINFO) perspectives. To ensure comprehensiveness, searches were not filtered in any way, e.g., by database internal filters, such as publication date, or by full-text articles (see Table 1 for exception in Scopus). If any full text could not be accessed the research team planned to contact the authors of the papers, and allow 1 week for an initial response before re-contacting. A total of 2 weeks was granted for authors to respond and provide access to papers.

Search strings (see Supplementary materials 1 for full details) were constructed using keywords, free-text terms, and search functions (Boolean operators, near searches, truncation, wild card symbols, quotations), to ensure specificity and sensitivity across databases. An example of the search terms included: "hearing loss" or "hearing impairment" or "presbycusis," and "voxel-based" or "morphometry" or "magnetic resonance imaging" or "cortical thickness" or "gray matter," and "older adult." The final search strings, selected keywords, and Boolean operators were reviewed by a librarian to ensure adherence to best practice insights. To manage resource and time constraints, the search was limited to titles and abstracts.

TABLE 1 The databases searched and the date on which the search was conducted.

Database	Date of last search*
Academic Search Ultimate	05 August 2021
CINAHL	05 August 2021
Embase	05 August 2021
MEDLINE Complete	05 August 2021
PsycINFO	05 August 2021
PubMed	05 August 2021
Scopus	10 August 2021†
The Cochrane Library	05 August 2021
Web of Science	05 August 2021

*Articles published after termination of each search on the respective date were not included. †The final search in Scopus was delayed relative to other databases, as the Scopus search initially retrieved over 30,000 articles. The search was optimized with advice sought from a librarian. Specifically, search terms of tangential relevance, e.g., cognition, that were included in the searches of other databases were omitted in the search of Scopus. Additionally, filters were applied to limit the search to articles in the English language published after 1980, when MRI was increasingly used clinically.

Prior to conducting the literature search, a strategy test of sensitivity was completed in which four key papers that satisfied the inclusion criteria were identified using a database not used in the final search to avoid bias (Google Scholar). The sensitivity of the search strings was evaluated by testing how many of these four key papers indexed in the selected databases (Table 1) could be retrieved. Once the search sensitivity was acceptable, the literature search was conducted across the selected databases. All key papers were retrieved with the search indicating high likelihood that the search would successfully identify relevant articles.

Article screening

Articles (n = 14,078) retrieved from the literature search were imported to the reference manager software CADIMA [https://www.cadima.info/; for a review, see (32)]. An overview of the articles retained at each stage of the screening process can be found in the PRISMA flow diagram presented in Figure 1 (33). Any duplicated articles, retrieved by more than one database, were removed in a two-step process: (1) automatic de-duplication based

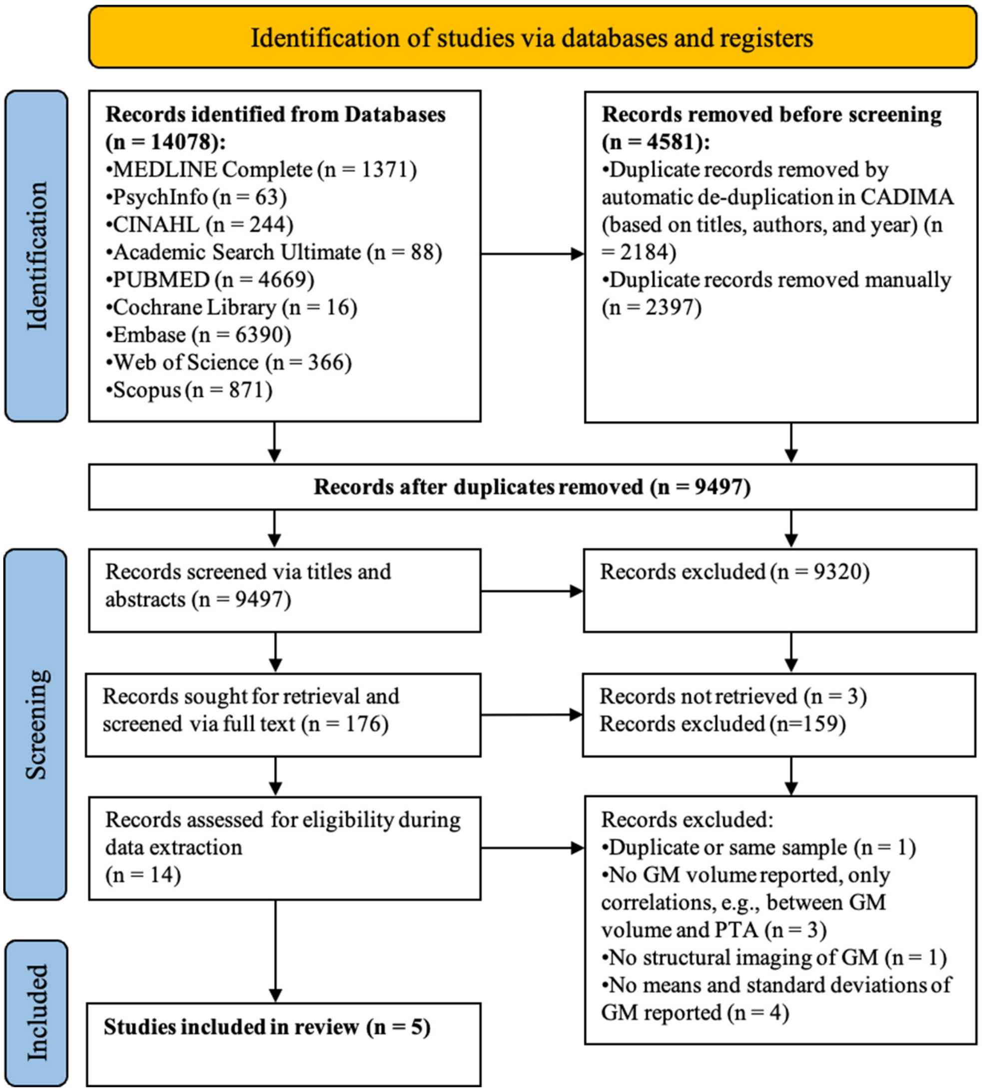

FIGURE 1
PRISMA flow diagram detailing the number of articles selected at each review stage. GM refers to gray matter.

on congruity in authors, title, and year of publication; and (2) manual de-duplication by two raters based on abstracts.

Unique articles ($n = 9,497$) were screened by four raters for inclusion according to specific criteria (see the associated OSF repository for the full criteria used: https://osf.io/g5qcb/) in two consecutive stages: (1) title-abstract; and (2) full-text screening. Before each screening stage, the consistency between raters was checked with inter-rater reliability tests (Table 2). A subset of articles (60 at title-abstract screening stage, and 40 at full-text screening stage) were screened by two raters in parallel until at least 80% agreement was reached for each criterion. During screening, a manual with the inclusion criteria, additional background information, and guidance for the use of CADIMA was provided (manuals are also available in the OSF repository).

After consistency checks, 10% of all titles and abstracts and 30% of full-texts were double screened by two independent raters in parallel. During this initial period in screening, inconsistencies were resolved through group discussion and if necessary, information was added to the screening manual to clarify eligibility criteria. Training and extensive guidance was provided to ensure all raters fully understood the application of eligibility criteria before the remaining articles were independently screened. Throughout this process, raters met weekly to resolve outstanding questions. Raters were instructed to include rather than exclude articles if unsure, to prevent false exclusion of papers.

TABLE 2 Proportional agreement of the inter-rater reliability at each screening stage.

Criteria	Proportional inter-rater agreement
Title-Abstract Screening	Overall 0.95
Criterion 1	0.10
Criterion 2	0.95
Criterion 3	0.92
Criterion 4	0.99
Criterion 5	0.90
Full-text Screening	Overall 0.87
Criterion 1	0.98
Criterion 2	0.86
Criterion 3	0.83
Criterion 4	0.80

The final set of articles that passed title-abstract ($n = 176$) and full-text screening stages ($n = 14$), were checked for listing in the Retraction Watch Database (http://retractiondatabase.org/) to ensure that only studies not retracted were included.

Articles were screened for inclusion along a set of pre-defined eligibility criteria for (1) the title-abstract and (2) the full-text screening stages. These criteria were designed in line with the PICO/PECO framework (34, 35), which clarifies the review objectives and inclusion criteria across four domains: Population (P), Intervention/Exposure (I/E), Comparator (C), and Outcomes (O). To meet the inclusion criteria, articles were required to be original research, containing empirical data, and provided in English. Additionally, the articles needed to meet the following PICO/PECO criteria. (P) it was required that participants be older adults (average age of 60+ at the time of at least one study session) without clinical psychological or neurological illnesses, who either had or did not have age-related hearing loss (ARHL). (I/E) ARHL was defined as a pure tone average (PTA) of >25 dB HL across 0.5–2 kHz and no-ARHL was defined as a PTA of ≤25 dB HL averaged across 0.5–2 kHz (36, 37). (C) Studies needed to compare at least two groups, one group with ARHL and one group with no-ARHL, either longitudinally or cross-sectionally. (O) Outcome measures needed to include voxel-based morphometry data (VBM) as measured by magnetic resonance imaging (MRI) available for both groups. The outcome measures of interest were gray matter (GM) volumes for specific brain regions or for the whole brain.

Data extraction

Data extraction was performed manually by four reviewers with identically structured Microsoft Excel (2018) forms. For each study, data were extracted by at least two independent reviewers and then checked for agreement, to decrease the possibility of manual errors (38). Any inconsistencies in the extracted data were resolved through discussion. A data extraction manual was provided (available in the OSF repository). Where data were presented visually only, means and standard deviations were read from graphs. If non-significance or significance was reported without associated exact p-values, the p-value was assumed to be $p = 0.05$ and $p = 0.04$, respectively [based on Anatürk et al. (38)]. The main source of heterogeneity in analysis is likely to stem from sample characteristics, study design, and imaging technique. Therefore, data extraction included participant demographics for both ARHL and no-ARHL groups (sample size, age, sex, PTA), study design (timeframe, sampling method, timescale of longitudinal measurements), details of image acquisition (MRI field strength, smoothing kernel, slice thickness, voxel size, mask, normalization space), and outcome measures (e.g., (un)corrected p-values, effect sizes, mean and standard deviation of whole-brain and regional GM volumetric measurements). Any papers found not to meet the inclusion criteria at data extraction stage were excluded (for details, see the PRISMA flowchart, Figure 1, and materials on the OSF).

Nine papers were excluded at this stage due to the nature of the reported data or ineligibility. One was a duplicate reference. The reasons for exclusion and main findings of the remaining eight papers are reported here. Three papers (39–41) reported only correlational or regression data; due to the nature of the statistical methodology, these papers did not meet the inclusion criteria of specific group comparison between no-ARHL and ARHL groups. Across two of these studies, authors reported that ARHL only had a small effect on: GM volume in Hershel's gyrus (41); and cortical thinning in the right superior temporal and left dorsolateral frontal areas, in women only with right ear hearing loss (39). The third study reported correlations between brain volume changes and functional impairment factors within ARHL groups only (40). Another paper was ineligible as only data on white matter were reported, for which there were no differences between ARHL and no-ARHL groups (42). Finally, four papers that did not report means, standard deviations, or statistical values that could be employed in this meta-analysis were excluded due to lack of data provision following the procedure for author contact mentioned in section 2.1. Two of these papers reported no significant differences in brain volume between ARHL and no-ARHL groups (43, 44). Another reported significant differences in brain volume and thickness across temporal lobe regions, and areas of the cingulate cortex, in ARHL compared to no-ARHL (45), whereas another reported reduced GM volume in the middle frontal gyrus, but not in auditory regions, in ARHL compared to no-ARHL (46).

The remaining papers ($n = 5$) were included in this meta-analysis.

Critical appraisal

A framework to appraise critically the quality of the studies included in this meta-analysis was created using previously established appraisal tools. These tools typically comprise a set of questions that raters use to evaluate the research methodologies of included studies. Such frameworks allow appraisal of study quality and risk of bias, to evaluate the reliability and validity of studies' findings, and whether findings are representative and generalizable at population-level. No automation tools were used in this process. The critical appraisal tool was based on an adapted version of the trialed AXIS appraisal framework (47) and response options were based on QualSyst (48). Individual criteria of the original AXIS tool were omitted or included based on Müller et al. (28), the STROBE statement (49), and GRADE (50, 51). To minimize subjectivity (28), each paper included in the analysis was appraised by two raters independently, and disagreements resolved by discussion or ultimately, a third rater. Raters were trained and received an explanatory manual. To assess homogeneity in methods and outcomes across studies, the critical appraisal accounted for whether or not research controlled for confounding factors (e.g., sex, education, smoking status, age), as well as methodological factors that could influence data interpretation (e.g., sample size). The appraisal manual and method of calculation are available in the OSF repository.

Statistical analysis

Statistical analysis was conducted using effect-size seed-based d mapping (ES-SDM) software to perform a random-effects meta-analysis (52), the software was developed to aid the meta-analysis of voxel-based data as obtained by VBM (www.sdmproject.com). VBM is a neuroimaging technique comparing GM concentration by mapping images onto a normalized stereotactic space and extracting GM volumes, smoothing data, and finally, comparing group GM volume differences via voxel-wise comparison (53). ES-SDM is described in detail elsewhere (52, 54) and has previously been tested for reliability (55, 56), including for GM volume comparison (57). ES-SDM calculates Hedges' *g* effect sizes for mean analysis, based on group means, and standard deviations (54). Hedges' *g* uses a pooled and weighted standard deviation based on sample size and is thus more accurate for small sample sizes ($<$20) than Cohen's *d* which uses a normal standard deviation (58–60). The inclusion of non-significant findings in the analysis addresses bias toward significant overall results.

The analysis of GM volumes in ES-SDM was a mean analysis providing Hedges' *g* and corresponding *z*- and *p*-values, as well as standard error, the lower and upper bounds of the effect size for each study, and a mean across studies. *Q* statistics were used to assess inter-study heterogeneity of effect sizes. The analysis followed the ES-SDM manual (available here www.sdmproject.com). Furthermore, we verified the analysis in RStudio [R version 4.1.0, (61)], using the *metafor()* package to conduct a random-effects model meta-analysis (62), and to produce the associated forest and funnel plots. The data analysis obtained was the same in ES-SDM and R. The R code is provided in the OSF repository: https://osf.io/g5qcb.

Calculation of missing standard deviations

Under the assumption that data were normally distributed, missing standard deviations were calculated from confidence intervals using the following formula (30):

$$\mathbf{SD} = \sqrt{N}\ \mathbf{x}\frac{upper\ limit - lower\ limit}{\mathbf{3.92}} \tag{1}$$

ES-SDM and R analysis

Sample sizes of both groups (ARHL vs. no-ARHL), means and standard deviations were entered for each study and each region of interest (ROI) into ES-SDM. Separate analyses were conducted for whole-brain and lobe-wise GM volume using the same ES-SDM "globals" calculator as it relies on mean analysis and is, therefore, also suitable for analysis of mean ROI data. To compare ROIs, ROIs were collated into frontal, temporal, parietal, and occipital lobes. The collation was completed following the papers' verbal labels of ROIs (e.g., superior temporal lobe was allocated to the temporal cortex) and widely accepted localisations, e.g., precentral gyrus is undisputedly considered to lie in the frontal lobe. If allocation to a lobe was unclear, a neuroanatomy textbook was consulted (63). The same data were entered into R and separate meta-analyses were conducted for whole-brain, frontal, temporal, parietal, and occipital lobe data, as was done in ES-SDM software.

Results

Of the 9,497 articles screened, five satisfied all inclusion criteria (see Figure 1 for the PRISMA flow diagram). During title-abstract screening, a total of 413 inter-rater inconsistencies were resolved of which only 102 affected inclusion ($n = 25$) or exclusion ($n = 77$) of the article. During full-text screening there were 37 inconsistencies of which 16 affected inclusion ($n = 2$) or exclusion ($n = 14$). The number of articles that were at first included, but through discussion of inconsistencies excluded, can be explained by the instructions to screeners to be more lenient than conservative in case of uncertainty when judging whether or not the articles fulfilled screening criteria.

Across both screening stages, the criteria that caused most inconsistencies were whether or not participants were at least 60 years old and (neurologically) healthy, as well as whether

TABLE 3 Means, and standard deviations where applicable, of the data extracted for papers used in the whole-brain analysis.

Study	Design	Sample size (M/F)		Age (SD)		PTA (SD)		NH PTA definition	MRI field strength (T)	Critical appraisal score
		HL	NH	HL	NH	HL	NH			
Chen et al. (64)	CS	22 (10/12)	23 (11/12)	63.59 (2.38)	64.74 (2.65)	34.54 (4.63)	14.82 (1.73)	≤25 dB at 0.25–8 kHz	1	0.83
Lin et al. (22)	L	51 (40/11)	75 (36/39)	73.80 (7.30)	67 (6.90)	N/A	N/A	≤25 dB at 0.5–4 kHz	1.5	0.88
Xing et al. (65)	CS	40 (19/21)	40 (18/22)	63.60 (7.07)	61.55 (3.72)	32.69 (3.87)	16.17 (2.22)	≤25 dB at 0.25–8 kHz	1	0.88

Chen et al. (64) ensured participant groups were matched on age, sex, and education, and also found minimal group differences across cognitive performance domains. Xing et al. (65) also ensured matched groups on age, sex, and education, and included these factors as covariates in analyses. Further, groups displayed statistically similar cognitive functioning across the majority of tests. Lin et al. (22) controlled for intracranial volume, smoking, interactions between, time, HL, age, and sex. CS refers to cross-sectional and L refers to longitudinal.

TABLE 4 Means, and standard deviations where applicable, of the data extracted for papers used in the lobe-wise analyses.

Study	Design	Sample size (M/F)		Age (SD)		PTA (SD)		NH PTA definition	MRI field strength (T)	Critical appraisal score
		HL	NH	HL	NH	HL	NH			
Belkhiria et al. (66)	CS	55 (23/32)	56 (19/37)	75.38 (5.20)	72.53 (5.41)	36.27 (9.50)	17.08 (4.80)	<25 dB at 0.5–4 kHz	3	0.83
Belkhiria et al. (24)	CS	33 (12/11)	31 (6/25)	73.78 (5.79)	70.84 (4.84)	25.68 (4.86)	14.16 (3.15)	≤0 dB at 0.5–4 kHz	1	0.89
Lin et al. (22)	L	51 (40/11)	75 (36/39)	73.80 (7.30)	67 (6.90)	N/A	N/A	≤25 dB at 0.5–4 kHz	1.5	0.88

Belkhiria et al. (66) controlled for education, cognitive abilities, visuospatial capacities, (neuro-) psychiatric symptoms. Belkhiria et al. (24) controlled for education, cognitive abilities, dementia, smoking, cardiovascular risk factors, diabetes, depression. Lin et al. (22) controlled for intracranial volume, hypertension, smoking, interactions between time, HL, age and sex. CS refers to cross-sectional and L refers to longitudinal.

or not the study made a direct comparison of neuroanatomical differences between groups.

Heterogeneity of effect sizes and evaluation of study quality

Descriptive statistics of the meta-analyzed studies are presented in Tables 3, 4. Only one of the five included studies adopted a longitudinal approach. As such it was not possible to meta-analyze rate-of-change in GM volume over time. Therefore, all included effects reflect cross-sectional comparisons between participant groups with and without ARHL, regardless of longitudinal or cross-sectional study design.

Critical appraisal of the included studies was conducted by a minimum of two raters to assess research quality and risk of bias to evaluate. Studies were assessed across a range of criteria, including whether or not research controlled for important confounding factors that could influence hearing status or brain structure (e.g., sex, age, education). In one study, it was unclear whether confounding variables were controlled for in analyses, but the two groups (ARHL and no-ARHL) were matched for age, sex, and education, and showed statistically similar cognitive functioning across a range of tests (64). Critically, the four remaining studies state explicitly that statistical analyses accounted for both age and sex (22, 24, 65, 66). Further,

TABLE 5 Available means and standard deviations extracted for meta-analysis of whole-brain data.

Study	Normalization space	GM volume (SD)	
		HL	NH
Chen et al. (64)	MNI	564.00 (24.40)	571.20 (20.80)
Lin et al. (22)	MNI	535.10 (40.99)	530.30 (39.32)
Xing et al. (65)	MNI	32.3 (1.80)	31.6 (1.40)

TABLE 6 Available means and standard deviations extracted for meta-analysis of lobe-wise data.

Study	MRI space	Region	GM volume (SD)	
			HL	NH
Frontal lobe				
Belkhiria et al. (66)	TAL	LH Anterior cingulate	2.41 (0.37)	2.42 (0.39)
		RH Anterior cingulate	1.84 (0.38)	1.79 (0.40)
		LH Orbitofrontal	7.32 (0.78)	7.44 (0.72)
		RH Orbitofrontal	7.41 (0.80)	7.48 (0.72)
Belkhiria et al. (24)	TAL	Frontal superior	4.91 (0.22)	4.91 (0.18)
		Anterior cingulate	4.78 (0.33)	4.81 (0.26)
		Precentral gyrus	4.90 (0.24)	4.97 (0.24)
Lin et al. (22)	MNI	Frontal lobe	156.90 (14.76)	155.10 (14.10)
Occipital lobe				
Belkhiria et al. (66)	TAL	LH Fusiform gyrus	7.25 (1.09)	7.57 (0.93)
		RH Fusiform gyrus	7.35 (1.32)	7.36 (1.01)
		LH Lingual gyrus	5.77 (1.01)	5.96 (0.87)
		RH Lingual gyrus	6.10 (1.00)	6.05 (0.79)
Lin et al. (22)	MNI	Occipital lobe	74.20 (8.02)	75.40 (7.71)
Temporal lobe				
Belkhiria et al. (66)	TAL	LH Superior temporal	14.05 (1.71)	13.74 (1.28)
		RH Superior temporal	13.05 (1.53)	13.21 (1.13)
		LH Transverse temporal	0.90 (0.18)	0.92 (0.15)
		RH Transverse temporal	0.72 (0.13)	0.75 (0.13)
		LH Middle temporal	11.28 (1.56)	11.29 (1.44)
		RH Middle temporal	11.24 (1.53)	11.43 (1.30)
		LH Fusiform gyrus	7.25 (1.09)	7.57 (0.93)
		RH Fusiform gyrus	7.35 (1.32)	7.36 (1.01)
		LH Posterior cingulate	2.85 (0.49)	2.83 (0.40)
		RH Posterior cingulate	2.74 (0.41)	2.74 (0.48)
		LH Insula	5.42 (0.64)	5.41 (0.56)
		RH Insula	5.55 (0.63)	5.55 (0.51)
		LH Hippocampus	3.38 (0.41)	3.53 (0.37)
		RH Hippocampus	3.51 (0.45)	3.74 (0.38)
		LH Amygdala	1.32 (0.22)	1.40 (0.21)
		RH Amygdala	1.54 (0.24)	1.60 (0.21)
Belkhiria et al. (24)	TAL	Temporal inferior	5.52 (0.26)	5.51 (0.19)
		Temporal middle	5.31 (0.21)	5.32 (0.17)
		Temporal superior	5.30 (0.25)	5.33 (0.25)
		Posterior cingulate	4.97 (0.25)	4.99 (0.18)
		Parahippocampus	5.33 (0.48)	5.36 (0.58)
Lin et al. (22)	MNI	Temporal lobe	114.80 (10.93)	114.20 (10.36)
Parietal lobe				
Belkhiria et al. (24)	TAL	Postcentral gyrus	3.99 (0.18)	4.08 (0.21)
Lin et al. (22)	MNI	Parietal lobe	86.1 (9.47)	85.5 (9.26)

The original region names provided by the studies were maintained. Belkhiria et al. (66) separated region data into left and right hemisphere data (LH and RH, respectively). This separation was maintained in analysis. The insula was included in the temporal lobe because although it is covered by both the frontal and temporal lobes (68), it connects strongly to cortical and subcortical structures in the temporal lobe, e.g., the superior temporal sulcus and limbic structures (69). The fusiform gyrus data, reported by Belkhiria et al. (66), were included in both the temporal and occipital lobes, because the gyrus spans across the basal surface of both lobes. Due to a lack of reported coordinates, the regions were allocated to lobes using their verbal labels, commonly accepted allocations, and a neuroanatomy textbook (63).

TABLE 7 Mean analysis results for whole-brain data.

Study	Hedges' *g*	Standard error	*z*-value	*p*-value	Confidence interval	
					Low	High
Chen et al. (64)	−0.31	0.30	−1.04	0.30	−0.90	0.28
Lin et al. (22)	0.12	0.18	0.66	0.51	−0.24	0.48
Xing et al. (65)	0.43	0.23	1.90	0.06	−0.01	0.87
Overall effect	0.12	0.19	0.64	0.52	−0.24	0.48

three studies controlled for education (24, 65, 66), and three controlled for total estimated intracranial volume (22, 24, 65). In the one longitudinal study included here, the additional variables of hypertension, smoking, hearing impairment, and years since baseline, were included as covariates in analyses (22). Importantly, across the studies included in this meta-analysis, all considered the impact of key confounding variables (e.g., age) on the analyzes, allowing for clearer interpretation of the relation between ARHL and GM volume.

Overall, critical appraisal scores did not lie below 0.83, indicating high methodological quality (48). In combination with the observation that all ratings fell between 0.83 and 0.89, it is unlikely that methodological inadequacies skewed results or studies formed subgroups of studies with high and low methodological quality. However, it should be noted that a source of bias might be the consistently partial fulfillment of a sampling process likely to represent the target population. All studies employed convenience sampling (recruiting from hospital settings or previous study cohorts) and acknowledged this as a limitation. The results in this meta-analysis are consequently subject to the same constraints in generalizability of results.

Across analyses, the Q statistic did not reach significance indicating no significant heterogeneity of effect sizes between studies (whole-brain, $Q(2) = 3.93$, $p = 0.14$; frontal lobe, $Q(7) = 3.11$, $p = 0.87$; temporal lobe, $Q(26) = 17.59$, $p = 0.67$; parietal lobe $Q(2) = 2.78$, $p = 0.10$; occipital lobe, $Q(4) = 2.43$, $p = 0.66$). This homogeneity, in combination with the results from the critical appraisal, suggest no significant variation in the studies' characteristics and that the heterogeneity likely stems from sampling error alone. Thus, it is unlikely that underlying variation in methodology or participant groups between studies skewed the results (67).

Whole-brain and lobe-wise analysis

A comprehensive overview and visualization of results is presented in Tables 5–8, and Figures 2–6, respectively. In comparison with group no-ARHL, group ARHL, the differences whole-brain GM volume were not significant, Hedges' $g = 0.12$, $p = 0.52$. Similar to the whole-brain GM volume, group ARHL showed lower GM volumes in lobe-wise analysis. This difference was significant in the temporal lobe (Hedges' $g = -0.12$, $p = 0.007$), but was not significant in the frontal (Hedges' $g = -0.03$, $p = 0.64$), parietal (Hedges' $g = -0.17$, $p = 0.52$), nor occipital (Hedges' $g = -0.12$, $p = 0.14$) lobes.

Discussion

This meta-analysis sought to collate and evaluate the existing evidence for a difference in brain volume, specifically GM volume, in adults (aged ≥60 years) with ARHL, compared to those without ARHL. We sought to include data from both cross-sectional and longitudinal study designs, in order to consolidate and analyse the available empirical evidence and provide a better understanding of cortical changes associated with ARHL. We employed ES-SDM software to conduct analysis of neuroanatomical data across the included studies (52).

Three studies, two of which took a cross-sectional approach and one of which took a longitudinal approach, which reported GM volumes for the whole brain were included in the analysis of global neuroanatomical changes associated with ARHL. This analysis served to investigate whether the entire brain displays significant GM atrophy in individuals with ARHL, compared to those without ARHL, in order to further understand how hearing loss contributes to brain aging. The findings did not support our hypothesis that adults with ARHL would display significantly decreased whole brain GM volume, compared to those without ARHL. While previous research suggests that cross-cortical and brain wide changes are associated with ARHL (10, 22), this meta-analysis of collated studies suggests that changes associated with ARHL are not significantly greater than changes which occur in aging. If this is the case, then it is possible, as suggested by the common cause hypothesis, that a neurodegenerative factor may underly the brain atrophies observed in both hearing loss and aging.

Elevated tau protein levels could be an indicator of a potential third factor that no meta-analyzed study has accounted for explicitly. Tau is a protein found to aggregate abnormally in Alzheimer's Disease and has, therefore, been considered as a viable biomarker (70). In a study on people with dementia, the prevalence of tau protein in the cerebral spinal fluid was found

TABLE 8 Mean analysis results for lobe-wise data.

Study	Region	Hedges' *g*	Standard error	*z*-value	*p*-value	CI	
						Low	High
Frontal lobe							
Belkhiria et al. (66)	LH Anterior cingulate	−0.03	0.19	−0.14	0.89	−0.40	0.35
	RH Anterior cingulate	0.13	0.19	0.67	0.50	−0.25	0.50
	LH Orbitofrontal	−0.16	0.19	−0.84	0.40	−0.53	0.21
	RH Orbitofrontal	0.09	0.19	−0.48	0.63	−0.46	0.28
Belkhiria et al. (24)	Frontal superior	0.00	0.25	0.00	>0.99	−0.49	0.49
	Anterior cingulate	−0.10	0.25	−0.40	0.69	−0.59	0.39
	Precentral gyrus	−0.29	0.25	−1.15	0.25	−0.78	0.21
Lin et al. (22)	Frontal lobe	0.13	0.18	0.69	0.49	−0.23	0.48
Overall effect		−0.03	0.07	−0.47	0.64	−0.18	0.11
Temporal lobe							
Belkhiria et al. (66)	LH Superior temporal	0.20	0.19	1.07	0.28	−0.17	0.58
	RH Superior temporal	−0.12	0.19	−0.62	0.53	−0.49	0.25
	LH Transverse temporal	−0.12	0.19	−0.63	0.53	−0.49	0.25
	RH Transverse temporal	−0.23	0.19	−1.20	0.23	−0.60	0.14
	LH Middle temporal	−0.01	0.19	−0.04	0.97	−0.38	0.37
	RH Middle temporal	−0.13	0.19	−0.70	0.48	−0.51	0.24
	LH Fusiform gyrus	−0.13	0.19	−1.64	0.10	−0.69	0.06
	RH Fusiform gyrus	−0.01	0.19	−0.05	0.96	−0.38	0.36
	LH Posterior cingulate	0.04	0.19	0.23	0.81	−0.33	0.42
	RH Posterior cingulate	0.00	0.19	0.00	>0.99	−0.37	0.37
	LH Insula	0.02	0.19	0.09	0.93	−0.36	0.39
	RH Insula	0.00	0.19	0.00	>0.99	−0.37	0.37
	LH Hippocampus	−0.38	0.19	−1.20	0.05	−0.76	−0.01
	RH Hippocampus	−0.55	0.19	2.84	0.01	−0.93	−0.17
	LH Amygdala	−0.37	0.19	−1.93	0.05	−0.75	0.01
	RH Amygdala	−0.26	0.19	−1.39	0.17	−0.64	0.11
Belkhiria et al. (24)	Temporal inferior	0.04	0.25	0.17	0.86	−0.45	0.53
	Temporal middle	−0.05	0.25	−0.21	0.84	−0.54	0.44
	Temporal superior	−0.12	0.25	−0.47	0.64	−0.61	0.37
	Posterior cingulate	0.09	0.25	−0.36	0.72	−0.58	0.40
	Parahippocampus	−0.06	0.25	−0.22	0.82	−0.55	0.43
Lin et al. (22)	Temporal lobe	0.06	0.18	0.31	0.76	−0.30	0.41
Overall effect		−0.12	0.04	−2.70	0.01	−0.20	−0.03
Parietal lobe							
Belkhiria et al. (24)	Postcentral gyrus	−0.46	0.25	−1.80	0.07	−0.95	0.04
Lin et al. (22)	Parietal lobe	0.06	0.18	0.35	0.73	−0.29	0.42
Overall effect		−0.17	0.26	−0.64	0.52	−0.67	0.34
Occipital lobe							
Belkhiria et al. (66)	LH Fusiform gyrus	−0.31	0.19	−1.64	0.10	−0.69	0.06
	RH Fusiform gyrus	−0.01	0.19	−0.05	0.96	−0.38	0.36
	LH Lingual gyrus	−0.20	0.19	−1.05	0.29	−0.57	0.17
	RH Lingual gyrus	0.06	0.19	0.29	0.77	−0.32	0.43
Lin et al. (22)	Occipital lobe	−0.15	0.18	−0.84	0.40	−0.51	0.20
Overall effect		−0.12	0.08	−1.47	0.14	−0.29	0.04

LH and RH refer to left and right hemisphere, respectively. The insula was included in the temporal lobe, and the fusiform gyrus was included in both the occipital and temporal lobes (see note in Table 6 for explanations).

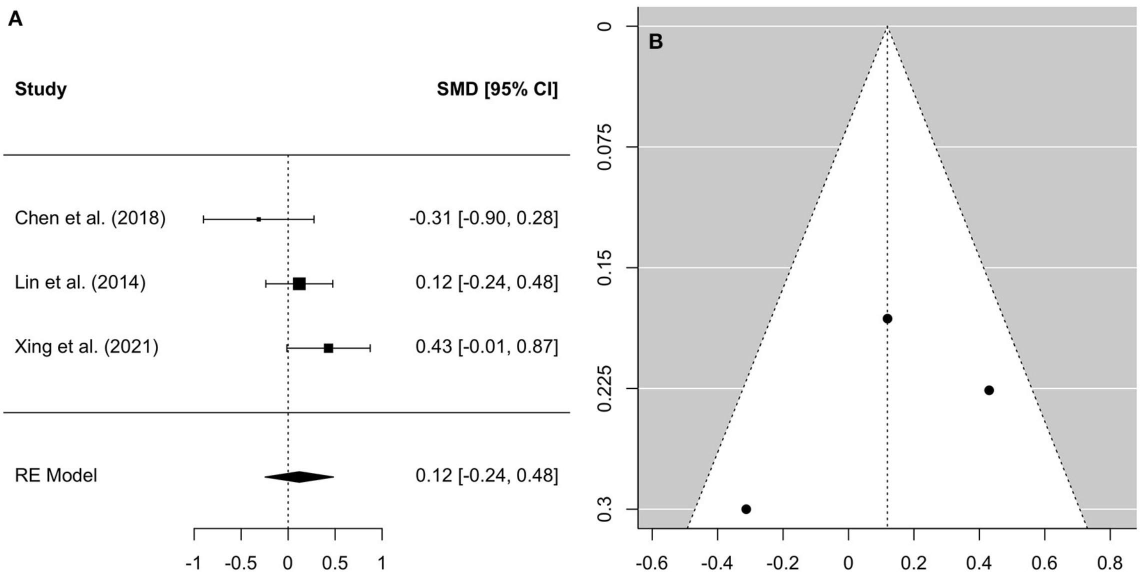

FIGURE 2
Forest plot **(A)** and funnel plot **(B)** of the whole-brain Analysis. In the forest plot **(A)** negative values on the x-axis indicate gray matter atrophy.

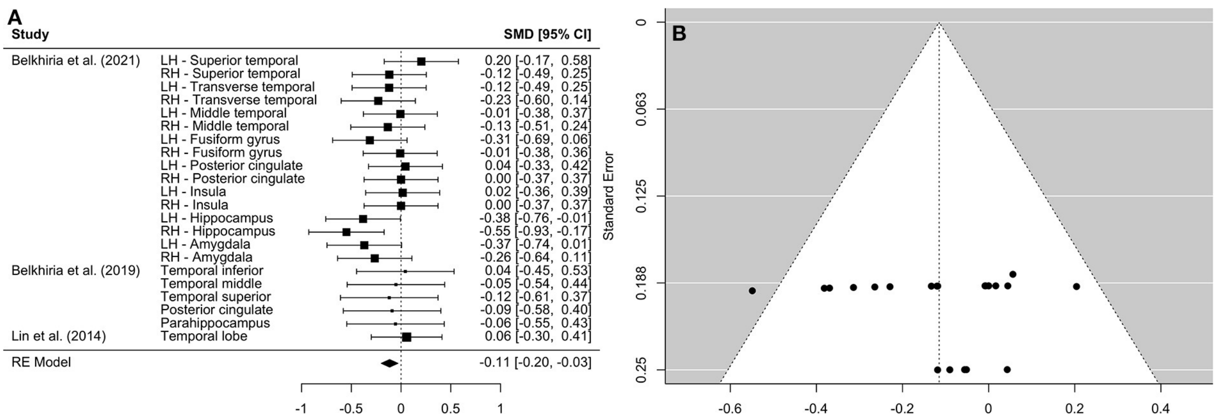

FIGURE 3
Forest plot **(A)** and funnel plot **(B)** of the temporal lobe analysis. In the forest plot **(A)** negative values on the x-axis indicate gray matter atrophy.

to be higher in participants who reported having hearing loss than in those who did not (71). Consequently, there may be an association between tau levels and hearing. Whilst this requires further investigation, it is possible that neuroanatomical findings in the meta-analyzed studies might be influenced by biomarkers of potential pre-clinical cognitive declines (such as tau levels) in participants with ARHL.

However, limiting neuroanatomical observations to whole brain analysis only may result in overlooking of essential information regarding lobe-wise cortical changes. Understanding in which cortical structures changes occur is important for establishing the role of potential underlying causal mechanisms. Three studies, two of which took a cross-sectional approach and one of which took a longitudinal approach, which reported GM volumes in specific brain areas were included in the lobe-wise analysis of GM volumes. This analysis enabled the investigation into cortical changes across brain lobes to establish whether GM atrophy extends beyond auditory cortex (situated in temporal lobe) in individuals with ARHL. The findings support our hypothesis that decreases in GM volume observed in individuals with ARHL compared to those without ARHL occur in the temporal lobe. This is consistent with existing literature which reports increased neural atrophy in auditory cortex in individuals with ARHL,

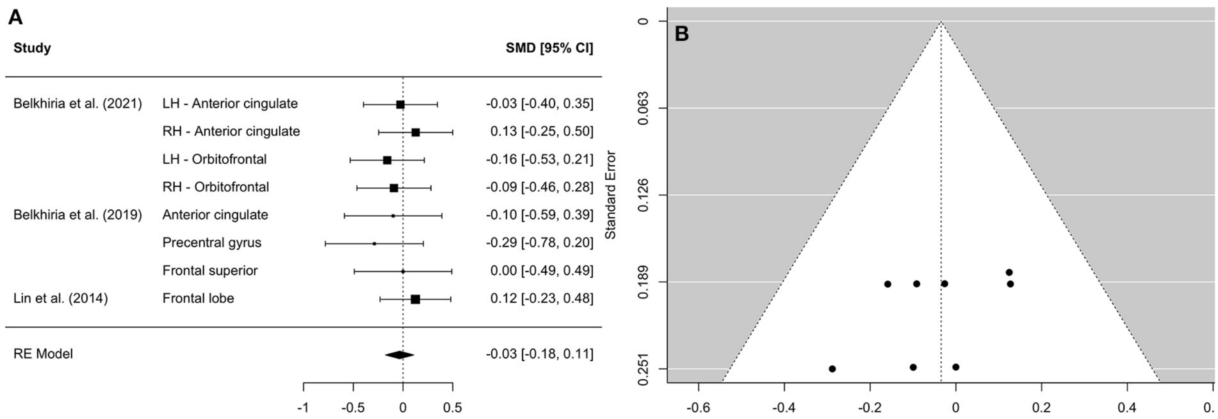

FIGURE 4
Forest plot **(A)** and funnel plot **(B)** of the frontal lobe analysis. In the forest plot **(A)** negative values on the x-axis indicate gray matter atrophy.

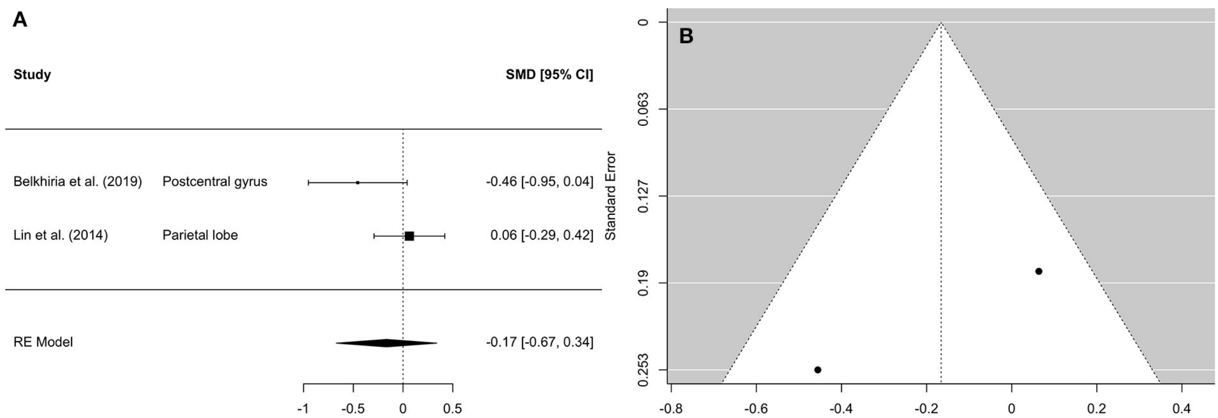

FIGURE 5
Forest plot **(A)** and funnel plot **(B)** of the parietal lobe analysis. In the forest plot **(A)** negative values on the x-axis indicate gray matter atrophy.

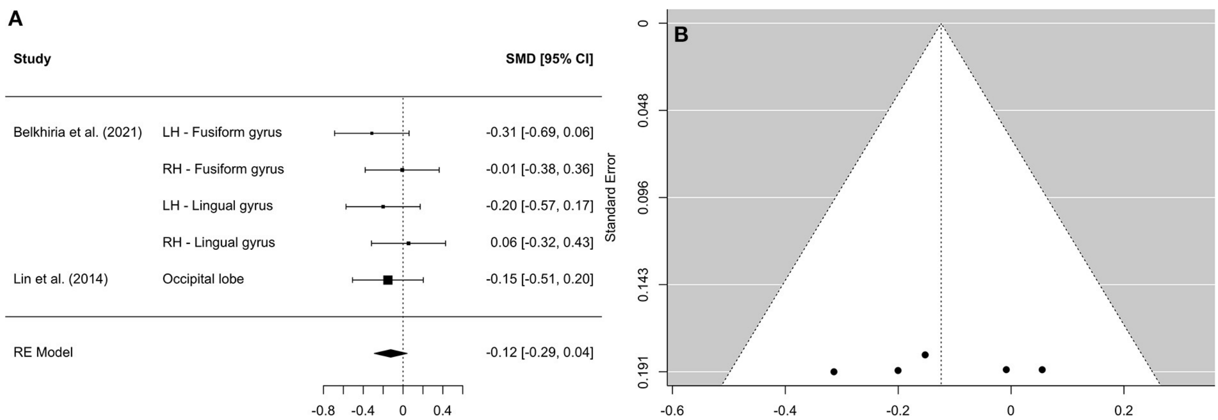

FIGURE 6
Forest plot **(A)** and funnel plot **(B)** of the occipital lobe analysis. In the forest plot **(A)** negative values on the x-axis indicate gray matter atrophy.

compared to those without ARHL (22). No evidence was found that declines in GM volume in people with ARHL occur in other lobes.

Research suggests that ARHL leads to up-regulation across brain networks to support speech perception, and there is evidence from functional imaging studies to support this, showing that ARHL is associated with increased functional connectivity between auditory cortex and cognitive networks (26). Increased use of such cortical resources has been theorized to trigger neurodegeneration due to over-use of neural resources and excitotoxic cell death. Yet, our data provide no evidence for declines in GM volume beyond temporal lobe and thus do not support the hypothesis that potential compensatory activity leads to neurodegeneration. This has implications for interpretation of the causal hypotheses underlying the association between hearing loss and cognitive decline. Importantly, previous research finds that declines in cognitive functioning are also associated with greater GM volume loss in temporal regions (72). This has important implications as temporal atrophies may be an underlying mechanism in the relation between hearing loss and cognitive declines.

An additional explanation for the relation between hearing loss and cognitive declines in aging not captured by this review, is the role of the psychosocial pathway in sensory deprivation: Hearing loss does not manifest exclusively in auditory deprivation due to poor hearing, but is also accompanied by mental health and well-being consequences. Adults with hearing loss may be more likely to withdraw from social interactions due to hearing difficulties, leading to experiences of increased depression, and loneliness or isolation (73). Some authors suggest that social withdrawal may exacerbate the relation between hearing loss and wider brain and cognitive health, because it increases sensory deprivation (74). As such, there may be consequences for neural and cognitive functioning if these brain areas are less utilized for stimulating social communication.

It is important to consider, with regards to both the whole-brain and lobe-wise analyses, that the included study designs varied between cross-sectional and longitudinal. First, it is possible that global GM atrophy, or atrophy across wider cortices, only occurs after prolonged sensory deprivation. In two previous longitudinal studies, a significant association between pure-tone hearing loss and reduced GM in auditory cortex was only present after at least 5 years (22, 23). Hence, it is possible theoretically that atrophies extending further than auditory cortex, or temporal lobe, may only occur after prolonged up-regulation or cortical resource reallocation to assist speech perception due to ARHL. Second, in both designs, consideration of confounding factors is important, but particularly for cross-sectional research. As such, it is important to note that differences in the controlled variables across the included studies may affect the results, and create ambiguity for interpretation. By design, longitudinal research allows for increased control over individual factors which may influence data, and hence any observed neural changes are more easily interpreted as occurring due to HL, rather than aging or another underlying neurodegenerative variable.

Importantly, to ensure homogeneity across studies included in this meta-analysis, included studies were limited to those which classified hearing status using pure tone audiometry. This method is the current gold-standard in clinical audiology, but does not account well for supra-threshold hearing difficulties, i.e., difficulties in hearing sounds presented above the auditory threshold of the listener, such as the perception of speech in background noise. Consequently, this meta-analysis does not capture the impact of such difficulties, which may present before observable declines in the audiogram are evident, on neural structure. Some studies have investigated the relation between speech reception threshold (SRT), obtained using digits-in-noise tests, on neuroanatomy. Such research found that, in older adults, poorer speech perception was associated with lower GM volume, particularly in the left superior temporal gyrus (75). Further, in older participants with Alzheimer's dementia, poorer speech perception was associated with lower cortical thickness bilaterally across many cortices (76).

Further, as many studies did not report stereotactic coordinates, the data analysis options were limited to general lobe comparisons. Hence it is not possible to interpret exactly where GM atrophy occurs within the temporal lobe. Without exact cortical locations, it is difficult to draw strong conclusions regarding the underlying neural processes or systems. Additionally, all included studies employed opportunity sampling techniques. Therefore, any generalizations were limited to the targeted populations in the included studies. Importantly, these data should be interpreted with consideration of the sample size of studies included. In order to control for confounding variables and ensure heterogeneity in methods, strict inclusion criteria were used to select the studies meta-analyzed. In-turn this resulted in a smaller number of studies selected for analysis, which resulted in a smaller number of individual data points. It has been suggested that a large sample size of individuals (across the selected studies) is required for adequate power in whole-brain meta-analysis (77). For this to be possible, there is explicit need for future large-scale longitudinal research which seeks to observe the effects of age-related hearing loss on brain morphology.

In conclusion, this meta-analysis explored the evidence for a difference in GM volume, in older adults with ARHL, compared to those without ARHL. The analysis found evidence for reduced GM volume in temporal lobes in individuals with ARHL, compared to those without ARHL. There was no evidence that GM atrophies extended to frontal, parietal, or occipital lobes, nor was there evidence for whole brain GM declines in individuals with ARHL. It is possible that significant differences in GM volume are limited to the temporal lobe, because further cortical changes only occur after a critical time period of prolonged cortical resource re-allocation. However, this finding has important implications and further longitudinal research into how neural changes across the temporal lobe in people with ARHL affects wider brain health is essential.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://osf.io/g5qcb/.

Author contributions

KS, HN, and CP contributed to conception of the study. KS, HN, CP, and JR contributed to the design of the study. LH provided expert advice. KS, JR, KJ, and ES contributed to article screening and data extraction. KS, JR, and LH contributed to and performed the statistical analysis. KS and JR wrote the manuscript. KS, JR, HN, CP, and LH contributed to manuscript revision, read, and approved the submitted version. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fneur.2022.950997/full#supplementary-material

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Intrinsic brain activity reorganization contributes to long-term compensation of higher-order hearing abilities in single-sided deafness

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Single-sided deafness (SSD) is an extreme case of partial hearing deprivation and results in a significant decline in higher-order hearing abilities, including sound localization and speech-in-noise recognition. Clinical studies have reported that patients with SSD recover from these higher-order hearing abilities to some extent over time. Neuroimaging studies have observed extensive brain functional plasticity in patients with SSD. However, studies investigating the role of plasticity in functional compensation, particularly those investigating the relationship between intrinsic brain activity alterations and higher-order hearing abilities, are still limited. In this study, we used resting-state functional MRI to investigate intrinsic brain activity, measured by the amplitude of low-frequency fluctuation (ALFF), in 19 patients with left SSD, 17 patients with right SSD, and 21 normal hearing controls (NHs). All patients with SSD had durations of deafness longer than 2 years. Decreased ALFF values in the bilateral precuneus (PCUN), lingual gyrus, and left middle frontal gyrus were observed in patients with SSD compared with the values of NHs. Longer durations of deafness were correlated with better hearing abilities, as well as higher ALFF values in the left inferior parietal lobule, the angular gyrus, the middle occipital gyrus, the bilateral PCUN, and the posterior cingulate gyrus. Moreover, we observed a generally consistent trend of correlation between ALFF values and higher-order hearing abilities in specific brain areas in patients with SSD. That is, better abilities were correlated with lower ALFF values in the frontal regions and higher ALFF values in the PCUN and surrounding parietal-occipital areas. Furthermore, mediation analysis revealed that the ALFF values in the PCUN were a significant mediator of the relationship between the duration of deafness and higher-order hearing abilities. Our study reveals significant plasticity of intrinsic brain activity in patients with SSD and suggests that reorganization of intrinsic brain activity may be one of the compensatory mechanisms that facilitate improvement in higher-order hearing abilities in these patients over time.

KEYWORDS

single-sided deafness, resting-state fMRI, intrinsic brain activity, speech recognition, sound localization, compensatory mechanism

Introduction

Single-sided deafness (SSD) is an extreme case of partial hearing deprivation and refers to severe to profound hearing loss in one ear and normal hearing in the other ear. Due to hearing deprivation in one ear, patients with SSD can only obtain monaural clues from the environment. This causes these patients to have sharply decreased higher-order hearing abilities, particularly sound localization and speech-in-noise (SIN) recognition (Agterberg et al., 2014; Asp et al., 2018; Liu et al., 2018; Adigun and Vangerwua, 2021). Studies have observed better hearing abilities in SSD patients with longer durations of deafness than in those with shorter durations of deafness, suggesting that functional compensation occurs over time (Peckham and Sheridan, 1976; Lieu et al., 2012; Liu et al., 2018). Since the peripheral auditory input in most patients with SSD could hardly be improved due to the irreversible property of sensorineural hearing loss and the lack of binaural clues remains unchanged, it could be conjectured that central plasticity promoting better usage of limited peripheral auditory input probably plays an important role in functional compensation.

To date, a growing number of neuroimaging studies have explored the central structural and functional plasticity that occurs due to SSD. Structural studies *via* magnetic resonance imaging (MRI) have observed extensive morphological alterations in gray and white matter, as well as structural connectivity involving auditory areas, other sensory areas, and higher-order cognitive-related brain areas (Lin et al., 2008; Wu et al., 2009; Rachakonda et al., 2014; Yang et al., 2014; Fan et al., 2015; Wang et al., 2016; Li et al., 2019). Regarding function, both functional MRI (fMRI) and event-related potential (ERP) studies using auditory stimuli have found that the auditory cortex shows a more symmetrical and synchronous response to monaural sound stimuli in patients with SSD than in individuals with normal hearing (NH) (Scheffler et al., 1998; Bilecen et al., 2000; Ponton et al., 2001; Khosla et al., 2003; Langers et al., 2005). Studies using visual or visual-audio tasks have revealed cross-modal plasticity in patients with SSD (Schmithorst et al., 2014; Qiao et al., 2019). Furthermore, functional alterations in brain regions related to higher-order cognitive function have been observed in auditory, visual, and visual-audio task studies (Schmithorst et al., 2014; Shang et al., 2018; Qiao et al., 2019). Compared with task-based studies examining task-related brain activity, an advantage of resting-state imaging approaches is that they allow the examination of intrinsic brain function in the absence of theory-driven tasks. Widespread resting-state functional connectivity alterations were observed in patients with SSD in brain regions and networks related not only to auditory processing but also to other sensory functions, such as vision, as well as higher-order cognitive control (Wang et al., 2014; Zhang et al., 2015, 2016, 2018a,b; Xu et al., 2016; Zhu et al., 2021). However, most of these studies did not investigate the relationship between central plasticity and higher-order hearing abilities in patients with SSD. Therefore, it is difficult to determine which of the above plasticity conditions contribute to auditory functional compensation in patients with SSD.

A previous fMRI study of children with unilateral sensorineural hearing loss performing SIN recognition tasks reported changes in activation in regions of the attention network, in addition to changes in secondary auditory processing areas and visual associated areas (Propst et al., 2010). However, this study did not investigate the correlation between brain activation and behavioral performance on the SIN recognition task. Therefore, this study does not provide reliable evidence that brain functional plasticity is compensatory for hearing abilities. Li's et al. diffusion tensor imaging (DTI) study revealed a strong correlation between SIN recognition ability and the strength of structural network connectivity, mainly in the frontoparietal regions, suggesting that the structural reorganization of cognitive-related networks may be one of the compensatory mechanisms (Li et al., 2019). However, to the best of our knowledge, no similar study has explored the relationship between functional reorganization and higher-order hearing abilities in SSD. Thus, the underlying mechanisms of compensation in SSD require further study.

The amplitude of low-frequency fluctuation (ALFF) of resting-state fMRI reflects the intensity of regional brain activity

Abbreviations: SSD, single-sided deafness; ALFF, amplitude of low-frequency fluctuation; NH, normal hearing control; LSSD, left single-sided deafness; RSSD, right single-sided deafness; PTA, pure-tone audiometry; SIN, speech-in-noise; ASL, accuracy rate of sound localization; RMS, root-mean-square.

at baseline (Zang et al., 2007; Zou et al., 2008; Wang et al., 2011). ALFF has been widely used in studies of various neurological and sensory dysfunctional diseases, such as Alzheimer's disease (Wang et al., 2011; Mu et al., 2020; Yang et al., 2020), attention-deficit hyperactivity disorder (An et al., 2013; Jiang et al., 2020), high myopia, and monocular blindness (Huang et al., 2016; Fang et al., 2020). A previous study using ALFF investigated the alteration in intrinsic brain activity in patients with right-sided unilateral hearing loss and observed decreased ALFF values in the precuneus (PCUN), inferior parietal lobule (IPL), inferior frontal gyrus (IFG), and insula (INS) and increased ALFF values in the inferior temporal gyrus and middle temporal gyrus compared with the values of NHs (Yang et al., 2014). Furthermore, a positive correlation between disease duration and ALFF values was observed in certain brain regions, including the superior temporal gyrus, IFG, INS, and superior frontal gyrus (SFG) (Yang et al., 2014). These results suggest that ALFF is a promising biomarker of neurophysiological consequences that can indicate changes in regional signals of brain intrinsic activity. However, no study has used ALFF to explore the contribution of brain functional plasticity to the compensation of higher-order hearing abilities in patients with SSD.

The present study aimed to investigate the alteration in intrinsic brain activity in patients with long-term SSD and clarify the relationship among brain activity, duration of deafness, and higher-order hearing abilities. We used ALFF to investigate the alteration in intrinsic brain activity. We also evaluated the patients' higher-order hearing abilities, including sound localization and SIN recognition, which are most often affected after losing the ability to detect binaural cues. We hypothesized that patients with SSD would exhibit significant alterations in intrinsic brain activity in sensory- and cognitive-related brain regions. In addition, we conjectured that SSD patients with longer durations of deafness would exhibit better hearing abilities than those with shorter durations of deafness. Furthermore, we hypothesized that alterations in intrinsic brain activity may be closely related to hearing abilities in patients with SSD and act as compensatory mechanisms to facilitate improvement in hearing abilities over time.

Materials and methods

Subjects

A total of 57 subjects participated in this study, including 21 NHs (12 men, 41.3 ± 14.4 years old), 19 patients with left SSD (LSSD, 13 men, 44.1 ± 10.5 years old), and 17 patients with right SSD (RSSD, 7 men, 39.1 ± 9.4 years old). All subjects were native speakers of Mandarin and had no history of neurological or mental illness or contraindications to MRI scans. The demographic information for these subjects is presented in Table 1. There was no significant difference in age, sex, handedness, or education time among individuals in the three groups. All the durations of deafness were longer than 2 years in individuals in the SSD group, and the durations were not different between patients in the LSSD and RSSD groups. Among all patients with SSD, three with LSSD and two with RSSD could not provide a clear onset age of deafness and probably had prelingual onset. All other patients with SSD had postlingual onset. There was no significant difference in the age of deafness onset between participants in the two SSD groups. No history of hearing aid usage was reported by any patient with SSD.

Audiological inclusion criteria

In our study, normal hearing was defined as air-conduction pure-tone audiometry (PTA) threshold of 25 dB HL or less from 0.5 to 2 kHz. The average PTA threshold was defined as the average air conduction threshold at 0.5, 1, 2, and 4 kHz. In the NH group, all subjects had normal hearing in their bilateral ears (Table 2). All patients with SSD had persistent severe to profound sensorineural hearing loss with an average PTA threshold of deaf ear >70 dB HL and had normal hearing on the other side (Table 2). The average PTA threshold was 98.82 ± 17.03 and 100.07 ± 17.49 dB HL in the LSSD and RSSD groups, respectively, and showed no significant difference ($t = -0.22$, $p = 0.828$) between them.

Evaluation of higher-order hearing abilities

SIN recognition evaluation

The SIN recognition test was implemented using the Hearing-in-Noise Test (HINT, Version 7.2; Bio-logic Systems Corp, Mundelein, IL, USA), which was administered in a soundproof booth. The speech material was the Mandarin HINT (Wong et al., 2007). The SIN threshold on the deaf side was measured for patients in the two SSD groups. The sentence materials were presented by a speaker on the deaf side 1 m from the subjects, while noise was presented by a speaker in front of the participant. For participants in the NH group, we evaluated the SIN thresholds on the left side and right side (with noise presented in the front), and the average value of both sides was recorded as their SIN threshold. The speech-shaped noise masker was fixed at an intensity of 65 dB SPL. The speech signals were presented beginning at a −10 dB signal-to-noise ratio and adjusted according to the correct or wrong response provided by the subjects. The threshold was defined as the signal-to-noise ratio at which the subjects repeated sentences correctly 50% of the time.

TABLE 1 Demographic characteristics of the three groups.

	LSSD ($n = 19$)	RSSD ($n = 17$)	NH ($n = 21$)	Statistics	
Sex (male/female)	13/6	7/10	12/7	$\chi^2 = 2.72$	$p = 0.257$
Age [year, mean (SD)]	44.1 (10.5)	39.1 (9.4)	41.3 (14.4)	$F = 0.81$	$p = 0.451$
Handedness (right/left)	18/1	15/2	20/1	Fisher's exact test = 0.97	$p = 0.674$
Education time [year, mean (SD)]	14.6 (3.4)	14.3 (4.2)	15.2 (2.9)	Kruskal–Wallis test = 0.61	$p = 0.736$
Duration of deafness [year, mean (SD)]	11.3 (11.2)	9.3 (12.2)	–	$t = 0.52$	$p = 0.608$
Age of deafness onset [year, mean (SD)]	32.7 (18.6)	29.8 (15.2)	–	$t = 0.52$	$p = 0.606$

TABLE 2 Auditory abilities of the left single-sided deafness, right single-sided deafness, and normal hearing control groups.

	LSSD ($n = 19$)	RSSD ($n = 17$)	NH ($n = 21$)	Statistics			
				ANOVA	*Post-hoc* test		
					LSSD vs. NH	RSSD vs. NH	LSSD vs. RSSD
Average PTA of normal ear [dB HL, mean (SD)]	16.32 (7.15)	14.78 (6.18)	12.79* (5.74)	$F = 1.54$, $p = 0.223$	$p = 0.259$	$p = 1$	$p = 1$
SIN threshold [dB, mean (SD)]	2.73 (1.59)	3.00 (1.68)	−6.88** (1.64)	$F = 236.02$, $p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 1$
ASL [%, mean (SD)]	35.32 (9.21)	32.13 (9.17)	84.95 (6.49)	$F = 253.01$, $p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.759$
RMS error [°, mean (SD)]	64.37 (17.05)	72.30 (18.01)	17.01 (4.19)	$F = 88.19$, $p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.295$

*The average PTA of normal ears in the NH group is the average value of both ears.
**The SIN threshold in the NH group is the average value of the SIN threshold for the left and right sides.
NH, normal hearing control; LSSD, left single-sided deafness; RSSD, right single-sided deafness; PTA, pure tone audiometry; SIN, speech-in-noise; ASL, accuracy rate of sound localization; RMS, root-mean-square. ANOVA, analysis of variance.

Sound localization evaluation

Sound localization evaluation was carried out in the sound field of a soundproof booth. Thirteen loudspeakers (15° apart and numbered 1-13) were horizontally placed in a 180° arc in front of the subjects, with the subject as the center, with a radius of 1 m. The height of the sound field speakers was consistent with the height of the subject's ears. During the test, the subjects were instructed to remain still and face forward. Low-frequency (0.5 kHz) and high-frequency (3 kHz) pure tones at 50 dB HL were randomly presented two times from each of the 13 speakers as sound stimuli. After each sound stimulus, subjects were instructed to determine from which speaker the sound came and report the speaker number. When the deviation between the speaker location reported by the subject and the actual position of the stimulus was ≤15°, the answer was defined as correct. The correct rate was recorded as the accuracy of sound localization (ASL). The root-mean-square (RMS) error between the azimuth of the speaker location and the listener's response was also used to quantify localization accuracy. A higher ASL value indicated better sound localization ability, while a higher RMS error indicated greater deviation in identifying the sound source position, suggesting poorer sound localization capability.

MRI acquisition

All MRI data were acquired on a 3 T Philips Achieva MRI scanner (Philips Healthcare, Best, The Netherlands) with a 32-channel head coil. Subjects were instructed to remain still in a supine position. Headphones and foam padding were used to reduce scanner noise and limit head motion. Subjects kept their eyes closed but remained awake during scanning. Resting-state functional images were collected axially using an echo-planar imaging (EPI) sequence with the following settings: 37 slices; slice thickness = 3.5 mm; gap = 0.5 mm; repetition time (TR) = 2,000 ms; echo time (TE) = 30 ms; flip angle (FA) = 90°; field of view (FOV) = 230 × 230 mm^2; and sampling matrix = 80 × 80. The resting-state scan lasted 368 s (184 volumes). Three-dimensional T1-weighted magnetization-prepared rapid-acquisition gradient-echo (MPRAGE) coronal images were collected by using the following settings: slice thickness = 1.0 mm without gap; TR = 7.6 ms; TE = 3.7 ms; FA = 8°; FOV = 256 × 256 mm^2; and sampling matrix = 256 × 256 × 180.

fMRI preprocessing

Data preprocessing was performed with Data Processing & Analysis for (Resting-State) Brain Imaging (DPABI V5.1) (Yan et al., 2016) based on Statistical Parametric Mapping (SPM12, http://www.fil.ion.ucl.ac.uk/spm). The first 10 volumes of the acquired fMRI images for each subject were discarded for magnetization equilibrium and the subject's adaptation to scanning noise. Then, slice timing and motion correction were performed. All participants were retained under the head motion criteria of translation <2 mm or rotation <2° in any direction. The remaining fMRI time series was coregistered to the T1 images. Then, the T1 images were normalized to the Montreal Neurological Institute (MNI) space, and the resulting deformation fields were used to project the functional images to the MNI space with a voxel size of 3*3*3 mm. Nuisance covariate regression including Friston 24 parameters (Friston et al., 1996) was performed to remove the effects of head motion. In addition, the linear trend of time courses was removed. Then, the functional images were spatially smoothed with a 6-mm full width at a half-maximum Gaussian kernel.

Calculation of ALFF values

The ALFF values of the preprocessed functional images were calculated using DPABI. Briefly, the time courses were first transformed to the frequency domain using the fast Fourier transform. The square root of the power spectrum obtained by fast Fourier transform was computed and then averaged across 0.01–0.08 Hz at each voxel, which was then taken as the ALFF value. To reduce the global effects of variability across the subjects and achieve standardization, the individual data were transformed to Z scores (i.e., the global mean value is subtracted from the score, and then the result is divided by the standard deviation) (Zou et al., 2008). Finally, we obtained the standardized whole-brain ALFF map.

Statistical analysis

Demographic and auditory data

Statistical analysis of the demographic and auditory data was performed using the SPSS 23.0 statistical package (SPSS Inc., Chicago, IL, USA). The age differences among individuals in the three groups were tested by analysis of variance (ANOVA). Sex and handedness differences among individuals in the groups were analyzed by the chi-square test and Fisher's exact test, respectively. The differences in education time among individuals in the groups were analyzed by the Kruskal–Wallis test. The differences in age and auditory parameters among individuals in the three groups were tested by analysis of variance (ANOVA), and then *post-hoc* tests were conducted by Bonferroni correction. The intergroup difference in PTA thresholds of the deaf ear between patients with LSSD and RSSD was tested using a two-sample *t*-test.

To explore the effect of deafness time on higher-order hearing abilities, we took the median duration of deafness (3 years) as the time point and used a two-sample *t*-test to compare the difference in higher-order hearing abilities of SSD patients with durations of deafness <3 years (including 3 years) and those with durations of more than 3 years. Considering that the duration of deafness in SSD did not conform to a normal distribution, Spearman's rank correlation analysis was used to explore the correlation between the duration of deafness and higher-order hearing abilities.

ALFF analysis

An ALFF analysis was performed with the Resting-State fMRI Data Analysis Toolkit (REST 1.8, http://rest.restfmri.net). To explore the within-group ALFF pattern, one-sample *t*-tests were performed on the individual ALFF maps in a voxelwise way for each group. The within-group statistical threshold was set at $Z > 3.09$ (voxel-level $p < 0.001$ and cluster-level $p < 0.05$, one-tailed) (Wang et al., 2011). The Gaussian random-field theory (GRF) correction was used to correct multiple comparisons. This correction was confined within the gray matter mask obtained by selecting a threshold of 0.2 on the mean gray matter map of all subjects (volume = 53,156 voxels). To compare the differences in the ALFF pattern, voxelwise two-sample *t*-tests were performed on the ALFF map between NHs and patients with LSSD and between NHs and patients with RSSD. Participants' age and sex were controlled as covariates. The between-group statistical threshold was set at $|Z| > 2.58$ (voxel-level $p < 0.01$ and cluster-level $p < 0.05$, two-tailed). GRF correction was used for correcting multiple comparisons, and this correction was also confined within the group gray matter mask. To further observe the different trends of the ALFF values between groups, region-of-interest (ROI)-wise two-sample *t*-tests were performed. The ROI was defined as a sphere with a radius of 10 mm (containing 171 voxels) and centered at the peak point of clusters in each contrast.

Correlation analysis

To explore the relationship between the ALFF values and duration of deafness in the patients with SSD, voxelwise partial correlation analysis was performed between the ALFF values and duration of deafness in patients with LSSD and RSSD together, controlling for the effects of age and sex. To explore the relationship between the ALFF values and higher-order hearing abilities in patients with SSD, voxelwise partial correlation analysis was also performed between ALFF values and hearing abilities of patients with SSD, including SIN threshold, ASL, and RMS error, controlling for the effects of age and sex. The statistical threshold was set at $|Z| > 1.96$ (voxel-level $p < 0.05$ and cluster-level $p < 0.05$, two-tailed) with GRF correction (Wang et al., 2011). Through the above voxelwise partial correlation analysis, brain areas showing a significant correlation between ALFF values and clinical parameters were found. We also performed ROI-wise partial correlation analysis, controlling for the effects of age and sex, between higher-order hearing abilities and the averaged ALFF values of the abovementioned areas.

Mediation analysis

Mediation analysis was performed using model 4 (simple mediation model) of the PROCESS (v3.3) macro in SPSS (Hayes and Ph, 2012). This model used a non-parametric bootstrap test with 5,000 resamplings to calculate the 95% confidence intervals for statistical significance. The mediation effect of the ALFF value on the relationship between deafness duration and higher-order hearing abilities was tested by controlling for sex and age (more details are provided in the Supplementary materials).

Results

Demographic characteristics and auditory abilities

As presented in Table 1, there were no differences among NHs, LSSD patients, and RSSD patients in sex ($\chi^2 = 2.72$, $p = 0.257$), age ($F = 0.81$, $p = 0.451$), handedness (*Fisher's exact test* = 0.97, $p = 0.674$), or education time (*Kruskal—Wallis test* = 0.61, $p = 0.736$). The duration of deafness ($t = 0.52$, $p = 0.608$) and the age of deafness onset ($t = 0.52$, $p = 0.606$) were not significantly different between patients with LSSD and RSSD.

The results of auditory ability are presented in Table 2. The average PTA of normal ears was not significantly different among NHs, patients with LSSD, and patients with RSSD ($F = 1.54$, $p = 0.223$). For the SIN recognition evaluation, the SIN threshold of NHs was significantly lower than that of patients with LSSD and RSSD ($F = 236.02$, $p < 0.001$), suggesting better performance in NHs. In the sound localization evaluation, NHs showed significantly higher ASL than did patients with LSSD or RSSD ($F = 253.01$, $p < 0.001$) and significantly lower RMS error than patients with LSSD or RSSD ($F = 88.19$, $p < 0.001$). Both results suggest better sound localization abilities in NHs than in patients with SSD, whether left or right. There was no difference between patients with LSSD and RSSD in the average PTA of the normal ear, SIN threshold, ASL, or RMS error.

The results of higher-order hearing abilities in SSD patients with different durations of deafness are shown in Figure 1. Taking the median duration of deafness (3 years) as the time point, we compared the higher-order hearing abilities of SSD patients with deafness durations <3 years (including 3 years) and longer than 3 years. There was no significant age difference between participants in the two groups ($t = 0.14$, $p = 0.257$). Although the SSD patients with deafness durations <3 years had lower average PTA both for deaf ears ($t = -3.25$, $p = 0.002$) and for normal ears ($t = -2.03$, $p = 0.048$) than SSD patients with longer deafness durations, SSD patients with longer deafness durations showed a significant reduction in RMS error ($t = -2.49$, $p = 0.018$), a marginally significant reduction in the SIN threshold ($t = -1.95$, $p = 0.060$), and a marginally significant increase in ASL ($t = 1.97$, $p = 0.057$) than SSD patients with deafness durations of <3 years (see Figure 1A). The results of Spearman's correlation analysis between the duration of deafness and higher-order hearing abilities are shown in Figure 1B. The duration of deafness showed a significant negative correlation with the SIN threshold ($rs = -0.37$, $p = 0.025$) and RMS error ($rs = -0.35$, $p = 0.036$), indicating that duration was positively correlated with hearing abilities. However, there was no significant correlation between ASL and duration of deafness ($rs = 0.16$, $p = 0.367$).

ALFF results

The within-group ALFF patterns of NHs, patients with LSSD, and patients with RSSD are shown in Figure 2. Visually, participants in all three groups showed similar patterns with higher ALFF values in the PCUN, IPL, posterior cingulate gyrus (PCG), medial prefrontal cortex (MPFC), and occipital areas. From the color intensity of Figure 2, it can be observed that participants in the NH group showed generally higher ALFF values than participants in the LSSD and RSSD groups.

The results of the between-group ALFF analysis are shown in Figure 3 and Table 3. The voxelwise between-group analysis showed that patients with LSSD exhibited significantly lower ALFF values in the bilateral PCUN than NHs (peak MNI = 12, −51, 36; $Z = -4.13$; cluster size = 81 voxels) (see Figure 3A). The patients with RSSD showed lower ALFF values than NHs in the bilateral lingual gyrus (LING, peak MNI = −18, −90, −9; $Z = -4.34$; cluster size = 149 voxels) and the left middle frontal gyrus (MFG, peak MNI = −36, 6, 48; $Z = -4.06$; cluster size = 102 voxels) (see Figure 3B). To further explore whether the patients with RSSD and patients with LSSD exhibited a similar trend of alteration, we performed an ROI analysis using the peak points found above as the center. For the PCUN ROI, obtained from the peak point of voxelwise analysis between patients with

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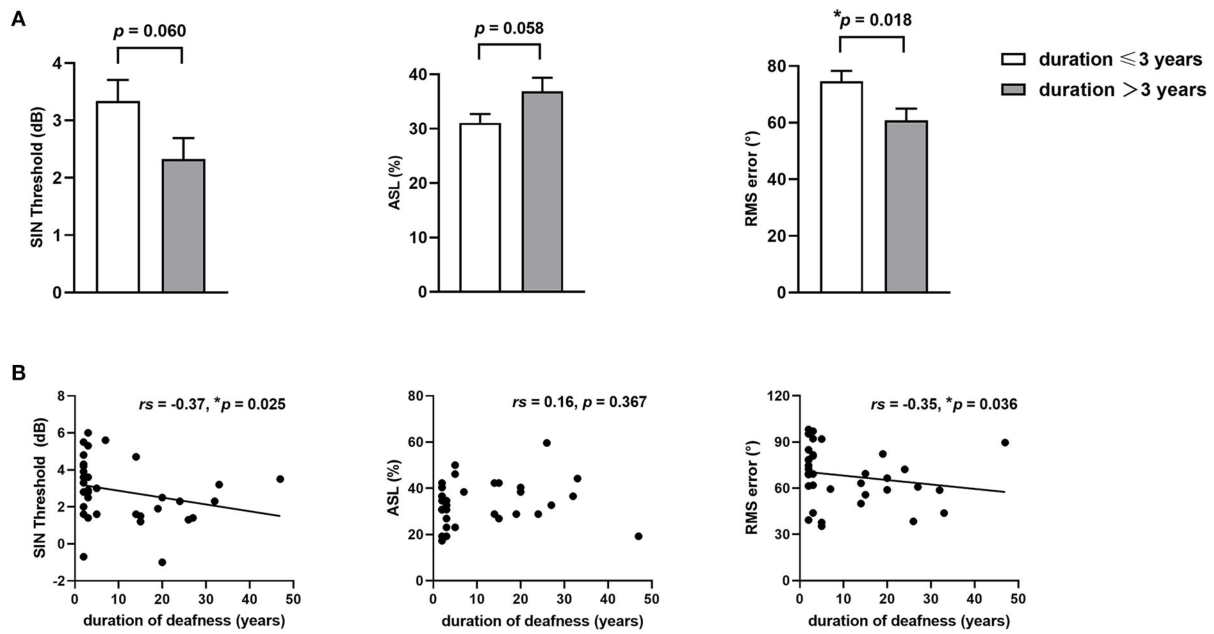

FIGURE 1
Higher-order hearing abilities in patients with SSD with different durations of deafness. **(A)** Comparison of higher-order hearing abilities, including the SIN threshold, ASL, and RMS error, between SSD patients with durations of deafness of up to 3 years and more than 3 years. **(B)** Spearman' correlations between duration of deafness and higher-order hearing abilities, including the SIN threshold, ASL, and RMS error. *$p <$ 0.05, SSD, single-sided deafness; SIN, speech-in-noise; ASL, accuracy rate of sound localization; RMS, root-mean-square.

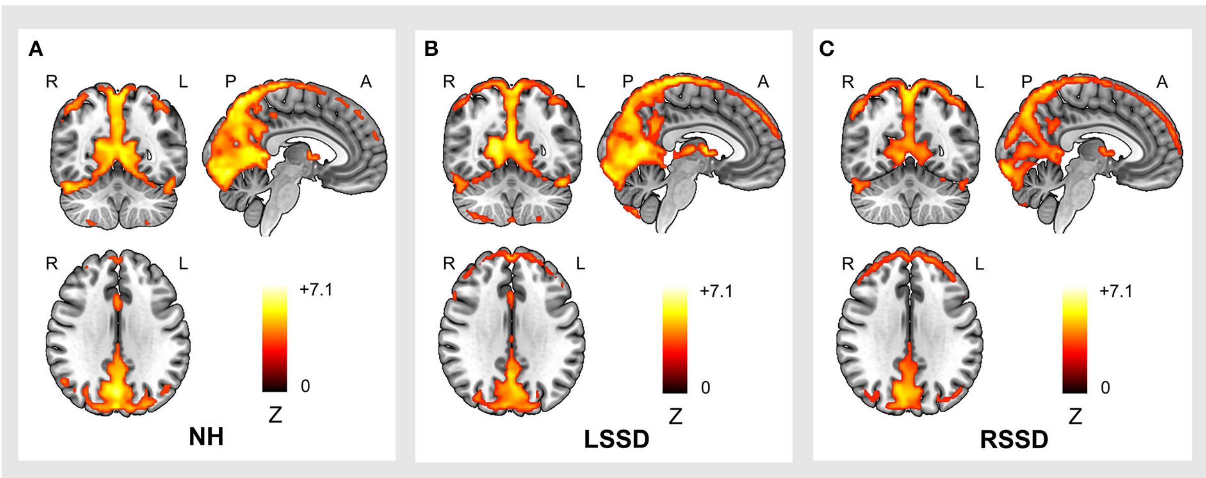

FIGURE 2
Within-group ALFF patterns of participants in the NH **(A)**, LSSD **(B)**, and RSSD **(C)** groups. NH, normal hearing control; LSSD, left single-sided deafness; RSSD, right single-sided deafness.

LSSD and NHs, patients with LSSD exhibited significantly lower ALFF values than NHs ($t = 3.26$, $p = 0.002$), and patients with RSSD exhibited lower ALFF values than NHs by a statistically nonsignificant margin ($t = 0.99$, $p = 0.328$) (see Figure 3C). Patients with RSSD exhibited significantly lower ALFF values than NHs in the ROIs of the LING ($t = 2.91$, $p = 0.006$) and MFG ($t = 2.66$, $p = 0.012$), and patients with LSSD showed lower ALFF values in the ROIs of the LING ($t = 1.60$, $p = 0.118$) and MFG ($t = 1.78$, $p = 0.084$) but without statistical significance (see Figures 3D,E).

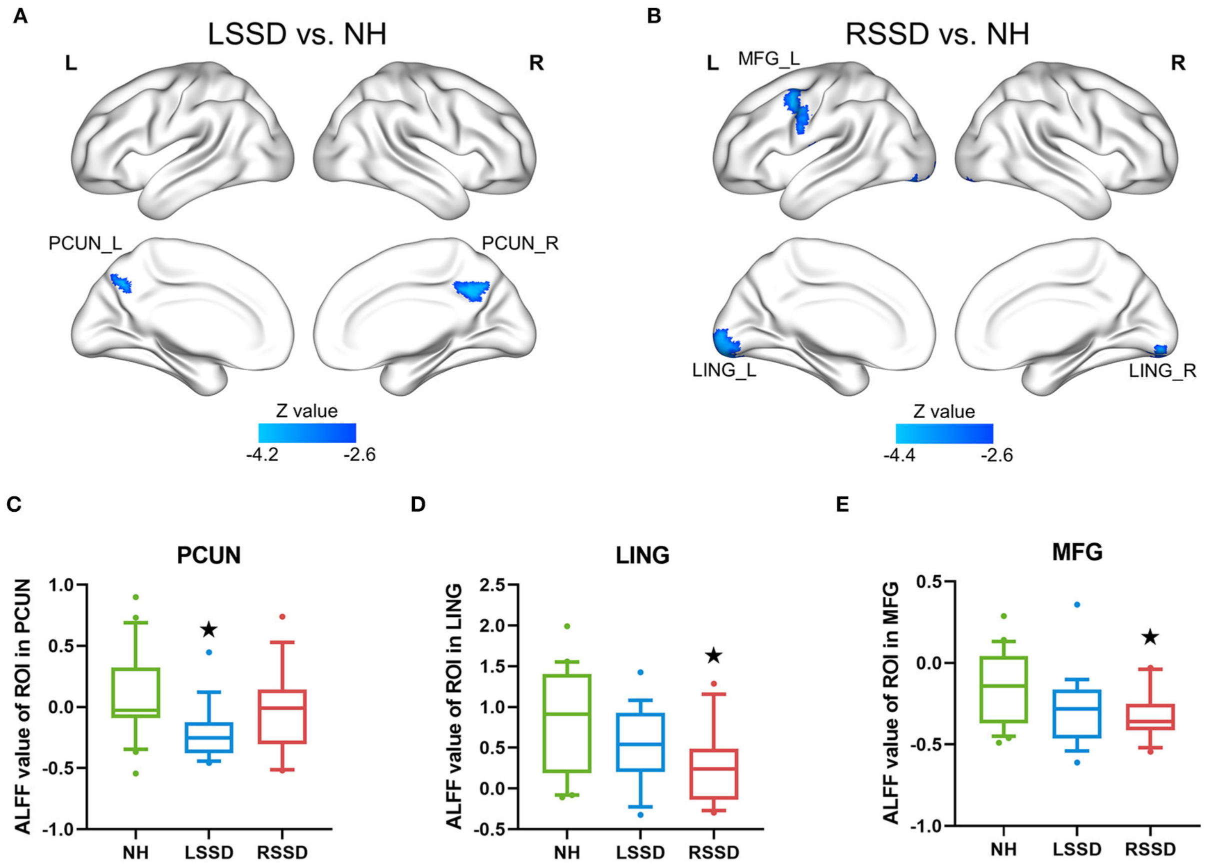

FIGURE 3
Differences in ALFF values among groups. **(A)** The patients with LSSD showed significantly lower ALFF values than NHs in the bilateral PCUN in the voxelwise comparison. **(B)** The patients with RSSD showed significantly lower ALFF values than NHs in the bilateral LING and left MFG in the voxelwise comparison. **(C)** Box plots showing the ALFF values of the three groups in the PCUN ROI. **(D)** Box plots showing the ALFF values of the three groups in the LING ROI. **(E)** Box plots showing the ALFF values of the three groups in the MFG ROI. The centerline indicates the median, box outlines show the 25th and 75th percentiles, and whiskers indicate the 10th–90th percentile. Extreme values are shown by dots. *$p < 0.05/3 = 0.017$ (Bonferroni corrected) compared with those of NHs. NH, normal hearing control; LSSD, left single-sided deafness; RSSD, right single-sided deafness; PCUN, precuneus; LING, lingual gyrus; MFG, middle frontal gyrus.

TABLE 3 Brain regions showing significant between-group differences in ALFF values.

Contrast	Region	Brodmann's area	Maximum Z value	Cluster size	MNI coordinates		
					X	Y	Z
NH vs. LSSD							
	Bilateral precuneus	7/23	−4.13	81	12	−51	36
NH vs. RSSD							
	Bilateral lingual gyrus	17/18	−4.34	149	−18	−90	−9
	Left middle frontal gyrus	6	−4.06	102	−36	6	48

NH, normal hearing control; LSSD, left single-sided deafness; RSSD, right single-sided deafness.

Correlation results

A voxelwise correlation map between ALFF values and the duration of deafness is shown in Figure 4. A significantly positive correlation was shown between the duration of deafness and ALFF values in the left IPL, the left angular gyrus (ANG), the left middle occipital gyrus (MOG), and the bilateral PCUN and extending to the PCG (see Figure 4A). The scatterplot of ROI-wise analysis displayed a trend of a significant positive correlation ($pr = 0.77$, $p <$

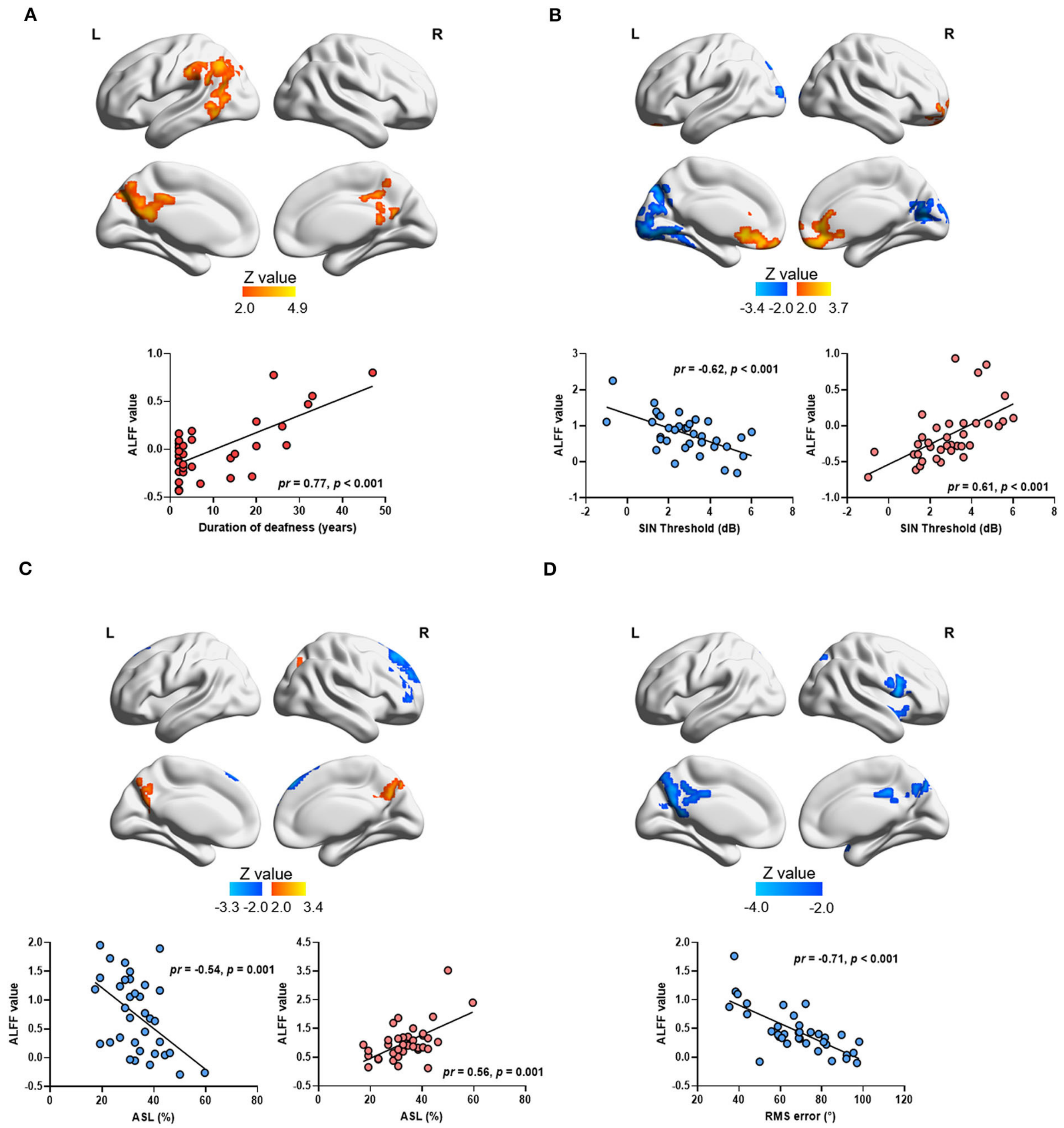

FIGURE 4
Correlation between ALFF values and auditory parameters in single-sided deafness after controlling sex and age. The brain map in the top panel shows the results of voxelwise correlation, and the scatterplot in the bottom panel shows the ROI-wise correlation between ALFF values and auditory parameters. The ALFF values in ROI-wise correlation analysis were extracted from the significant brain area in the voxelwise correlation in the top panel. Brain regions with positive and negative correlations were extracted separately. **(A)** Regions showing a significant correlation between the duration of deafness and ALFF values. **(B)** Regions showing a significant correlation between ALFF values and the SIN threshold. **(C)** Regions showing a significant correlation between ALFF values and ASL. **(D)** Regions showing a significant correlation between ALFF values and RMS error. SIN, speech-in-noise; ASL, accuracy rate of sound localization; RMS, root-mean-square.

0.001) between ALFF values and duration of deafness (see Figure 4A).

Correlations between ALFF values and higher-order hearing abilities in all SSD subjects are also shown in Figure 4. A significant negative correlation was observed between the SIN thresholds and ALFF values in the left superior occipital gyrus (SOG), the left LING, bilateral calcarine (CAL), and the bilateral PCUN (see Figure 4B and Table 4). At the same

TABLE 4 Brain regions showing significant correlations between ALFF values and auditory parameters in voxelwise correlation analysis in SSD.

Auditory parameters	Region	Brodmann's area	Maximum Z-value	Cluster size	MNI coordinates		
					X	Y	Z
Duration of deafness							
Positive correlation							
	Left inferior parietal lobule	40	4.92	189	−51	−39	36
	Left angular gyrus	39	4.679	110	−45	−60	39
	Left middle occipital gyrus	19		97			
	Bilateral precuneus	7/23	4.34	254	−18	−63	33
	Bilateral posterior cingulate	30	3.41	81	−3	−48	21
SIN threshold							
Positive correlation							
	Bilateral medial frontal gyrus	11	3.72	134	15	24	−6
	Bilateral anterior cingulate			106			
Negative correlation							
	Left superior occipital gyrus	19	−3.40	47	−18	−84	42
	Left precuneus	7		81			
	Left lingual gyrus	18	−3.20	146	−12	−63	−6
	Left calcarine	17		52			
	Right calcarine	17/18	−3.09	111	18	−72	15
	Right precuneus	23		112			
ASL							
Positive correlation							
	Bilateral precuneus	7	3.40	187	3	−72	45
Negative correlation							
	Right superior frontal gyrus	8/9/10	−3.33	264	27	66	9
	Right middle frontal gyrus			152			
RMS error							
Negative correlation							
	Right inferior frontal gyrus	44/6	−4.00	64	51	9	15
	Bilateral precuneus	7	−4.01	224	−3	−60	33
	Bilateral cingulate gyrus	23		97			

SIN, speech-in-noise; ASL, accuracy rate of sound localization; RMS, root-mean-square.

time, a significantly positive correlation was observed between the SIN threshold and ALFF values in the bilateral MFG and anterior cingulate gyrus (ACG) (see Figure 4B and Table 4). The scatterplot of ROI-wise analysis is displayed in the bottom panel for ROIs extracted from regions showing significant negative correlations ($pr = -0.62$, $p < 0.001$) and positive correlations ($pr = 0.61$, $p < 0.001$) between SIN thresholds and ALFF values (see Figure 4B). A significant negative correlation was observed in the right SFG and right MFG, and a significant positive correlation was observed in the bilateral PCUN between ALFF values and ASL (see Figure 4C and Table 4). The scatterplot for ROIs extracted from regions showing a significant negative correlation ($pr = -0.54$, $p = 0.001$) and positive correlation ($pr = 0.56$, $p = 0.001$) between ASL and ALFF values is displayed (see Figure 4C). A significant negative correlation was revealed between RMS error and ALFF values in the right IFG, bilateral PCUN, and bilateral PCG (see Figure 4D and Table 4). The scatterplot for the ROIs extracted from regions showing a significant negative correlation ($pr = -0.71$, $p < 0.001$) between RMS error and ALFF values is displayed in the bottom panel.

Mediation analysis results

As described above, a significant correlation was observed in patients with SSD between the duration of deafness and higher-order abilities, and ALFF values in the PCUN were observed to be correlated with both these aspects. Thus, it was speculated that ALFF values in the PCUN may be a mediator of the relationship between the duration of deafness and higher-order hearing abilities, including SIN threshold, ASL, and RMS error. The ALFF values were extracted in the ROIs located in the

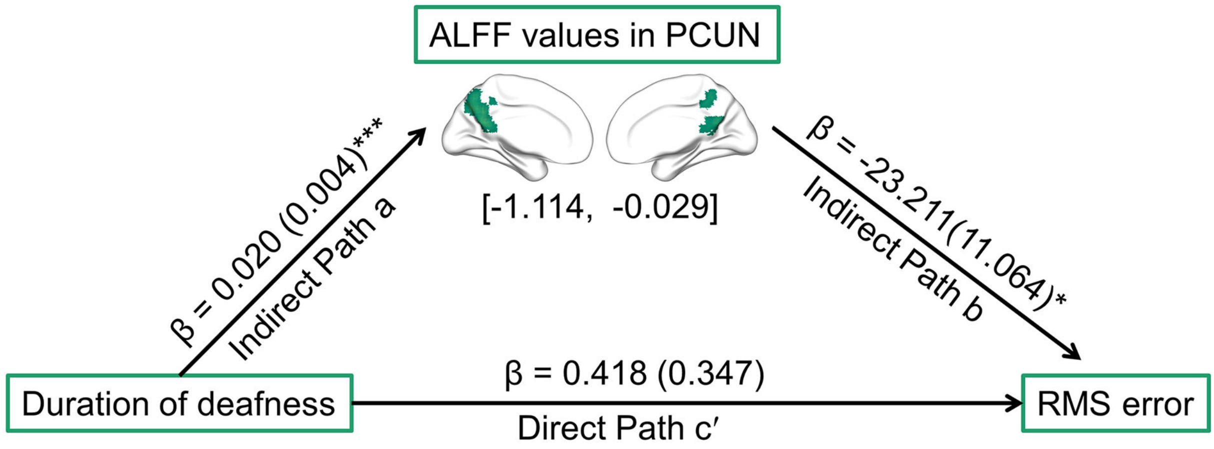

FIGURE 5
Path diagram showing the relationships among duration of deafness, ALFF values in ROIs located in the PCUN, and RMS error in patients with SSD according to mediation analysis. The lines are labeled with path coefficients, and standard errors are shown in parentheses. The values in brackets are the upper and lower limits of the bootstrap 95% confidence interval for indirect effects. The predictor (duration of deafness) connection to the mediator factors (ALFF values in the PCUN) is indirect path a. The connection from the mediator factor (ALFF values in the PCUN) to the outcome (RMS error) is indirect path b. The connection from the predictor (duration of deafness) to the outcome (RMS error) is direct path c′. *$p < 0.05$, ***$p < 0.001$. RMS, root-mean-square; PCUN, precuneus.

PCUN, which were defined by the overlap between the PCUN, as delineated by the Automated Anatomical Labeling atlas, and regions showing a significant correlation between duration of deafness and ALFF values. The results of the mediation analysis are shown in Figure 5. ALFF values in the PCUN had a significant negative predictive effect on RMS error ($\beta = -23.211$, SE $= 11.064$, $p = 0.044$). Furthermore, the indirect effect of duration of deafness on RMS error was significant [95% CI $= (-1.114, -0.029)$], while duration of deafness had no significant direct predictive effect on RMS error in the mediation model ($\beta = 0.418$, SE $= 0.347$, $p = 0.237$). Therefore, ALFF values in the PCUN are a significant mediator of the relationship between the duration of deafness and RMS error. However, ALFF values in the PCUN showed no significant mediating effect in the relationship between duration of deafness and SIN threshold [95% CI $= (-0.057, 0.036)$] or in the relationship between duration of deafness and ASL [95% CI $= (0.000, 0.006)$] (more details are provided in the Supplementary materials).

Discussion

In the present study, we investigated the alteration in intrinsic brain activities and their correlations with higher-order abilities in patients with long-term SSD using ALFF of resting-state fMRI. Our study provided several key findings. First, we confirmed that SSD patients with longer durations of deafness had better higher-order hearing abilities. Second, we observed a consistent trend of decreased ALFF values in multiple brain areas for both patients with LSSD and patients with RSSD. Third, higher ALFF values were observed to correlate with longer durations of deafness in multiple parietal-occipital regions, especially the PCUN. Furthermore, a generally consistent trend of correlation between ALFF values in specific brain areas and higher-order hearing abilities was observed in patients with SSD. That is, better abilities correlated significantly with lower ALFF values in the frontal areas and higher ALFF values in the PCUN and the surrounding parietal-occipital regions for both SIN recognition and sound localization. Finally, mediation analysis revealed that ALFF values in the PCUN were a significant mediator of the relationship between the duration of deafness and higher-order hearing abilities.

Due to hearing deprivation in one ear, no binaural cues (e.g., interaural time difference, intensity difference, and binaural squelch) could be detected by the peripheral auditory system in patients with SSD. Since these cues are crucial for sound localization and SIN recognition, these hearing abilities are most affected in patients with SSD (Agterberg et al., 2014; Asp et al., 2018; Liu et al., 2018; Adigun and Vangerwua, 2021). However, according to our behavioral results, SSD patients with longer durations of deafness showed better sound localization ability, although their PTA thresholds were even higher than those of patients with shorter durations of deafness. Furthermore, a significant correlation between duration and hearing ability was observed for both SIN recognition and sound localization. These findings were consistent with previous behavioral studies in both children and adults (Peckham and Sheridan, 1976; Lieu et al., 2012; Liu et al., 2018; Nelson et al., 2018). In addition, studies have reported that sound localization may be improved by active training in patients with SSD (Firszt et al., 2015; Yu et al., 2018).

These findings demonstrated that higher-order hearing abilities could be improved over time without the recovery of binaural cues. Researchers generally believe that, on the one hand, this outcome may be due to the adaptation to the loss of binaural cues over time *via* the remediation of other sound cues (Liu et al., 2018). On the other hand, central plasticity in patients with SSD may be an important mechanism that recruits more brain resources for auditory processing to make better usage of limited auditory input (Chang et al., 2016; Li et al., 2019).

Individuals in all three groups (NH, LSSD, and RSSD) showed higher ALFF values in brain regions of the default-mode network (DMN), including the PCUN, IPL, PCG, and MPFC, as well as occipital areas, which were consistent with previous studies of ALFF (Yan et al., 2009; Spunt et al., 2015; Mak et al., 2017; Jenkins, 2019). Studies have indicated that regions of the DMN in the human brain have a distinctive functional profile, with higher activity than other regions of the brain at baseline (Zang et al., 2007; Yan et al., 2009; Wang et al., 2011; Spunt et al., 2015; Mak et al., 2017; Jenkins, 2019; Jiang et al., 2020). Moreover, we observed a decreasing trend of ALFF in several regions in patients with SSD compared with those with NHs. Patients with LSSD showed significantly decreased ALFF in the bilateral PCUN. In many studies, ALFF on resting-state fMRI has been considered a promising neurophysiological marker reflecting intrinsic brain activity (Wang et al., 2011; Liu et al., 2014; Cheng et al., 2020). Pertinently, decreased ALFF may indicate brain dysfunction (Wang et al., 2011; Liu et al., 2014; Mu et al., 2020). The PCUN is considered a key functional hub in the DMN at rest and plays a distinct role in many high-level functions, such as episodic memory retrieval (Dörfel et al., 2009), self-processing (Lou et al., 2004), visuospatial processing (Wenderoth et al., 2005), and deductive reasoning (Knauff et al., 2003; see also Cavanna and Trimble, 2006 for review). An increasing body of evidence suggests that the PCUN participates in attentional monitoring and is responsible for continuously collecting and automatically distributing information from the self and the surrounding environment (Hutchinson et al., 2009; Halbertsma et al., 2020; Li et al., 2020). Consistent with the findings of the present study, Yang et al. observed decreased ALFF in the PCUN in patients with unilateral hearing loss (Yang et al., 2014). Studies have also observed altered functional connectivity of the DMN, including the PCUN, during the resting state (Wang et al., 2014; Zhang et al., 2015, 2018a; Shang et al., 2020) and have reported altered activation during tasks in DMN regions in patients with SSD (Schmithorst et al., 2014; Shang et al., 2018). Based on the information mentioned above, the decreased ALFF values in the PCUN observed in the present study may indicate an abnormality in higher-order cognitive function in patients with SSD after losing auditory input from one ear.

In the present study, we observed a significant positive correlation between deafness duration and ALFF values in the bilateral PCUN and the surrounding parietal regions in patients with SSD. In other words, the longer the duration of deafness, the closer to normal the ALFF. This finding suggested a compensatory mechanism, that is, brain function tended to recover to a near normal state over time. Furthermore, we investigated the relationship between ALFF values and higher-order auditory function. For both SIN recognition and sound localization, better abilities correlated significantly with higher ALFF values in the bilateral PCUN. Together with our behavioral findings that patients with longer durations showed better auditory performance, it could be conjectured that the recovery of ALFF values in the PCUN may be one of the mechanisms mediating the compensation of higher-order auditory function. The results of the mediation analysis revealed that ALFF values in the PCUN showed a significant mediation effect on the relationship between the duration of deafness and sound localization ability, which further confirmed this conjecture.

In addition to the PCUN, the MFG showed a significantly lower ALFF value in patients with SSD. Furthermore, a similar pattern was observed in the correlation analysis for both SIN recognition and sound localization, and better abilities were observed to be correlated with lower ALFF values in the frontal areas, including the SFG and MFG. The MFG is one of the secondary language areas that is involved in the nuances of language expression, such as grammar (Wang et al., 2008), semantics (Brown et al., 2006), and verbal fluency (Abrahams et al., 2003). There is also evidence suggesting that the MFG is involved in information storage and cognitive processing in working memory (Leung et al., 2002). The SFG has also been demonstrated to contribute to higher cognitive functions, particularly to working memory (du Boisgueheneuc et al., 2006; Alagapan et al., 2018). These results suggested that functional reorganization of intrinsic activity in the frontal lobe, particularly regions subserving working memory, not only occurred in patients with SSD but also had a close relationship with higher-order auditory abilities.

Previous studies have demonstrated that degraded peripheral input leads to increased processing demands, that is, listening effort, including increases in the attentional focus and time needed to process auditory information (Shinn-Cunningham and Best, 2008). In addition, more cognitive areas are engaged in auditory processing when more listening effort is required (Davis and Johnsrude, 2003; Tyler et al., 2010; Peelle et al., 2011; Hervais-Adelman et al., 2012; Peelle, 2018; Rosemann and Thiel, 2018). In NHs, both the ANG and the extensive prefrontal cortex were demonstrated to be recruited when higher-order linguistic factors improved speech comprehension under adverse listening conditions (Obleser et al., 2007). In adults with mild to moderate hearing loss, Campbell and Sharma observed increased activation in the frontal areas (e.g., the SFG, MFG, and IFG) when individuals tried to recognize speech when background noise was presented simultaneously (Campbell and Sharma, 2013), and Rosemann and Thiel observed higher activation in the medial, middle, and inferior frontal gyri during a task of incongruent audio-visual conditions that required more listening effort (Rosemann and Thiel, 2018).

The subjects with SSD have also been demonstrated to require more listening effort than NHs when performing the same auditory processing tasks (Lewis et al., 2016). Previous data-driven studies in SSD have demonstrated that both structural and functional reorganization in cognitive-related regions and networks are the most important patterns of plasticity (Zhang et al., 2018a,b; Li et al., 2019; Zhu et al., 2021). Furthermore, Li et al. observed a strong correlation between hearing abilities and connection strength, mainly in the frontoparietal areas (Li et al., 2019). A previous auditory working memory task study in patients with SSD using magnetoencephalography observed reduced gamma band activity over the frontoparietal cortices related to attention and working memory, and the author conjectured that the attention and working memory network were overburdened chronically in patients with SSD such that no comparable resources could be allocated relative to the resources available to NHs while performing challenging auditory tasks (Shang et al., 2018). Our results further demonstrated that the functional reorganization of the DMN and other cognitive-related regions, especially those subserving attention and working memory, contribute to the compensatory mechanism for the recovery of hearing abilities in patients with SSD. These alterations happen not only during auditory processing but also in intrinsic brain activity during the resting state.

In the current study, significantly decreased ALFF values were observed in the bilateral LING in patients with RSSD, and there was a similar lower alteration trend in patients with LSSD, but the difference was not statistically significant. Furthermore, brain regions showing significant correlations between ALFF values and deafness durations involved the left MOG; moreover, brain regions showing significant correlations between ALFF values and SIN recognition involved the left SOG. These findings suggest that the intrinsic activity of the visual cortex was reorganized in patients with SSD and that this reorganization has a close relationship with auditory function, implying cross-modal plasticity. Cross-modal plasticity has been well-demonstrated in patients with bilateral severe to profound hearing loss, that is, total hearing deprivation. Recently, growing evidence has suggested that there is cross-modal plasticity in patients with partial hearing deprivation, that is, SSD. Structurally, decreased gray matter volume and decreased white matter structural network strength in visual brain regions were found in patients with SSD (Wang et al., 2016; Li et al., 2019). Functionally, altered regional homogeneity and functional connections in visual areas were also observed in patients with SSD using resting-state fMRI (Wang et al., 2014; Liu et al., 2015; Xu et al., 2016; Zhang et al., 2016, 2018a). Altered activation in the visual cortex was also observed in studies in which individuals performed audio-visual, visual, or auditory tasks (Propst et al., 2010; Schmithorst et al., 2014; Shang et al., 2018; Qiao et al., 2019). Our findings were consistent with those of these studies to some extent and further suggested that the functional reorganization of the visual cortex correlated closely with the recovery of auditory function.

Since quite a few previous studies on patients with SSD have reported significant alterations in the interhemispheric symmetry and synchronization of the auditory cortex, alterations in the ALFF values were expected in the auditory cortex (Ponton et al., 2001; Khosla et al., 2003; Langers et al., 2005). However, it is notable that the auditory cortex is not among the areas showing significant ALFF alterations or areas showing a close relationship between ALFF values and higher-order auditory functions. This is probably because, although the auditory input is abolished in the deaf ear, most of the auditory function is retained due to the normal input from the good ear. Thus, the basic function of the auditory cortex, especially the primary auditory cortex, remains unchanged. Using a data-driven approach, our results suggested that the intrinsic activity of the auditory cortex remains stable in patients with SSD; at least, it is not among the most obvious alterations. Similar findings were observed in other data-driven studies in patients with SSD SSD. A previous study of structural connectivity networks in patients with SSD observed increased connectivity strengths in the frontoparietal subnetwork and decreased connectivity strengths in the visual network but not in the auditory network (Li et al., 2019). A data-driven functional connectivity study in patients with SSD observed that brain regions showing the most obvious alterations are mainly those related to higher-order cognitive functions instead of the auditory cortex (Zhu et al., 2021). Another possible reason for this phenomenon is that the auditory cortex is not among the regions showing high ALFF values during the resting state. Thus, this region is less likely to exhibit reduced ALFF.

It has been well-accepted that there are two streams for auditory processing: a ventral "what" stream and a dorsal "where" stream (Hickok and Poeppel, 2000, 2004; Rauschecker and Tian, 2000). The dorsal stream is also involved in mapping sound to articulatory-based representations (Hickok and Poeppel, 2004; Elmer et al., 2017). In the present study, regions showing a close relationship between ALFF and duration of deafness involved the IPL and ANG, which are important parts of the dorsal processing pathway and are linked to the "phonological-articulatory loop" (Rauschecker and Scott, 2009). The ANG was demonstrated to be recruited when higher-order linguistic factors improve speech comprehension (Obleser et al., 2007). Our findings suggested that functional reorganization occurred in the dorsal auditory processing pathway over time, especially in regions related to higher-order linguistic functions. Furthermore, although SIN recognition and sound localization were believed to be processed by different mechanisms, a similar pattern was observed in voxelwise correlation analysis between ALFF and auditory abilities.

There were several limitations in the present study. First, the sample sizes for both the SSD and NH groups were relatively modest, resulting in reduced sensitivity for ALFF comparisons between groups. Voxelwise correlation analysis was implemented for all SSD subjects without differentiating the deafness laterality to achieve suitable statistical power. Second, the present study was not able to analyze the prelingual and postlingual SSD separately due to the relatively small size of prelingual patients in our cohort. Since there is a critical period for auditory development and plasticity pattern may be different between prelingual and postlingual SSD cases (Kral et al., 2013), further studies are still needed to clarify it. At last, the effects of other otological symptoms, such as tinnitus and vertigo, were not assessed. Brain function during the resting state has been demonstrated to be affected by tinnitus in previous imaging studies (Schmidt et al., 2013; Hinkley et al., 2015).

Conclusion

In the present study, significant alterations in intrinsic brain activity were observed in multiple regions of the brain in patients with SSD, including cognitive-related regions. These alterations were closely related to the duration of deafness and higher-order hearing abilities. These findings suggested that alterations in intrinsic brain activity, especially in cognitive-related regions, may be one of the compensatory mechanisms that develop over the duration of deafness to restore the higher-order hearing abilities in patients with SSD.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Committee of Peking Union Medical College Hospital. The patients/participants provided their written informed consent to participate in this study.

Author contributions

YQ and YSh contributed to the conception and design of the study. YQ, MZ, and WS contributed to data acquisition and organized the database. YQ, MZ, WS, and YSu performed the statistical analysis. YQ, MZ, HG, and YSh wrote the manuscript. All authors contributed to manuscript revision and read and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnins.2022.935834/full#supplementary-material

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Executive functioning and spoken language skills in young children with hearing aids and cochlear implants: Longitudinal findings

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Deaf or hard-of-hearing (DHH) children who use auditory-oral communication display considerable variability in spoken language and executive functioning outcomes. Furthermore, language and executive functioning skills are strongly associated with each other in DHH children, which may be relevant for explaining this variability in outcomes. However, longitudinal investigations of language and executive functioning during the important preschool period of development in DHH children are rare. This study examined the predictive, reciprocal associations between executive functioning and spoken language over a 1-year period in samples of 53 DHH and 59 typically hearing (TH) children between ages 3–8 years at baseline. Participants were assessed on measures of receptive spoken language (vocabulary, sentence comprehension, and following spoken directions) and caregiver-completed executive functioning child behavior checklists during two in-person home visits separated by 1 year. In the sample of DHH children, better executive functioning at baseline (Time 1) was associated with better performance on the higher-order language measures (sentence comprehension and following spoken directions) 1 year later (Time 2). In contrast, none of the Time 1 language measures were associated with better executive functioning in Time 2 in the DHH sample. TH children showed no significant language-executive functioning correlations over the 1-year study period. In regression analyses controlling for Time 1 language scores, Time 1 executive functioning predicted Time 2 language outcomes in the combined DHH and TH samples, and for vocabulary, that association was stronger in the DHH than in the TH sample. In contrast, after controlling for Time 1 executive functioning, none of the regression analyses predicting Time 2 executive functioning from Time 1 language were statistically significant. These results are the first findings to demonstrate that everyday parent-rated executive functioning behaviors predict basic (vocabulary) and higher-order (comprehension, following directions) spoken language development 1 year later in young (3–8 year old) DHH children, even after accounting for initial baseline language skills.

KEYWORDS

hearing loss, children, executive functioning, language, hearing aids, cochlear implants

Introduction

Children who are deaf or hard-of-hearing (DHH) and use hearing aids (HAs) or cochlear implants (CIs) for auditory-oral communication display considerable variability in language and neurocognitive outcomes (Niparko et al., 2010; Kronenberger et al., 2014; McCreery and Walker, 2022). Neurocognitive contributors to language outcomes are of considerable interest to researchers and clinicians because they offer a potential intervention target that may help to explain and improve language outcomes in the DHH population (Eisenberg et al., 2007; Pisoni et al., 2018). One domain of neurocognitive functioning that may support language development in DHH populations is executive functioning (EF; Kronenberger and Pisoni, 2020). EF encompasses a broad set of neurocognitive abilities required to actively control thought, behavior, and emotion in order to remain focused and goal-directed (Barkley, 2012). EF is composed of neurocognitive skills in distinct, yet interrelated, domains including working memory, inhibition, and shifting (Miyake et al., 2000). Working memory involves the capacity to retain and manipulate novel information (Barkley, 2012). Inhibition refers to the ability to resist and overcome initial impulsive, prepotent responses to achieve goal-directed behavior (Barkley, 2012). Shifting encompasses the ability to adjust to novel or competing stimuli in problem-solving (Barkley, 2012). Working memory has been the most-frequently investigated EF domain involved in language processing and learning in typically hearing (TH) children (e.g., Baddeley, 2003). Working memory is thought to enable and maximize in-the-moment language processing that supports higher-order language development (Carpenter and Just, 2013) as well as play a reciprocal role in vocabulary learning and retention (Gathercole and Baddeley, 1993). Inhibitory control has been related to higher-order language grammatical ability in TH children through its proposed role in active evaluation of language and grammatical rules during language processing (Ibbotson and Kearvell-White, 2015). Conversely, inhibition has been implicated as an outcome of robust vocabulary development in TH toddlerhood providing a scaffold to strengthen inhibitory skills (Chow et al., 2019). EF domains are interrelated with each other and with language throughout development, but especially in children. Indeed, previous research has supported fewer functional, measurable differences in EF domains earlier in development (Messer et al., 2018). For example, shifting has not been supported as a separate, measurable construct for performance-based EF tasks until later school-age (Messer et al., 2018). Some research has also suggested that working memory and inhibition are most strongly associated in younger children and then become more distinct and less tightly associated as children age (Lerner and Lonigan, 2014). Examination of related domains of child EF skills in fewer or single constructs representing children's overall functioning is therefore, a common practice in the field of developmental research (e.g., Gooch et al., 2016).

Longitudinal evidence in preschool and early elementary years in TH children has found that EF and language are strongly related concurrently and largely resilient to influence over time (Gooch et al., 2016). Increasing evidence supports the findings that EF and language in TH children may exhibit smaller transactional and bidirectional effects at least to age 5 (Fuhs et al., 2014; Weiland et al., 2014; Slot and von Suchodoletz, 2018). One avenue by which EF is hypothesized to play a role in scaffolding language development is by providing attentional and behavioral support to maximize language learning opportunities (Bishop et al., 2014).

In DHH children, there is emerging evidence that EF may play an outsized role during language processing and learning relative to TH children, due to challenges in listening effort, quality of language exposure, and underspecified phonological-lexical representations of words in short- and long-term memory associated with hearing loss (Rönnberg et al., 2013; Pichora-Fuller et al., 2016; Kronenberger et al., 2018). Even with best-fit hearing technology and appropriate and timely early intervention, DHH children, on average, exhibit language delays, incomplete or underspecified phonological and lexical representations, and weaker lexical networks for spoken words (Pisoni et al., 2011). Any interruptions or difficulties with the underlying auditory and linguistic skills needed to process language increases the cognitive effort involved (Beckage et al., 2011; Kenett et al., 2013), placing greater demands on EF in language processing tasks (Kronenberger et al., 2018). In fact, in a study with a dual-task paradigm designed to vary cognitive load and EF demands, DHH children displayed greater language decrements when they had fewer EF resources available to support language processing, compared to TH peers (Kronenberger et al., 2018). Even for tasks with smaller EF loads, the language processing of DHH children was found to be slower and more effortful than that of TH children, as a result of DHH children's use of EF skills as a compensatory strategy to successfully encode and process language (Kronenberger et al., 2018). In DHH children, EF skills may not simply maximize available learning opportunities, as hypothesized in TH children, but operate as a mandatory skill to overcome consistent language processing difficulties to enable language learning. Hypotheses positing the opposite causal direction, that language abilities facilitate later EF skills, suggest that language may serve as a method to facilitate control of behavior when the environment or task demands make successful EF performance difficult (Zelazo and Frye, 1998). Thus, although the co-development of language and EF across childhood is very likely reciprocal, bidirectional, and important for childhood development (Bohlmann et al., 2015), EF and language may be more tightly linked in DHH children than in TH children (Kronenberger et al., 2018).

Most of the current evidence supporting an association between EF and language skills in DHH children has been obtained using cross-sectional methods (e.g., Botting et al., 2017; McCreery and Walker, 2022). Predictive, causal, and mechanistic claims cannot be fully supported by cross-sectional data, warranting more longitudinal investigations. However, longitudinal investigations of EF and language during the critical preschool period of rapid, early language development are rare in DHH children (Kronenberger et al., 2020), with most cross-sectional and longitudinal studies focusing on school ages or older (e.g., Jones et al., 2020), after most of the significant, early, transactional effects of language and EF may have already occurred. For example, Jones et al. (2020) evaluated DHH and TH children aged 6–11 at first test and 2 years later using individually administered behavioral measures of expressive vocabulary and lab/performance-based EF. They found that expressive vocabulary significantly predicted later EF for a majority of EF tasks, but not the reverse. An earlier study by Harris et al. (2013) evaluated DHH children in the same age range at first test (6–11 years) and found the opposite result: performance-based EF (specifically, working memory) predicted both receptive vocabulary and higher-order language ability over a range of 1.5–4.5 years later. A recent study with a younger group of DHH and TH children (3–6 years at first study visit) over a period of 1–5 years showed that EF predicted vocabulary and global language 1 year later, but language only predicted later verbal short-term memory, as opposed to inhibition, shifting, or parent-rated executive functioning behaviors (Kronenberger et al., 2020).

In addition to behavioral measures, Kronenberger et al. (2020) also included a parent-rated, questionnaire-based measure of EF in analyses, the Behavior Rating Inventory of Executive Functioning (BRIEF; Gioia et al., 2000). Measuring EF using parent-rated behaviors observed in the child's daily life may add ecological validity to understanding associations between language and EF and their expression in real life for the development of interventions (Kronenberger et al., 2014; Castellanos et al., 2018), given that individually administered neurocognitive measures of EF correlate only modestly with actual EF behaviors in the day-to-day environment (Barkley, 2012). When BRIEF scales of Working Memory, Inhibit, and Shift were added into the predictive models, BRIEF Shift significantly predicted later vocabulary scores only in the DHH sample, not in TH children (Kronenberger et al., 2020). Recent cross-sectional investigations further explored this pattern of findings that language and EF of DHH children may exhibit stronger associations than TH children of the same age (Blank et al., 2020; Jamsek et al., 2021).

Thus, while existing research suggests associations between EF and language that may be stronger in DHH than TH samples, methodological limitations constrain the current body of knowledge. Cross-sectional/concurrent studies comprise the vast majority of language-EF research with DHH children but cannot address longitudinal, predictive, or causal influences. Longitudinal research has significant advantages, but very few longitudinal studies have been undertaken in this area, all of which have additional limitations. For example, only one longitudinal study (Jones et al., 2020) controlled for baseline language or EF when predicting later language or EF scores. Controlling for baseline values of an outcome variable (as in cross-lagged analyses) has the advantage of removing the effects of the baseline (concurrent) correlation between two variables (in this case, language and EF) when testing the longitudinal association between the variables. However, that strategy may mask earlier causal relationships between the variables in question, which created the baseline (concurrent) correlation in the first place. As a result, earlier reciprocal or unidirectional influences between language and EF may be responsible for a strong concurrent association found later in development, and removing that later concurrent association obscures the earlier EF-language effect. The best way to address this latter issue may be to investigate language-EF influences at very young ages when children are in a period of rapid development and change. Studies at later ages, even early to middle school ages, may miss the critical early influences transacting between language and EF that occur during preschool and very early school ages, particularly when controlling for baseline language and EF. Finally, very little research has investigated EF in the child's daily behavior, based on parent-report. While parent-reports of child behavior have well-known limitations (Toplak et al., 2013; Friedman and Gustavson, 2022), compared to lab/performance-based measures they are also a much more ecologically valid assessment of the child's EF in daily life (Barkley, 2012), which would be expected to more closely correspond to language exposure and processing.

The objective of this study was to examine the predictive, reciprocal associations of EF on language and language on EF over a 1-year period in samples of preschool- and early school age DHH and TH children (3–8 years of age; henceforth referred to as "preschool-age" for simplicity and recognition that many DHH children enter early school grades at slightly later ages). This study extends previous research by incorporating parent-report questionnaire measures of EF, controlling for baseline language/EF measures in analyses, and assessing multiple domains of language in a sample of young children. Study hypotheses were as follows: (1) Preschool-aged children will demonstrate reciprocal, longitudinal associations between EF and language after accounting for baseline EF/language skills; and 2) those associations will be stronger for DHH than for TH children.

Materials and methods

Participants and procedure

One hundred and twelve children between the ages of 3–8 years at their first study visit participated in a larger longitudinal study of family environment and developmental outcomes in children who are DHH and primarily use auditory-oral communication (Families and Hearing Study; Holt et al., 2020). All participants were screened for non-verbal reasoning ability on the Differential Ability Scales–Second Edition Picture Similarities subtest (Elliott et al., 2007), and were included in the study if they scored higher than 2 standard deviations below the mean (T-score > 30). In addition, each child's primary caregiver reported typical hearing, English as the primary home language, and no history of developmental disabilities/delays in their child (other than known sequelae of hearing loss in the DHH sample). Inclusion criteria for all TH children included passing a bilateral behavioral hearing screening at 25 dB HL at octave frequencies between and including 250–4,000 Hz (re: American National Standards Institute, 2010) at their first visit. The screening was administered by clinical researchers in the families' homes using an Earscan 3 handheld screening audiometer with insert earphones (Micro Audiometrics Corporation, 2018). DHH children were included if they had a bilateral, sensorineural hearing loss that was identified before 2 years of age and received intervention with amplification (HAs or CIs) before 2 years of age. The children with CIs were implanted before 3.5 years of age, the majority before 3 years.

The DHH sample was primarily recruited from hospital databases of DHH children with HAs and/or CIs in Ohio and Indiana. Both TH and DHH children were also recruited via online and hard copy recruitment posters in the surrounding communities, including medical settings and organizations serving both TH and DHH children. Participants completed two in-person research home visits [Time 1 (T1) and Time 2 (T2)] separated by 10–14 months. During home visits, which typically lasted 2.5 h, one clinical researcher administered child assessments (including spoken language measures), while the other worked with the child's primary caregiver, who also completed study questionnaires just before each visit (including EF, background/demographic, and hearing history questionnaires). Fifty-five of the TH child caregivers were mothers and four were fathers. Forty-three of the DHH child caregivers were mothers, three were fathers, five were adoptive mothers, and two were grandmothers. The sample (demographics displayed in **Table 1**) was composed of 59 TH children and 53 DHH children (24 HA users and 29 CI users) with no significant differences in gender composition between hearing groups. The TH sample was significantly younger and had significantly higher levels of parental education and annual family income than the DHH sample (**Table 1**). Children who used bilateral HAs had a significantly longer amount of time since first device fit and better hearing as measured by lower unaided better ear 4-frequency pure-tone average (PTA) than children who used at least one CI (**Table 1**).

Measures

Receptive spoken language

Children were individually administered three measures designed to assess different domains of receptive language: single-word vocabulary [Peabody Picture Vocabulary Test-4 (PPVT); Dunn and Dunn, 2007], sentence comprehension [Comprehensive Assessment of Spoken Language-2 (CASL) Sentence Comprehension subtest; Carrow-Woolfolk, 2017], and following spoken directions [Clinical Evaluation of Language Fundamentals (CELF) Following Directions subtest; Wiig et al., 2004; Semel et al., 2013]. The CELF-Preschool-2 Concepts and Following Directions subtest (Semel et al., 2013) was used for children ages 3–5 years and the CELF-5 Following Directions subtest (Wiig et al., 2004) was used for children ages 6 years and older. Receptive language measures were chosen to reduce task demands and avoid scoring ambiguity from potentially distorted speech in children who are DHH, because these receptive measures do not require a verbal response from the participant. The PPVT is a widely used, normed measure of single-word receptive vocabulary that requires participants to identify a picture from among a set of four choices that corresponds to a word spoken aloud by the examiner. The CASL Sentence Comprehension subtest requires participants to indicate the picture that corresponds to a sentence spoken by the experimenter. If participants reach the end of that section, they are also asked to evaluate a pair of sentences spoken by the experimenter for their semantic equivalence. The CELF Following Directions subtest requires participants

TABLE 1 T1 participant demographics and audiological characteristics.

Characteristics	TH M (SD)	DHH (HA and CI) M (SD)	HA M (SD)	CI M (SD)
Demographics				
N	59	53	24	29
N females/males	27/32	27/26	12/12	15/14
Chronological age, child (years)	5.78 (1.61)	6.55* (1.55)	6.55 (1.71)	6.55 (1.43)
Parental education[a]	8.12 (1.26)	7.66* (1.22)	7.75 (1.15)	7.59 (1.30)
Annual family income[b]	8.81 (1.58)	7.77* (2.64)	8.33 (2.12)	7.31 (2.95)
Audiological characteristics				
Hearing age (years)[c]	n/a	4.88 (1.94)	5.61 (1.75)	4.27* (1.90)
Unaided 4-frequency PTA[d] (dB HL)	n/a	72.3 (28.59)	50.21 (15.06)	92.64*** (22.24)
Aided 4-frequency PTA[e] (dB HL)	n/a	23.51 (6.41)	21.14 (9.82)	24.52 (4.12)

Independent samples t-tests were used to compare between hearing groups; N, number of participants; TH, typical hearing; DHH, deaf or hard-of-hearing; HA, hearing aid; CI, cochlear implant; PTA, pure-tone average re: American National Standards Institute (2004); n/a = not applicable. [a]Parental education was coded based on highest level of formal education: 1 = elementary school through 10 = doctorate degree. [b]Parents indicated their annual income on a 1 (under $5,000) to 10 ($95,000 and over) scale. [c]Calculated by subtracting age at which child was first fit with HAs or CIs from their chronological age. [d]Calculated at 0.5, 1, 2, and 4 kHz in the better ear based on data from 50 children (24 HA and 26 CI users, respectively) due to lack of access to the medical information for a subset of children. [e]Calculated at 0.5, 1, 2, and 4 kHz in the better ear based on data from 37 children (11 HA and 26 CI users, respectively). $^{*}p < 0.05$, $^{***}p < 0.001$.

to sequentially point to items indicated by the experimenter in directive sentences of increasing length and complexity. Scoring for all three language measures includes standard scores (scaled scores in the case of the CELF) based on their respective normative samples, in which higher scores correspond to better receptive spoken language ability. These measures were chosen to assess distinct areas of language learning under active development in early school-age children. Single-word vocabulary is a basic building block of language development, while sentence comprehension and following directions are considered higher-order language processes. The CASL is a broader measure of the stage of language development, while the CELF involves attentional components that could implicate EF skills to a greater degree.

Executive functioning behavior checklists

Caregivers completed the Behavior Rating Inventory of Executive Functioning (BRIEF; BRIEF-Preschool for 3–5 years and BRIEF-2 for 6 + years; Gioia et al., 1996, 2015) and the Learning, Executive, and Attention Functioning scale (LEAF; Castellanos et al., 2018). BRIEF scores have been extensively validated as measures of their respective constructs and consistently identify EF dysfunction in clinical populations with poor EF, such as children with attention-deficit/hyperactivity disorder (Gioia et al., 2000; Roth et al., 2014). BRIEF scores have also been used and validated in children who are DHH (e.g., Beer et al., 2014). BRIEF raw scores can be converted to T-scores using an age-based normative sample, such that higher scores indicate poorer EF. Two BRIEF subscales were chosen because they involve core subdomains of EF (e.g., Miyake et al., 2000) that have been identified as at-risk for delays in preschool-aged DHH children (Kronenberger et al., 2020): Inhibit (example item: “Does not think before doing”) and Working Memory (“When given three things to do, remembers only the first or last”). The LEAF is a behavior checklist that focuses on everyday child behaviors related to more cognitively-based EF behaviors in daily life (Castellanos et al., 2018). The LEAF demonstrated strong internal consistency, test-retest reliability, and validity as an EF measure, including significant correlations with scores on other EF behavior checklists and neurocognitive performance-based measures (Castellanos et al., 2018). Three LEAF subscales were selected because of evidence of delays in these EF domains in preschool-aged CI users (Kronenberger et al., 2014): Attention (example item: “Does not stay focused on learning material”), Working Memory (“Forgets things that he or she knew how to do a few hours or days before”), and Sustained Sequential Processing (“Loses track of step-by-step directions”). The LEAF yields raw scores, with higher scores corresponding to poorer EF. The LEAF and BRIEF scales capture overlapping yet complementary aspects of EF behavior because of their item choice and scale design (Castellanos et al., 2018). To create a comprehensive measure of children’s daily functioning and behaviors corresponding to EF, BRIEF and LEAF were combined into one composite score for analysis.

Statistical analysis

Statistical analyses were performed using IBM SPSS v.28 (IBM Corporation, 2021); all p-values are two-tailed. For the language tests (PPVT, CASL, CELF), age norm-based (standard or scaled) scores were used in all analyses. To represent EF in daily life, an aggregate variable was created for each participant by averaging standardized z-scores [using the mean

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and standard deviation (SD) of the full sample) from *T*-scores of BRIEF Inhibit and Working Memory subscales and raw scores of LEAF Attention, Working Memory, and Sustained Sequential Processing subscales. Higher aggregate EF variable scores correspond to poorer EF. The T2 EF variable was missing for two DHH participants at T2 because parents failed to complete both LEAF and BRIEF. The selected EF scales all fall under the umbrella construct of EF, but are also theorized to work together and are connected cognitively to support functioning in daily life (Barkley, 2012). In addition, aggregation of the LEAF and BRIEF subscales into a single EF variable was supported by correlational and principal components analysis of T1 data. Concurrent full-sample bivariate Pearson correlations of included BRIEF (*T*-scores) and LEAF (raw scores) subscales ranged from $r = 0.549$ to 0.794 with a median correlation of $r = 0.616$ (full correlation tables are available upon request from the corresponding author). In a principal components analysis, a single component solution accounted for over half of the variance (Eigenvalue = 3.56), and all 5 T1 BRIEF and LEAF scores had loadings of 0.79 or greater on the component (median loading = 0.84). When all subsequent analyses were repeated with separate inhibitory control and working memory aggregate variables, the same trends reported below were found. Consequently, for parsimony, one EF aggregate variable was used in the remaining analyses.

Descriptive statistics (means, SDs, or frequency counts, as appropriate) were used to characterize the demographic and audiological characteristics of the TH and DHH samples, as well as the HA and CI subsamples within the DHH sample. Comparisons between samples and subsamples were carried out using independent samples *t*-tests for continuous data or chi-square tests for categorical data. To compare language and EF scores between the samples (TH vs. DHH) and subsamples (HA vs. CI) at both time points, analyses of covariance (ANCOVAs) were used, controlling for T1 child chronological age. Separately within each hearing group, predictive bivariate Pearson correlations were then performed between T1 language and T2 EF scores and T1 EF and T2 language scores to investigate longitudinal associations between EF and language separately for each hearing group.

Finally, hierarchical regression analyses (using the combined DHH and TH samples) were performed with each of the three T2 language scores as the criterion variable (3 separate equations for PPVT, CASL, and CELF). The first block of predictor variables (all entered into the equation regardless of statistical significance) consisted of hearing group, parental education, and the T1 language score corresponding to the language measure used as the criterion variable. The second variable block consisted of the T1 EF score (entered into the equation regardless of significance), to investigate the predictive association of T1 EF on T2 language, over and above the first block. Finally, the third variable block consisted of the product (interaction) of hearing group × T1 EF to investigate whether the T1 EF-T2 language association was moderated by hearing group; this term was retained in the final equation only if statistically significant, in order to reduce multicollinearity and adverse effects on power.

Conversely, hierarchical regression equations were also calculated predicting T2 EF from T1 language scores. The first block of predictor variables (all entered into the equation regardless of statistical significance) consisted of hearing group, parental education, and the T1 EF score. The second variable block consisted of the T1 language scores (PPVT, CASL, and CELF, each entered separately into the equation and tested for significance), to investigate the predictive association of T1 language on T2 EF, over and above the first block. Finally, the third variable block consisted of the three products (interactions) of hearing group x T1 language (PPVT, CASL, and CELF) to investigate whether the T1 language-T2 EF association was moderated by hearing group; this term was retained in the final equation only if statistically significant, in order to reduce multicollinearity and adverse effects on power.

Results

Longitudinal language/executive functioning scores and associations

Table 2 displays means and SDs of T1 and T2 language and EF for both hearing groups. As expected, TH children showed significantly better standard/scaled language scores than DHH children for all language measures at both T1 and T2 (T1 PPVT: $F = 54.31$, $p < 0.001$; T2 PPVT: $F = 37.39$, $p < 0.001$; T1 CASL: $F = 12.74$, $p < 0.001$; T2 CASL: $F = 16.03$, $p < 0.001$; T1 CELF: $F = 23.21$, $p < 0.001$; T2 CELF: $F = 19.21$, $p < 0.001$). TH children also had significantly lower (i.e., better) EF scores than DHH children at T1 ($F = 11.11$, $p = 0.001$), but not T2 ($F = 3.02$, $p = 0.09$). Children who use HAs also had significantly better language scores than children who use CIs at both timepoints (T1 PPVT: $F = 5.53$, $p = 0.02$; T2 PPVT: $F = 4.73$, $p = 0.03$; T2 CASL: $F = 7.68$, $p = 0.008$; T2 CELF: $F = 8.92$, $p = 0.004$), except for T1 CASL ($F = 0.54$, $p = 0.47$) and T1 CELF ($F = 2.48$, $p = 0.12$). Children who use HAs had significantly better T1 EF than children who use CIs ($F = 7.00$, $p = 0.01$), but did not show a significant difference in T2 EF ($F = 2.35$, $p = 0.13$).

Table 3 reports predictive correlations between T1 language-T2 EF and T1 EF-T2 language. In the TH sample, no significant correlations were found between T1 language and T2 EF or T1 EF and T2 language. In contrast, DHH children showed significant correlations between T1 EF and two T2 language measures, T2 CASL ($r = -0.353$, $p = 0.009$) and T2 CELF ($r = -0.381$, $p = 0.005$; poorer EF associated with lower language scores), while no significant correlations were found between T1 EF and T2 PPVT or any T1 language measure and T2 EF.

TABLE 2 T1 and T2 language and EF descriptive statistics.

Characteristics	TH M (SD)	DHH (HA and CI) M (SD)	HA M (SD)	CI M (SD)
T1 PPVT	116.88 (10.19)	97.30*** (17.62)	103.33 (16.57)	92.31* (17.15)
T2 PPVT	117.25 (12.83)	98.70*** (18.38)	104.58 (15.45)	93.83* (19.24)
T1 CASL	111.19 (12.55)	103.21*** (16.28)	105.00 (15.45)	101.72 (17.07)
T2 CASL	115.49 (10.54)	105.55*** (15.63)	111.75 (13.61)	100.41** (15.52)
T1 CELF	10.81 (2.84)	8.30*** (3.47)	9.08 (3.28)	7.66 (3.55)
T2 CELF	11.32 (3.02)	8.75*** (3.62)	10.25 (3.40)	7.52** (3.37)
T1 EF	−0.29 (0.78)	0.33** (1.12)	−0.10 (1.07)	0.68* (1.05)
T2 EF	−0.16 (0.97)	0.19 (1.02)	−0.06 (1.04)	0.39 (0.97)

Analyses of Covariance controlling for T1 child chronological age were used to compare between hearing groups; T1, timepoint 1; T2, timepoint 2, 10–14 months after T1; EF, executive functioning score; TH, typical hearing; DHH, deaf or hard-of-hearing; HA, hearing aid; CI, cochlear implant; PPVT, Peabody Picture Vocabulary Test–Fourth Edition, standard scores; CASL, Comprehensive Assessment of Spoken Language, Second Edition Sentence Comprehension subtest, standard scores; CELF, Clinical Evaluation of Language Fundamentals–Fifth Edition/Clinical Evaluation of Language Fundamentals Preschool–Second Edition, scaled scores. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Longitudinal/predictive regressions

Six hierarchical multiple linear regression analyses were conducted with both TH and DHH children combined in each analysis. For the first 3 analyses, the three T2 language variables served as criterion variables, and the primary predictor of interest was T1 EF, in order to investigate whether T1 EF predicted T2 language with T1 language, hearing group, and parental education controlled. In equations predicting the three language variables at T2 (**Table 4**), T1 language emerged as a significant predictor, and T1 EF added significantly to T1 language in predicting T2 language for CASL ($t = -2.22$, $p = 0.03$) and CELF ($t = -2.67$, $p = 0.009$). However, none of the hearing group × EF interaction terms were significant for the latter two outcomes. For PPVT, however, a significant hearing group x EF interaction was found ($t = -2.71$, $p = 0.008$). *Post hoc* analysis of the interaction using the Johnson-Neyman technique, as shown in **Figure 1**, revealed no significant relation between T1 EF and T2 PPVT for TH children ($t = 0.99$, $p = 0.33$), but a marginally significant negative relation for DHH children ($t = -1.91$, $p = 0.06$), such that lower (better) T1 EF scores were significantly related with higher (better) T2 PPVT scores.

For the final 3 analyses, T2 EF served as the criterion variable, and separate analyses were conducted with each T1 language variable entered in the second block to test prediction

TABLE 3 T1 and T2 longitudinal language/EF correlations.

	T1 EF			T2 EF	
	TH	DHH		TH	DHH
T2 PPVT	0.157	−0.224	T1 PPVT	−0.066	−0.089
T2 CASL	−0.028	−0.353**	T1 CASL	0.071	−0.169
T2 CELF	−0.143	−0.381**	T1 CELF	−0.163	−0.227

T1, timepoint 1; T2, timepoint 2 10–14 months after T1; EF, executive functioning score; TH, typical hearing; DHH, deaf or hard-of-hearing; PPVT, Peabody Picture Vocabulary Test–Fourth Edition, standard scores; CASL, Comprehensive Assessment of Spoken Language, Second Edition Sentence Comprehension subtest, standard scores; CELF, Clinical Evaluation of Language Fundamentals–Fifth Edition/Clinical Evaluation of Language Fundamentals Preschool–Second Edition, scaled scores. **$p < 0.01$.

TABLE 4 Hierarchical linear regressions predicting T2 language outcomes.

	T2 Language (Criterion)		
	PPVT	CASL	CELF
Model 1	0.73***	0.44***	0.49***
Hearing group	−0.04	−0.19*	−0.13
T1 language	0.81***	0.54***	0.65***
Parental education[a]	0.07	0.11	−0.04
Model 2	0.73***	0.46***	0.52***
Hearing group	−0.05	−0.14	−0.08
T1 language	0.81***	0.52***	0.62***
Parental education	0.07	0.12	−0.04
T1 executive functioning	0.04	−0.17*	−0.19**
Model 3	0.75***	NS	NS
Hearing group	−0.06		
T1 language	0.81***		
Parental education	0.06		
T1 executive functioning	0.23*		
Hearing group × T1 executive functioning	−0.23**		

Values for Model row are R^2 (statistical significance is reported for the R^2 value); values for variable rows are standardized regression weights. T1, timepoint 1; T2, timepoint 2 10–14 months after T1; PPVT, Peabody Picture Vocabulary Test–Fourth Edition (standard scores); EF, executive functioning score. [a]Parental education was coded based on highest level of formal education: 1 = elementary school through 10 = doctorate degree. T1 Language = Language predictor variable (PPVT, CASL, or CELF) at T1 corresponding to T2 language criterion variable (e.g., PPVT at T1 for equation with PPVT at T2 as criterion variable). NS = Hearing Group × Executive Functioning terms were non-significant for equations predicting CASL and CELF. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

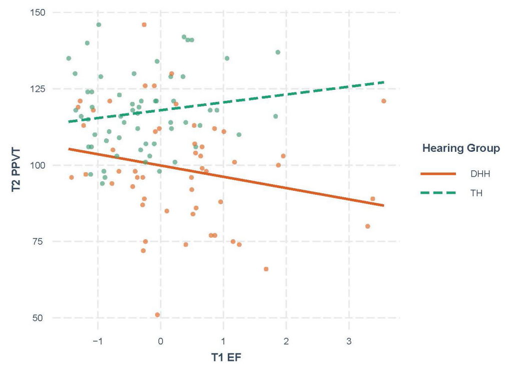

FIGURE 1
Interaction between TH and DHH children for the association of T1 EF and T2 PPVT. Children who are DHH demonstrate a marginally significant negative longitudinal association while the TH children do not show a significant association. T1, timepoint 1; T2, timepoint 2 10–14 months after T1; PPVT, Peabody Picture Vocabulary Test–Fourth Edition (standard scores); EF, executive functioning score; TH, typical hearing; DHH, deaf or hard-of-hearing.

of T2 EF from T1 language with T1 EF, hearing group, and parental education controlled. **Table 5** reports the regression analyses with T2 EF as the dependent variable and separate tests for each language score in Model 2 (three models). For all three models, the only significant main effect was T1 EF. No language score significantly predicted T2 EF in Model 2, and the addition of the hearing group x T1 language interaction in Model 3 did not significantly improve model fit.

Discussion

The purpose of this study was to examine the predictive, reciprocal associations between EF and spoken language over a 1-year period in DHH and TH samples of preschool-aged children at entrance into the study. Consistent with our first hypothesis, DHH children demonstrated longitudinal associations between EF and measures of later language in correlational analyses as well as regression analyses even after controlling for baseline language, whereas evidence for the reverse was not found. Consistent with our second hypothesis, correlations for T2 higher-order language (comprehension and following directions) and T1 EF were statistically significant in the DHH sample but not in the TH sample, and for T2 receptive vocabulary, the significant interaction term for hearing group and T1 EF demonstrated a stronger association between T1 EF and T2 vocabulary in the DHH group than in the TH group. These results are the first to demonstrate that everyday parent-rated EF behaviors predict basic (vocabulary) and higher-order (comprehension, following directions) language development 1 year later in preschool-aged DHH children even after accounting for baseline language skills. The current study was also the first longitudinal study to focus exclusively on parent-rated EF behaviors in daily life; prior work has focused either exclusively (Jones et al., 2020) or partly (Kronenberger et al., 2020) on individual ability testing of EF in the office/lab setting, which shares method variance with individually administered language tests.

The finding in this study that T1 EF significantly predicted T2 language in preschool-aged DHH children, but not the reverse, is similar to results obtained by Kronenberger et al. (2020), providing further evidence of the importance of early EF for later language development of DHH children at young ages. On the other hand, this finding contrasts with that of Jones et al. (2020), who found that T1 language predicted T2 EF, but not the reverse, in their sample of DHH children. The discrepancy of these findings may be due to the different ages of the children in these studies. The current study (ages 3–8 years) and the study of Kronenberger et al. (2020; ages 3–6 years) included much younger (many preschool-aged) children than Jones et al. (2020) (6–12-year-old children). Language learning is more rapid earlier in development, increasing the potential for factors

TABLE 5 Hierarchical linear regressions predicting T2 executive functioning.

	T2 Executive functioning (Criterion)
Model 1	0.63***
Hearing group	−0.06
T1 executive functioning	0.81***
Parental education[a]	0.07
Model 2 (T1 PPVT as Predictor)	0.63***
Hearing group	−0.04
T1 executive functioning	0.82***
Parental education	0.06
T1 PPVT	0.05
Model 2 (T1 CASL as Predictor)	0.63***
Hearing group	−0.06
T1 Executive functioning	0.82***
Parental education	0.06
T1 CASL	0.03
Model 2 (T1 CELF as Predictor)	0.64***
Hearing group	−0.09
T1 Executive functioning	0.80***
Parental education	0.08
T1 CELF	−0.10

Model 1 is the same for each language variable tested in Model 2. Each Model 2 shown is for one of the language variables (PPVT, CASL, CELF) predicting T2 Executive Functioning. Values for Model rows are R^2; values for variable rows are standardized regression weights. Model 3 is not shown because all Hearing Group × Language product (interaction) variables were non-significant ($p > 0.10$) and did not meet criteria for model entry. T1, timepoint 1; T2, timepoint 2 10–14 months after T1; PPVT, Peabody Picture Vocabulary Test–Fourth Edition (standard scores); EF, executive functioning score. [a]Parental education was coded based on highest level of formal education: 1 = elementary school through 10 = doctorate degree. ***$p < 0.001$.

to influence its development at younger ages. In support of this hypothesis, Jones et al. (2020) report a path coefficient of 0.88 from their T1 vocabulary to T2 vocabulary score in their older sample, indicating extremely high language stability and leaving little unexplained variance for EF (or any other variable) to account for. On the other hand, in the current younger sample, the models with T1 CASL and CELF as predictors accounted for 44–49% of the variance in their respective T2 scores, leaving over half of the T2 language variance available for explanation by other contributing factors.

Another potential explanation for the discrepancy between the current study and Jones et al. (2020) may be the domains of language processing assessed. The current study assessed receptive language and included one measure of word knowledge (vocabulary) and two measures of higher-order language/discourse processing involving concept formation, integration of linguistic meaning, and memory (comprehension and following directions). In contrast, Jones et al. (2020) focused on expressive single word vocabulary as their only measure of language and did not include any higher-order language measures. Of note, a cross-sectional study reporting that language accounted for EF differences between hearing groups—but not the reverse (EF accounting for language)—also used only single word expressive vocabulary as the sole measure of language in a sample of school aged children 5–11 years of age (Botting et al., 2017).

In the current study, the correlation between T1 EF and the T2 measure of single-word vocabulary (PPVT) was not significant (**Table 3**), nor was the main effect of T1 EF predicting T2 PPVT in Model 2 of the hierarchical regression (**Table 4**), although the full regression equation for PPVT (including the interaction block) did indicate T1 EF as a significant predictor for T2 PPVT for the DHH sample. On the other hand, T2 higher-order language measures were significantly predicted by T1 EF not only in the current study but also in another prior longitudinal study of children with CIs, using the Preschool Language Scale-2 to assess higher-order language (Kronenberger et al., 2020). This pattern of findings suggests that more basic vocabulary knowledge scores may be more stable over time and less influenced by earlier EF than higher-order language, which was predicted by earlier EF in the current study and in other studies. Higher-order language processing is at greater risk for delay, more dependent on EF, and not fully explained by vocabulary skills in DHH samples, suggesting that EF may have a greater longitudinal role in development of higher order language than basic vocabulary skills (Kronenberger and Pisoni, 2019).

It is also possible that some domains of language may contribute more to EF development than others, allowing for a predictive association of language explaining later EF outcomes. Expressive vocabulary as measured in Botting et al. (2017) and Jones et al. (2020), for example, may better account for the contribution of language to EF development. One hypothesis for this mediating effect of language on EF development may be that expressive language is used to regulate and direct thinking and behavior in a goal-directed manner (Zelazo and Frye, 1998). On the other hand, receptive vocabulary, used in this study, is a measure of word understanding, not use, and so may better reflect the ability of EF skills to facilitate hearing, learning, and understanding surrounding language during processing. Alternatively, single-word vocabulary (whether expressive or receptive) may be a better predictor of later EF skills than higher-order language skills. In addition to Jones et al. (2020) finding that single word expressive vocabulary predicting later EF skills, Kronenberger et al. (2020) found that single word receptive vocabulary (PPVT scores) predicted one measure of verbal short-term/working memory (digit span forward) in preschoolers, whereas a higher-order language measure did not. Overall, this pattern of findings across different studies suggests that developmental stage, domain of language, and domain of EF should be considered when examining the predictive longitudinal associations between language and EF; simple, broad, unidirectional effects do not appear to accurately represent the complexity of reciprocal contributions of language and EF skills (Kronenberger and Pisoni, 2020).

An additional consideration in integrating results across studies is the measurement modality used for language and EF. Most of the early investigations of EF skills in DHH children with CIs or HAs relied on individually administered tests of ability in a controlled (lab, office, clinic) setting to operationalize EF (Figueras et al., 2008; Pisoni et al., 2010), while some later research has assessed EF using parent-report behavior checklists (Kronenberger et al., 2014). A large body of research has demonstrated that these different measurement modalities produce only modestly (albeit significantly) correlated EF scores (Barkley, 2012; Toplak et al., 2013), making the measurement modality a crucial consideration in application and interpretation of EF results. Because almost all language tests are individually administered behavioral performance tests in a controlled setting, language tests share method variance with individually administered, office/lab-based EF tests, and some of their shared variance may therefore reflect the effects of shared administrative methodology (e.g., good ability test-takers vs. poor ability test-takers; focus/motivation during individually administered tests of any ability, including language or EF). Parent-report questionnaire measures of EF do not share this method variance with individually administered, office/lab-based language tests, providing an advantage to studies such as the current one, which use EF questionnaires. On the other hand, parent-report questionnaires suffer from their own limitations, including parental response bias, variation in parent awareness/familiarity with child behavior, and parent personality factors. Hence, because any measurement methodology has limitations, integration of findings using different measurement modalities offers the greatest potential for understanding associations between constructs (Holmbeck et al., 2002). As a result, this study reports important novel information about EF and language development in DHH children by focusing on a relatively underused method for assessing EF skills—parent-report questionnaires.

Our second hypothesis, that the EF-language association would be stronger in DHH than in TH children, was partially supported by study findings. We expected a stronger EF-language association in DHH children than in TH children because language processing in TH children is typically fast and automatic, requiring less scaffolding by EF skills (Posner and Snyder, 2004). In contrast, DHH children may use more cognitive effort and working memory resources (components of EF) in the context of slow-effortful language processing to compensate for underspecified, coarse-coded phonological-lexical representations of words in memory (Rönnberg et al., 2013; Pichora-Fuller et al., 2016). Furthermore, when auditory access or linguistic representations are disrupted, as can happen for DHH children, the use of available EF in detection, processing, and encoding language may be more important for DHH than for TH children (Houston et al., 2020). Therefore, we would expect that the relation between EF and language to be stronger in children who are DHH than in TH children. Consistent with these predictions, results of an earlier experimental study demonstrated that DHH children with CIs are more reliant on a specific EF subdomain, verbal working memory, during language processing, than TH peers (Kronenberger et al., 2018).

In the current study, we found statistically significant correlations between T1 EF and T2 higher-order language (CASL and CELF) only in the DHH sample and not in the TH sample, consistent with our hypothesis of stronger EF-language associations in DHH children. However, *z*-tests comparing these correlations across the DHH and TH samples failed to reach statistical significance [$z = 1.74$ ($p = 0.10$) and 1.32 ($p = 0.19$) for CASL and CELF, respectively]. Furthermore, the hearing group x EF interaction predicting language outcome was significant only for the PPVT, such that EF was a stronger predictor of PPVT scores 1 year later in the DHH group than in the TH group. Thus, despite some indications of a stronger role for EF in language outcomes for DHH children, results were not consistently statistically significant. Future research with larger samples is recommended to further investigate this association, because results could have been affected by insufficient power.

Examining language and EF outcomes between groups revealed that TH children had significantly better T1/T2 language and T1 EF scores than DHH children when controlling for age differences between groups. This is consistent with extensive previous literature documenting language and EF delays, difficulties, and variability in DHH children who use auditory-oral spoken language as their mode of communication (e.g., Niparko et al., 2010; Kronenberger et al., 2014). Auditory and language development are inextricably related with neurocognitive development, especially early in life when neural development and organization are dependent on a wealth of sensory experiences (Kronenberger and Pisoni, 2018); any interruptions, delays, or distorted auditory or language input as a result of hearing loss would be expected to introduce more variability into related development in DHH children than TH children. One example for spoken language development is a prolific and ongoing research area documenting that the amount of parental language spoken in the home plays a significant role in later language development (e.g., Hart and Risley, 2003). Children who are DHH often inconsistently overhear language spoken in their environment that is not directed at them (McCreery et al., 2015). Overhearing contributes to language development and DHH children's altered auditory experience with overhearing can differentially influence their development. In relation to EF variability in DHH children, the primary hypotheses for this difference lies in early auditory (e.g., Kral et al., 2016) and/or language deprivation (e.g., Hall, 2017) due to hearing loss that causes cascading neurocognitive effects during time-sensitive periods of neural development and organization (Kronenberger and Pisoni, 2018). In this study, the focus was on how DHH children who primarily use auditory-oral spoken language utilize their available EF skills in relation to later language learning, given underlying population variability.

It is also worth noting that TH children performed approximately one standard deviation above the mean on all language measures except the CELF. TH children as a group had significantly higher parental education and household income levels, although the differences between groups functionally represented a difference in type of college degree or about $15,000 per year in household income. Despite our attempts to use similar recruitment strategies for DHH and TH samples, use of a volunteer sampling strategy likely resulted in a higher-than-average functioning TH sample. In order to address parental education differences between samples, we controlled for parental education in our regression analyses; we did not also control for family income because of the strong association between parental education and family income in the study sample ($r = 0.425$, $p < 0.001$).

The DHH sample in this study was heterogeneous in several ways, most notably in device used. DHH participants used either HAs or CI(s), and varied in number of CIs (one or two) and audiological functioning (**Table 1**). The use of a DHH sample comprised of both HA and CI users has both advantages and limitations. One advantage is the investigation of outcomes across a wide range of audiological functioning and intervention history, particularly for children with HAs, who are an understudied clinical population (Donahue, 2007). Recent research efforts have begun to document more extensive data on language and EF development in children with HAs, showing cross-sectional associations of language with BRIEF WM and Inhibit (McCreery and Walker, 2022). An additional advantage of a combined HA/CI sample is the potential to compare outcomes. Studies examining language and EF in samples comprised of children who use HAs and children who use CIs are relatively rare. In this sample, children who use HAs tended to show better language and EF outcomes than children who use CIs, consistent with differing degrees of hearing loss and intervention. However, children who use HAs also tended to demonstrate lower scores and more variability than children with TH, extending previous findings as to the research and clinical needs of these children (Stiles et al., 2012). The primary limitation of a combined sample of HA and CI users is the added heterogeneity in outcomes and possibility of different associations with outcomes in HA vs. CI users. In order to have sufficient power for predictive/longitudinal analyses in the current study, HA and CI users were combined into a single DHH sample, as has been done in previous studies (e.g., Figueras et al., 2008). However, future research with larger sample sizes allowing for comparison of HA and CI users is recommended.

Limitations

The results of this study should be interpreted in light of some methodological limitations, in addition to the use of a combined sample of HA/CI users discussed earlier. The TH and DHH samples differed along several demographic dimensions (age, parent education, parent income), although these dimensions were statistically controlled in analyses. Additionally, while longitudinal/predictive models constrain causal directions somewhat (e.g., a T2 variable cannot retrospectively cause a T1 variable), causality cannot be definitively concluded from predictive correlations or regressions alone in the absence of experimental manipulation. Thus, it is possible that third variables or mediating variables could affect the predictive associations found between EF and language in this study. Furthermore, while the sample size of 53 DHH and 59 TH participants is large in the context of previous studies of preschool-aged DHH children, it may not have provided sufficient power to detect small to medium effect sizes. Particularly for TH children, larger sample sizes may have produced greater variability and greater power to detect language-EF associations, and therefore non-significant results for TH children should be interpreted with caution. Smaller sample sizes may be sufficient to detect significant effect sizes in DHH children because of the larger associations between EF and language. Finally, while not a limitation *per se*, the results of this study should be interpreted in the context of the EF measurement modality of parent-report questionnaires and the specific use of two questionnaires—the BRIEF and LEAF. We selected these questionnaires and subscales because of prior results demonstrating their validity and importance in characterizing EF in samples of DHH children (Pisoni et al., 2010). Questionnaires with other content or other EF domains may produce different results.

Conclusion and future directions

Findings in this study documented the first longitudinal, predictive relations of parent-rated EF behaviors in daily life with later language abilities when accounting for earlier language over a period of 1 year in a sample including preschool-aged DHH children. These results support the potential malleability of language development in young DHH children depending on earlier EF at preschool ages. In addition to enhancing our understanding of EF effects on language development in DHH children, these findings have significant clinical implications by suggesting that interventions to improve EF in everyday behavior at early ages may provide an opportunity to enhance language outcomes in DHH children. Previous research and clinical work have suggested early and continued EF intervention in DHH children can scaffold later EF and language development (Robbins and Kronenberger, 2021); these results support that expectation and should be further investigated. Future work should also continue to explore the mechanistic process by which EF supports language in young DHH children and should test the impact of improving EF on language outcomes in the DHH population.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Biomedical Sciences Institutional Review Board at the Ohio State University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

IJ, WK, DP, and RH contributed to conception and design of the study. RH organized the database. IJ and WK performed the statistical analysis. IJ wrote the first draft of the manuscript. RH, WK, and DP contributed edits to the manuscript. All authors contributed to manuscript revision, reading, and approving the submitted version.

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Conflict of interest

Author WK was a paid consultant for Takeda Pharmaceuticals and the Indiana Hemophilia and Thrombosis Center (neither are relevant to the content of this article).

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Can cochlear implantation prevent cognitive decline in the long-term follow-up?

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Cognitive function and hearing are known to both decline in older adults. As hearing loss is proposed to be one modifiable risk factor for dementia, the impact of auditory rehabilitation on cognitive decline has been gaining increasing attention. Despite a large number of studies, long-term data are still rare. In a large prospective longitudinal monocentric study, 50 adults (aged $\geq$ 50 years) with severe postlingual bilateral hearing loss received a cochlear implant (CI). They underwent comprehensive neurocognitive testing prior to implantation (T1), at 12 months (T2) and up to 65 months (T3) after implantation. Various cognitive subdomains such as attention, inhibition, working memory, verbal fluency, mental flexibility and (delayed) recall were assessed by the computer-based non-auditory test battery ALAcog©. The observed trajectories of two exemplary cognitive subdomains (delayed recall and working memory) were then fitted over time using multilevel growth models to adjust for sociodemographic covariates and compared with 5-year longitudinal data from a sample of older adults from the representative Survey of Health, Aging and Retirement in Europe (SHARE) study. Postoperatively, auditory functions improved from 6.98% (SD 12.83) to 57.29% (SD 20.18) in monosyllabic speech understanding. Cognitive functions significantly increased from T1 to T3 in attention ($p = 0.001$), delayed recall ($p = 0.001$), working memory (OSPAN; $p = 0.001$), verbal fluency ($p = 0.004$), and inhibition ($p = 0.002$). A closer look at follow-up revealed that cognitive improvement could be detected between T1 and T2 and thereafter remained stable in all subtests ($p \geq 0.06$). Additional longitudinal analysis confirmed these findings in a rigorous multilevel approach in two exemplary cognitive subdomains. In contrast to the SHARE data, there was no evidence for age-differential associations over time in CI recipients. This suggests that older adults benefit equally from cochlear implantation. CI users with worse preoperative cognitive skills experienced the most benefit ($p < 0.0001$). Auditory rehabilitation by cochlear implantation has a stimulating effect on cognitive functions beyond an improvement in speech understanding and an increased well-being. Large multicenter studies using standardized protocols have to be undertaken in the future to find out whether hearing restoration might help to prevent cognitive decline.

KEYWORDS

dementia, hearing loss, prevention, cochlear implant, auditory rehabilitation

Introduction

With more people living longer, the issue of healthy aging is of increasing importance (1). In addition to preserving a good physical constitution, maintaining cognitive function is quite important (2). According to the World Health Organization, more than 55 million people currently suffer from dementia worldwide and this number is predicted to rise to 78 million by 2030, and to 139 million by 2050 (3). As no causal treatment exists to reverse cognitive decline, efforts must focus on prevention (4). Recently, 12 risk factors in midlife were identified that account for 40% of dementia risk. Hearing loss is one of them (5). Livingston et al. estimated that appropriate treatment of hearing loss can reduce the prevalence of dementia by 8% (5). Therefore, the question arises: can auditory rehabilitation *via* hearing devices in middle age delay or even reverse cognitive decline (6, 7).

During the last decade studies have analyzed the benefit of hearing aids on cognitive performance; however, data were heterogeneous (8–11). In severe hearing loss cochlear implants (CI) are the option of choice (12–14). However, only 8.5% of people who would benefit from a CI actually receive one (15). This is alarming, as people with severe hearing loss are at a 4.94% higher risk of developing dementia than people with mild hearing loss (1.89%) (16).

Thus, people with a severe to profound hearing loss are of special interest in terms of preventing cognitive decline with age. To this end, a number of studies have been performed recently on cognitive changes after cochlear implantation (17–22). Mosnier et al. were among the first who evaluated, in a multicenter study, the cognitive function on 91 CI candidates, classified into normal and abnormal based on normative data from six different cognitive tests (23). 20% of the subjects aged 65–85 years had an abnormal score on at least three out of six subtests before CI provision; this decreased to only 5% after cochlear implantation. In general, cognitive functions significantly improved at six or at 12 months of CI use (22, 24). This is in line with data reporting on the improvement in speech perception (25). However, the effect size was smaller and the results were different for each subtype of cognitive function (26).

Despite these promising findings, data are not yet conclusive due to the large heterogeneity across the studies, as the test material and the study protocols used were mainly based on in-house standards and thus hard to compare (27). Whereas some studies used a single-center design (18, 20, 26, 28, 29) other authors collected data in multi-center settings (30–32) in different countries or even different languages and inconsistency in data sets due to language or cultural background cannot be ruled out (33). In addition to differences in subjects' ages, a huge number of different cognitive assessments were applied (34). Some studies used test batteries covering only a few cognitive domains or screening tests which might have overlooked slight cognitive changes (17, 24, 29, 35). Others applied auditory-based test material which was not suitable for people with severe hearing loss (23, 32). Despite authors' claim that audibility was ensured, misunderstanding cannot fully be excluded because verbally based cognitive tests may be influenced by auditory deprivation and can cause false positive results in up to 16% of tests (36–38).

Another challenge is that follow-up intervals were quite short. Most researchers published data on a follow-up interval of ≤12 months after cochlear implantation (24, 29). So far, only two studies have analyzed data on a much longer follow-up (28, 32). Cosetti et al. published data in seven female CI recipients after a mean follow-up of 3.7 years, ranging between 2 and 4.1 years (28). The longest follow-up measure was provided by Mosnier et al. in 70 CI recipients (32). Building up on their initial sample (23), data on preoperative and 1-year performance as well as a third assessment which took place 5–8.5 years after implantation were reported (32).

Most studies lack a suitable control group due to ethical reasons, as it would be unethical to deny hearing devices to people with severe hearing loss (6, 18, 27, 39). In the few studies that did include controls, the effect of age and education was not controlled for (19) or the number of control subjects included was quite small considering the huge variability in cognitive performance in older age (30, 31, 40–43). Furthermore, in most studies mean cognitive changes were evaluated for the whole study group, but not on an individual level. Only a few have analyzed the performance of individuals themselves (23, 28, 44).

In other words, we know that CI users perform better in some neurocognitive domains shortly after cochlear implantation, but we do not know if cochlear implantation can reverse the general cognitive decline in individual users in the long-term follow-up (18). This is highly relevant because it takes a couple of years for mild cognitive impairment to develop into dementia (45) and it is hard to differentiate healthy physiological aging from a pathological process (41) because there is a huge variability in cognitive performance in age (40) and cognitive decline is (a) influenced by major environmental, psychosocial and biological factors and (b) not linear.

From the perspective of cognitive aging research, benefits of CI use on cognition are expected. Robust evidence exists proving the plasticity of the aging brain (46, 47). One potential pathway to explain such plasticity is the cognitive stimulation provided by social and physical environments (48). Studies have indicated positive effects of a socially and physically active lifestyle on cognition among healthy older adults (49–51) and even subjects with dementia (52). Accordingly, reversing deficits in hearing after cochlear implantation may have a direct impact on cognition through the experience of richer and cognitively more stimulating environments (44).

Therefore, the aims of the study were firstly, to assess cognitive function before and after long-term CI use in a prospective single-center approach in a large sample of CI users.

Focus will be put on the users as a whole and also on users as individuals. And secondly, to compare average trajectories in cognitive abilities in CI users with a sample of older adults from the representative SHARE (Survey of Health, Ageing and Retirement in Europe) study as a control group. This was done to approximate the effect of CI use on specific cognitive domains in the absence of a control condition.

Materials and methods

This study was approved by the ethics institution of the Ruhr-University Bochum (No. 16-5727-BR). The study meets the guidelines set forth in the Declaration of Helsinki. All participants gave their written consent.

We describe the methods separately for primary and secondary data. The primary data analyses are based on the analytical state-of-art commonly used in biomedical research by comparing differences and exploring intraindividual clinical trajectories in cognitive measures over time. The secondary analyses contribute to this approach in two ways: firstly, the SHARE data allows us to explore effects of cochlear implantation on exemplary cognitive domains in relation to observed changes in a specific population; secondly, the statistical approach used to compare both datasets is more rigorous, adding further robustness regarding the primary data. For example, multilevel models use all data, account for correlations of repeated measures, and are robust against differences in length of follow-up (53). Moreover, this approach accounts for variability at the individual subject level, which may otherwise introduce bias when estimating changes in cognition over time.

Primary data

Participants/study samples

Since 2016 CI candidates aged ≥50 years presented at the comprehensive hearing center, Ruhr-University Bochum, were screened for study participation according to pre-defined inclusion/exclusion criteria (21, 26). Seventy one subjects performed cognitive assessment prior (T1) to as well as 12 months post cochlear implantation (T2). 50 CI recipients who had been implanted at least 42 months before (mean follow-up of 4.5 years, SD 0.5) were re-assessed at T3; 21 had to be excluded due to: critical health conditions ($n = 5$), death ($n = 2$), unwillingness to participate further ($n = 4$), relocation ($n = 4$), or loss to follow-up ($n = 6$). Only the 50 subjects who underwent testing at T1 as well as at T2 and at T3 were included in the data analysis. Educational level was assessed by the number of educational years and grouped according to the International Standard Classification of Education 2011 (54). Level 1 represents primary education; level 2 lower secondary education; level 3 upper secondary education; level 4 post-secondary, non-tertiary education; level 5 first stage of tertiary education; and level 6 second stage of tertiary education. Participants' demographic data are summarized in Table 1.

TABLE 1 Sociodemographic data on the cochlear implant recipients and the SHARE sample.

	Cochlear implant recipients		SHARE sample	
	M (SD) or %	Range	M (SD) or %	Range
Age	63.98 (9.13)	50–81	64.74 (5.86)	51–81
Male	38%	0–1	47%	0–1
Education[a]	2.84 (0.77)	2–4	2.83 (0.60)	2–4
Memory[b]	0.00 (1.00)	−1.55 to 1.16	0.00 (1.00)	−2.28 to 2.86
Working memory[c]	0.00 (1.00)	−1.40 to 1.40	0.00 (1.00)	−4.05 to 0.51

[a]ISCED-2011 coded educational level (0 = lowest to 6 = highest).
[b]Standardized scores of delayed recall across all measurements.
[c]Standardized scores of Serial 7s (SHARE) and OSPAN (CI recipients) across all measurements.

Audiometric assessment

Preoperatively, pure-tone thresholds were measured for each ear at 0.25–8 kHz in a soundproof booth (DIN EN ISO 8253). Speech understanding in quiet was assessed *via* the German language Freiburg monosyllabic speech test at 65 dB sound pressure level (SPL) at three intervals: preoperatively and 12 months and up to 65 months after implantation. Postoperatively, tests were performed in CI-only testing condition. All testing was conducted by an experienced audiologist.

Neurocognitive assessment

Subjects underwent a cognitive evaluation preoperatively (T1), 12 (T2) and up to 65 months (T3) after cochlear implantation with a mean T3 follow-up of 4.5 (SD 0.5) years described as 5-year data. In a few cognitive subtests data were not available for all subjects at each assessment. Therefore, sample size varied in the different subdomains. Neurocognitive testing was done by the computer-based neurocognitive assessment tool ALAcog, which consists of nine subtests covering the following cognitive domains, as described in detail by Falkenstein et al. and by Völter et al. (55, 56): in the M3 test, which assesses attention, a target letter and some distractors are presented, and the target has to be clicked as fast as possible. In the recall and the delayed recall task, 10 words are shown which have to be memorized immediately and after 30 min. For working memory, (1) the 2-back task was used, where a reaction is required in case the letter shown is identical to the second last, (2) further the Operation Span (OSPAN) task. In this dual task, letters have to be memorized, while equations have to be performed. The Flanker test measures the ability to suppress and to inhibit stimuli. The participant is asked to respond to a target flanked by arrow pointers above and underneath pointing in the same (compatible Flanker) or in different directions (incompatible Flanker). Two Trail Making Test (TMT) tasks were also included: the TMT A, which measures simple processing speed, and the TMT B, which assesses executive function. In both TMTs, participants have to sort randomly shown items as quickly as possible, in TMT A numbers from 1 to 26 and in TMT B numbers from 1 to 13 and letters from A to M. In the verbal fluency task, as many animals as possible starting with a particular letter have to be named within 90 s.

A total score, the inverse efficiency (IE), was calculated based on the time needed and the number of correct answers given. A lower IE score indicated a better performance. Practice effects were minimized by different test versions.

Questionnaires

The **Nijmegen Cochlear Implant Questionnaire (NCIQ)** was used to evaluate the health-related quality of life (HRQoL) (57). A total score was calculated from three domains, (1) *physical domain*: (a) basic sound perception, (b) advanced sound perception, and (c) speech production; (2) *psychological domain*: (a) self-esteem; (3) *social domain*: (a) activity limitations and (b) social interactions. A higher score indicates better HRQoL. The **Cognitive Reserve Index Questionnaire (CRIq)** was used to assess cognitive reserve (CR) throughout lifetime including several psychosocial and environmental factors: (1) education, (2) leisure time, and (3) working activity, and the demographic data. A total score is calculated by combining the three subdomains adjusted for age. A score <70 points represents a low CR, 70–84 a medium-low CR, 85–114 a medium CR, 115–130 a medium-high CR, and >130 a high CR (58). Depressive symptoms were questioned by the **Geriatric Depression Scale 15 (GDS-15)** (59). A score of 0–5 points indicates no depressive symptoms, 6–10 points indicates slight to moderate symptoms, and ≥11 points indicates severe depression.

Statistical analysis

Statistical analysis was done by Medas (Grund, Margetshochheim, Germany). First, data were tested for distribution. In case of non-parametric data (all cognitive subtests, except the recall task), the median and the 68% confidence interval, and in case of parametric data (NCIQ, CRIq, GDS-15, duration of hearing aid use, duration of deafness, and speech perception), mean and standard deviation were reported. In order to provide consistency in cognitive data, also the median of the recall was reported. For all data, rank correlation between two variables were calculated by using Kendall's τ. To compare pre- and postoperative results, the Wilcoxon-test and the Mann-Whitney-U test were used to analyze the different groups. If a participant was not able to finish the TMT test within 3 min, the rule of proportion was applied.

Multiregression analysis based on educational background, sex, and cognitive baseline score was done to discover which variable is the most predictive regarding cognitive performance at T3. Cohen's d was used for the calculation of effect sizes ($d = 0.2$– 0.4 is a small, $d = 0.5$– 0.7 a medium, and $d \geq 0.8$ a large effect size) for parametric data and after transformation for non-parametric data. To analyze the individual performance first data transformation for each subtest (M3, delayed recall, Flanker and OSPAN) was calculated for a parametric distribution. Later on, the standard error of the mean (SEM) was calculated. A score which was below the mean ± of the SEM, was considered as an improvement. A score that was higher indicated a poorer performance, a score within the range of the mean ± of the SEM was considered as a stable performance. Statistical significance was set to $p < 0.05$. To correct for multiple comparisons, Bonferroni correction was applied with $p < 0.005$.

Secondary data

Participants/study samples

Secondary data analyses were done based on the Survey of Health, Ageing and Retirement in Europe (SHARE), an ongoing cross-national representative panel study of ≥50 years old adults which addresses various key areas of individual and social aging including health variables, socio-economic information, social networks, physical measures, biomarkers, and psychological variables. Episodic memory (delayed recall) and working memory (Serial 7s task) are two cognitive key domains of the neurobiologically based cognitive mechanics that typically show age-related declines in later life (60, 61). They were assessed in the SHARE study and in the primary data selected for detailed analysis. A detailed summary of SHARE sampling procedures and study design is described in Börsch-Supan et al. (62).

For the current study, we used three waves with an observational period of 5 years (T1: 2015; T2: 2017, and T3: 2020). We followed a two-stage procedure to ensure comparability with the primary data. Firstly, we included SHARE participants who: (a) were at least 50 years and no more than 81 years old at time of first assessment and (b) had an International Standard Classification of Education (ISCED) range between level 2 (lower-secondary education) and level 4 (post-secondary education). We excluded SHARE participants who (a) reported diagnoses of cognitive impairments or other neurological diseases such as Alzheimer's or Parkinson's disease, and (b) suffered from depression as per a scale score of 4 or higher on the EURO-D scale (63). This resulted in a sample of 2,709 participants who provided full information on the data.

Secondly, we used this sample and applied sampling weights for chronological age to draw a random sample of 1,000 participants to match the age distribution of the primary data. The resulting sample provided a mean age of 64.74 (SD 5.86) years and a mean ISCED level of 2.83 (SD.60). Two-sample *t*-tests confirmed that there was no statistical difference between SHARE participants and CI recipients. Table 1 provides a description of the sample.

Neurocognitive assessment

SHARE includes various cognitive measures at each wave. We selected two measures that assessed central cognitive domains that were also measured in the participants with a CI, namely (delayed) recall of a 10-word list to measure short and long-term memory and the Serial 7s task to evaluate working memory capacity and attention. For the delayed recall test, participants listened to a list of 10 words and were asked to recall the list immediately (first trial) and once after a delay time of ~10 min. For the Serial 7s task, participants had to count backwards from 100 by 7s, stopping after the fifth answer. We standardized both test scores with higher values reflecting better cognitive performance. For a detailed description of the survey measures see Dewey and Prince (64).

Covariates

These included chronological age in years, sex (0 = female; 1 = male), and highest educational level by ISCED-2011. The SHARE data did not include objective audiometric assessments, which may have introduced bias with regard to the influence of hearing impairment on cognitive trajectories. We performed supplementary analyses and included a covariate of subjective evaluation of hearing to account for this issue.

Statistical analysis

Statistical analysis was conducted with R 4.2.1. (65). In order to compare the SHARE and the cochlear implanted participants, cognitive tests were standardized on their means and SDs for each sample and at each measurement. The raw scores of CI participants were transformed into a reverse-coded 5-point scale prior to standardization. This was necessary to harmonize the interpretation of the standardized scores between the samples (i.e., higher values indicate better cognitive performance). We estimated fixed-effects multilevel growth models for each study and outcome using the nlme package (66). The models included measurement occasions (level 1) nested within participants (level 2) to assess the effect of time on change in the cognitive outcomes across the samples. We used this approach because it easily handles unbalanced data with uneven time points (67), which is the case for the CI group. Time X age interactions were also included to test whether change over time depended on the age of the participants. The interactions were illustrated by plotting time slopes at two different mean values of chronological age based on median splits in the respective samples. These values reflect two age-categories that were defined as "young-old adults" (SHARE sample: 51–63 years; cochlear sample: 50–66 years) and "old-old adults" (SHARE sample: 64 to 81 years; cochlear sample: 67–81 years). Please note that these categories were empirically derived from the respective samples and only used for analytical purposes to illustrate the overall direction of the interaction effects. This method is recommended by Preacher and colleagues to facilitate the interpretation of interaction terms and is widely used in empirical research (68). All models were controlled for chronological age, sex, and educational status as time-independent predictors at level 2. Chronological age and educational status were centered around the mean for each study to make the intercepts interpretable. The time variable was recorded (i.e., 0 = T1; 1 = T2; 2 = T3) to ensure that intercepts reflect predicted values of cognitive measures at the first measurement. Therefore, change in the slope factor was interpreted as the average change for each additional measurement within the respective samples.

Results

Audiometric data

Mean 4-PTA of the better ear was 88.15 (SD 18.95) dB and for the poorer ear 98.2 (SD 15.55) dB at T1. On average, subjects suffered from a severe to profound hearing loss for 21.43 (SD 13.92) years prior to implantation. Preoperatively, subjects' mean unaided monosyllabic speech perception was 5.12% (SD 10.05) at 65 dB for the ear to be implanted. Speech perception in quiet at 65 dB significantly improved from 6.98% (SD 12.83) at T1 (with hearing aids) to 57.29% (SD 20.18) at T2 ($p < 0.0001$) and remained stable at 54.39% (SD 20.04) at T3. No further benefit was found between T2 and T3 at 65 dB ($p = 0.46$). Regarding gender, men had significantly better scores at T1 (men 13.0 (SD 17.2); women 3.33 (SD 6.86); $p = 0.03$) and T3 [men 66.75 (SD 11.62); women 45.86 (SD 20.31); $p = 0.0001$]. Improvement in speech perception between T1 and T3 was greater for men than women ($p = 0.04$). Age did not correlate to speech perception at any interval (both $p \geq 0.2$). No correlation was found between the cognitive reserve in total or in any subscore and speech perception at 65 dB at any time (each $p \geq 0.2$).

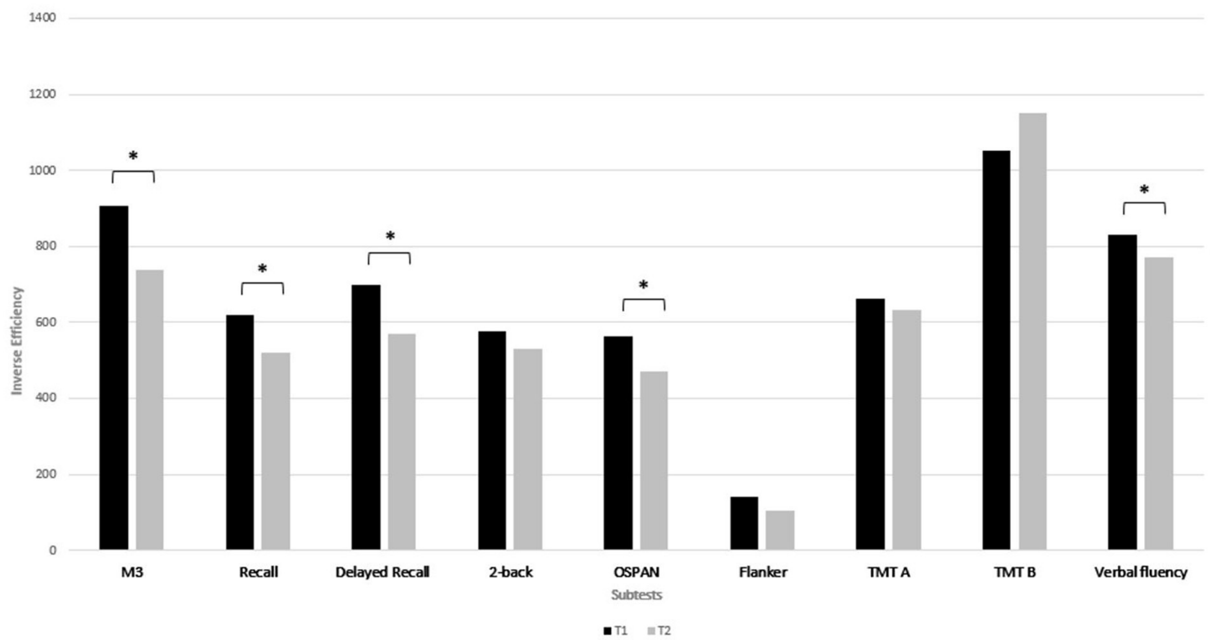

FIGURE 1
Median of the IE (inverse efficiency) of the neurocognitive subtests at T1 and at T2. A lower IE score indicates a better performance. *Indicates a p-value of $p < 0.005$ after Bonferroni correction.

HRQoL

At T1 HRQoL in the subdomain of activity limitations was rated to be the lowest with a mean score of 44.69 (SD 20.28) out of 100 points, contributing to a poor HRQOL in the social domain [mean 45.73 (SD 19.17)]. The highest score was obtained in speech production [mean 65.9 (SD 18.63)]. At T2 improvements were found in the total score from 49.99 (SD 15.87) to 66.22 (SD 14.38) and in all subdomains (all $p \leq 0.0001$). The highest scores were speech production [78.92 (SD 14.49)] and basic sound perception [69.74 (SD 16.57)], contributing to a high physical domain score [70.95 (SD 13.79)].

Although the total score [mean T2 66.22 (SD 14.38), mean T3 70.7 (SD 16.07); $p = 0.02$] and the scores of the subdomains self-esteem [mean T2 61.06 (SD 15.76), mean T3 67.38 (SD 16.83); $p = 0.008$] and activity limitation [mean T3 61.4 (SD 20.71), mean T3 68.02 (SD 25.28); $p = 0.04$] slightly improved between T2 and T3, this was not significant after Bonferroni correction. In line with that, none of the other subscores significantly improved between T2 and T3 ($p \geq 0.06$). Comparing HRQoL from T1 to T3, a significant improvement was detected in all subdomains (each $p < 0.0001$).

Cognitive reserve and depression

The overall CRIq score significantly improved from 111.08 (SD 14.15) to 117.32 (SD 15.04; $p = 0.01$). This indicates a change from medium to high-medium cognitive reserve. This was due to significant improvements in the subcategory leisure activities [mean 117.7 (SD 19.87) at T1; mean 127.66 (SD 27.77) at T3 ($p = 0.007$)]. The subcategories of education ($p = 0.16$) and work ($p = 0.23$) remained stable. Further, the mean level of depressive symptoms did not significantly change over time [2.17 (SD 2.42) at T1 vs 2.4 (SD 2.71) at T3 ($p = 0.94$)].

Cognitive performance in the total CI group

Scores on five of the nine cognitive subtests significantly improved from T1 to T2 (M3, recall, delayed recall, OSPAN and verbal fluency), with a large effect size in the OSPAN task ($d = 0.8$), a medium effect size in the M3 ($d = 0.69$), the delayed recall ($d = 0.68$), and in verbal fluency ($d = 0.7$), and a small effect size in the recall task ($d = 0.47$) (Figure 1). Score on the other four subtests did not change from T1 to T2 (each $p \geq 0.04$). Between T2 and T3, no further significant benefit was found in any cognitive subtest (each $p \geq 0.06$) (Figure 2).

Improvement with a medium effect size from T1 to T3 was seen for attention ($p = 0.001$, $d = 0.58$), delayed recall ($p = 0.001$, $d = 0.5$), for working memory ($p = 0.001$, $d = 0.54$), and inhibition ($p = 0.002$, $d = 0.5$) (Table 2; Figure 3) and with a small effect size for verbal fluency ($p = 0.004$, $d = 0.43$). In contrast, the 2-back only slightly improved ($p = 0.03$), without any significance after multiple correction. Recall ($p = 0.21$),

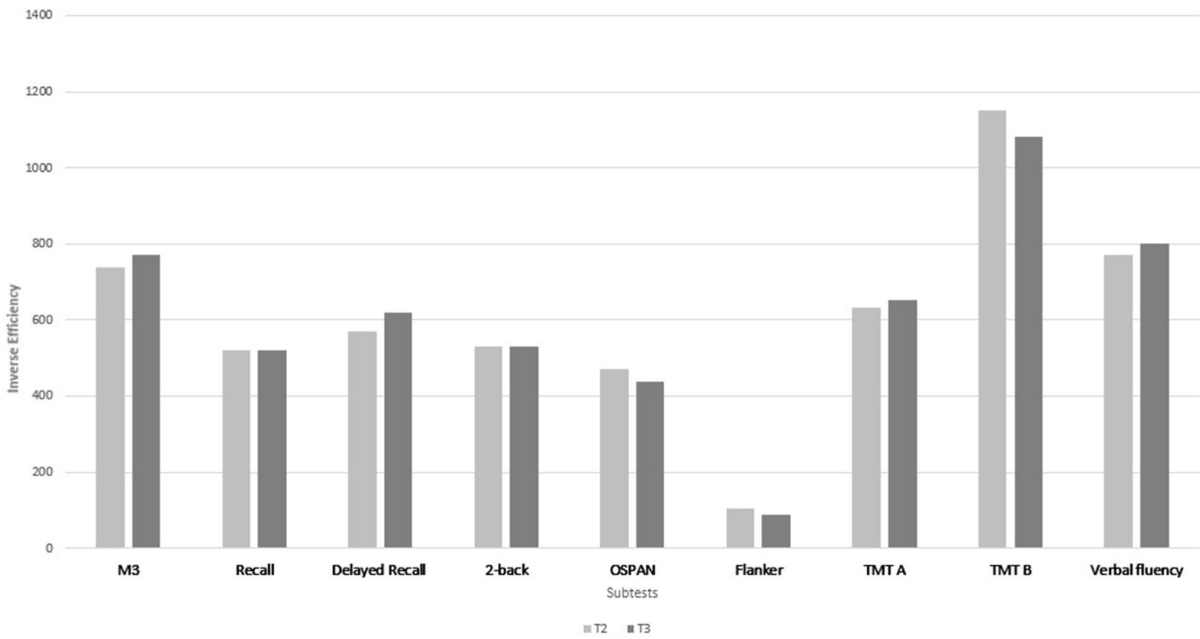

FIGURE 2
Median of the IE (inverse efficiency) of the neurocognitive subtests at T2 and at T3. A lower IE score indicates a better performance. Between T2 and T3 no significant change was found in any cognitive subtest after Bonferroni correction.

TMT A ($p = 0.1$) and TMT B ($p = 0.56$) were comparable between T1 and T3.

The delayed recall and M3 were the tasks, in which most of the subjects improved between T1 and T3 (60.9 % each), followed by the Flanker task (59%). Furthermore, 28 subjects improved in the M3 and 21 subjects in the OSPAN. About 20% of the subjects remained stable in attention, in memory and inhibition and 40% in working memory. Cognitive performance declined only in 15–20% of the subjects in the M3, the Flanker and in the delayed recall and in the OSPAN task in 11%.

Comparison of cognitive changes in CI recipients and in the general population

We report our findings based on two models. The first model (Model 1) predicted variation in cognitive measures as a function of time and of the other covariates. The second model (Model 2) included an additional time X age interaction to explore effects of age on change over time. With regard to **memory**, Model 1 (main effect) intercepts indicated that average participants in SHARE started from a higher average delayed recall level than the CI recipients. It also indicated that delayed recall was lower for each year of increased age (−0.022) and for males (−0.270) and higher for better educated individuals (0.143) in the SHARE group. The time slope showed a linear decrease in delayed recall for each measurement (−0.076), indicating an overall decline in this cognitive domain over the observational period. Model 2 (interaction affect) revealed a significant time × age interaction (−0.010) suggesting that declines in delayed recall over time were stronger with higher age. Model 1 in the CI sample provided a negative effect of age (−0.034) on delayed recall. A different pattern emerged with respect to the time slope, which showed an increase (0.169) in delayed recall over the observational period. Model 2 did not reveal a significant time × age interaction, suggesting that positive changes were not dependent on chronological age (see Table 3A; Figure 4).

Concerning **working memory**, intercepts in model 1 (main effect) indicated that the average SHARE participants had higher initial levels in working memory than the CI recipients. The serial 7s task score was lower for older adults (−0.011), whereas positive associations were found for males (0.104) and participants with a better education (0.113). The time slope did not show a significant decrease in the serial 7s task, indicating overall stability in the SHARE data in this domain over time. Model 2 did not provide a significant time × age interaction, indicating that longitudinal changes in the serial 7s task did not differ for older adults. Regarding the OSPAN measure in the CI sample, model 1 indicated a negative effect of age (−0.040) and a positive effect of higher education (0.559). Again, a different pattern emerged with respect to change over time suggesting

TABLE 2 Median and 68% confidence interval of the Inverse efficiency of the neurocognitive subtests at T1, T2 and at T3.

Subtest		Median	68% confidence interval		p1	p2	p3
M3	T1	906	694.45	1,375.52	0.0001*	0.71	0.001*
	T2	737.5	603.94	1,033.43			
	T3	771	574.16	1,131.79			
Recall	T1	620	400	700	0.002*	0.22	0.21
	T2	520	260	620			
	T3	520	260	700			
Delayed recall	T1	700	533.95	830	0.00004*	0.51	0.001*
	T2	570	400	821.63			
	T3	620	260	830			
2-back	T1	578	439.77	1,012.07	0.2	0.97	0.03
	T2	532	423.56	839.16			
	T3	530.5	393.1	826.2			
OSPAN	T1	562	359.88	804.71	<0.0001*	0.48	0.001*
	T2	472	326.46	664.2			
	T3	439	334.69	781.02			
Flanker	T1	141.5	53.77	236.45	0.04	0.07	0.002*
	T2	103.5	38.91	222.12			
	T3	89	47.69	151.08			
TMT A	T1	661	513.61	1,293.91	0.08	0.52	0.1
	T2	632	473	1,190.28			
	T3	652	507	891.92			
TMT B	T1	1,051	738.62	1,897.53	0.68	0.68	0.56
	T2	1,151	701.44	1,857.06			
	T3	1,080.5	778.74	1,937.35			
Verbal fluency	T1	830	735	880	0.00002*	0.06	0.004*
	T2	770	660	855			
	T3	800	684.62	855			

Comparison between performance at T1 and T2 was labeled with p1, between T2 and T3 with p2 and between T1 and T3 with p3. A lower IE score indicates a better result. A *p*-value <0.005 indicates significance (*) after Bonferroni correction.

positive changes in OSPAN scores over time (0.167). We did not find a time × age interaction (see Table 3B; Figure 5).

After accounting for subjective assessment of hearing impairment, all reported findings remained robust except for the time slope showing a negative significant decrease in the serial 7s task (see Supplementary Table S1).

The **performance of individual subjects** in the four most important neurocognitive subtests (Flanker, M3, OSPAN, and delayed recall) was analyzed across intervals. Due to the high variability in the performance among the individuals, only CI recipients' data that either increased, decrease, or remained stable in at least three out of the four tests were reported.

Performance on three or four tests improved in 21 subjects, remained stable in four subjects, and declined in only one subject between T1 and T2; improved in five subjects, remained stable in four subjects, and declined in three participants between T2 and T3; and improved in 19 subjects and declined in only one subject between T1 and T3.

Data analysis further revealed that only a minority of the CI recipients had a poorer performance in one ($n = 17$) or two ($n = 6$) subtests between T1 and T3. With regard to the different subtests, some CI recipients had a gain between T1 and T2 and a poorer performance between T2 and T3. This was the case in nine subjects in the M3, in 10 CI recipients in the Flanker and in 11 subjects in the OSPAN and in the delayed recall. Notably, this decline did not outweigh the gain in performance achieved in the long-term follow-up, so that at T3 the majority of the CI recipients scored equally or even better than preoperatively (see Figures 6–9).

Subjects with a poorer T1 performance also had worse results at T2 and T3 in all subtests (each $p \leq 0.0001$) although improvement was significantly greater in these subjects. This was the case at T2 for the M3 (tau = −0.39, $p < 0.0001$), the 2-back (tau = −0.3, $p = 0.003$), the OSPAN (tau = −0.52, $p < 0.0001$), the Flanker (tau = −0.38, $p = 0.0001$), and the TMT A (tau = −0.39, $p = 0.0001$); and at T3 for the M3 (tau = −0.3, $p = 0.002$),

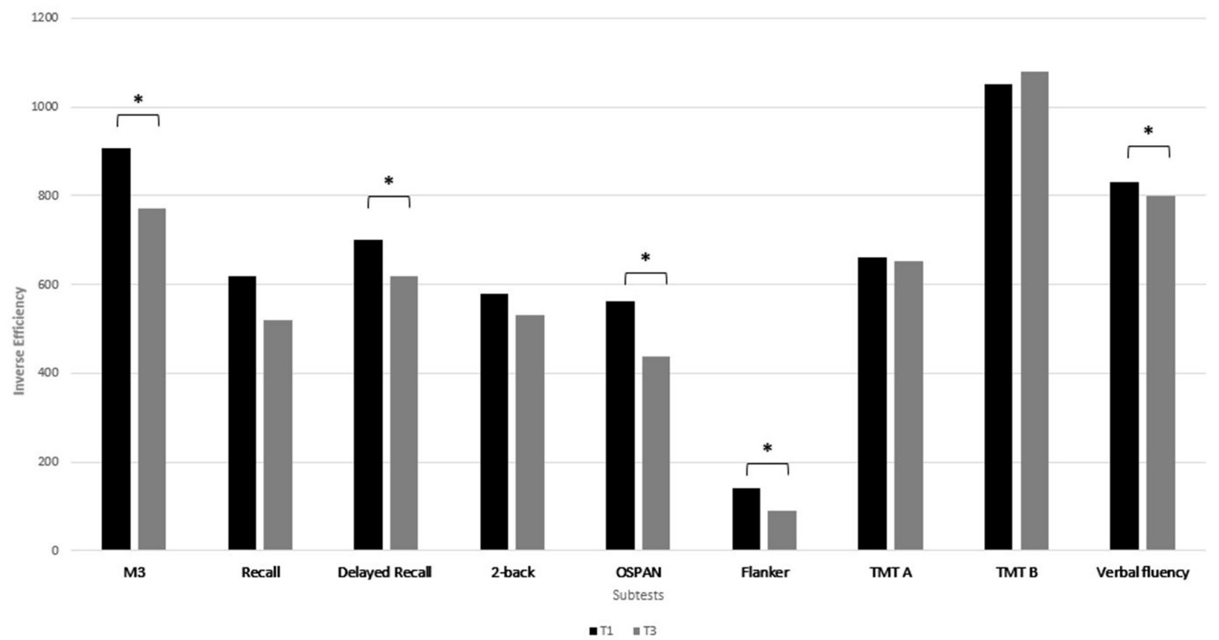

FIGURE 3
Median of the IE (inverse efficiency) of the neurocognitive subtests at T1 and at T3. A lower IE score indicates a better performance. *Indicates a p-value of $p < 0.005$ after Bonferroni correction.

TABLE 3A Multilevel regression growth models predicting change in delayed recall in the CI recipients and the SHARE sample.

	Cochlear implant recipients				SHARE sample			
	Model 1		Model 2		Model 1		Model 2	
	B	SE	B	SE	B	SE	B	SE
Intercept	0.011	0.168	0.011	0.168	0.203***	0.038	0.203***	0.038
Age	−0.034*	0.014	−0.030	0.016	−0.022***	0.004	−0.012*	0.004
Male	−0.466	0.261	−0.496	0.261	−0.270***	0.050	−0.270***	0.050
Education	0.168	0.163	0.401	0.249	0.143***	0.042	0.143***	0.042
Time	0.169*	0.068	0.169*	0.068	−0.076***	0.016	−0.076***	0.015
Time × age			−0.005	0.008			−0.010***	0.002

B, unstandardized regression coefficient; SE, standard error. Intercept reflects the outcomes when all predictors are equal to zero (i.e., average age, female, average education, first measurement).
*$p < 0.05$; ***$p < 0.001$.

the OSPAN (tau = −0.32, $p = 0.002$), the Flanker (tau = −0.55, $p < 0.001$) and the TMT A (tau = −0.55, $p < 0.001$).

At T3, after adjusting for age and education (each $p \leq 0.005$), the baseline score was the most important predictive in all cognitive subtests. Preoperative and postoperative speech perception score in quiet at 65 dB did not correlate with any cognitive subtest (each $p \geq 0.13$ and each $p \geq 0.19$). This was also true for the improvement of cognitive functions at T1 and T3 (each $p \geq 0.18$).

Covariates

Age had an impact on cognition pre- and post-implantation. This was the case for the TMT A ($p \leq 0.001$), the TMT B ($p \leq 0.002$), and the Flanker tasks ($p \leq 0.001$) at T1 and T3 as well as at T2 in the TMT A ($p = 0.001$). Improvement in cognitive functions did not correlate with age in any subtest (each $p \geq 0.06$). Men and women performed equally in all cognitive subtests (each $p \geq 0.05$) except on the 2-back task after 12 months, where men outperformed women ($p = 0.00006$).

TABLE 3B Multilevel regression growth models predicting change in the OSPAN (cochlear implant recipients) and in the serial 7s (SHARE sample).

	Cochlear implant recipients				SHARE sample			
	Model 1		Model 2		Model 1		Model 2	
	B	SE	B	SE	B	SE	B	SE
Intercept	−0.147	0.162	−0.147	0.162	−0.027	0.038	−0.027	0.038
Age	−0.040**	0.014	−0.038*	0.015	−0.011**	0.004	−0.012*	0.005
Male	−0.057	0.263	−0.057	0.263	0.104*	0.050	0.104*	0.050
Education	0.559**	0.165	0.559**	0.164	0.113**	0.041	0.113**	0.041
Time	0.167***	0.046	0.167***	0.046	−0.022	0.017	−0.022	0.017
Time × age			−0.002	0.005			−0.001	0.002

B, unstandardized regression coefficient; SE, standard error. Intercept reflects the outcomes when all predictors are equal to zero (i.e., average age, female, average education, first measurement).
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

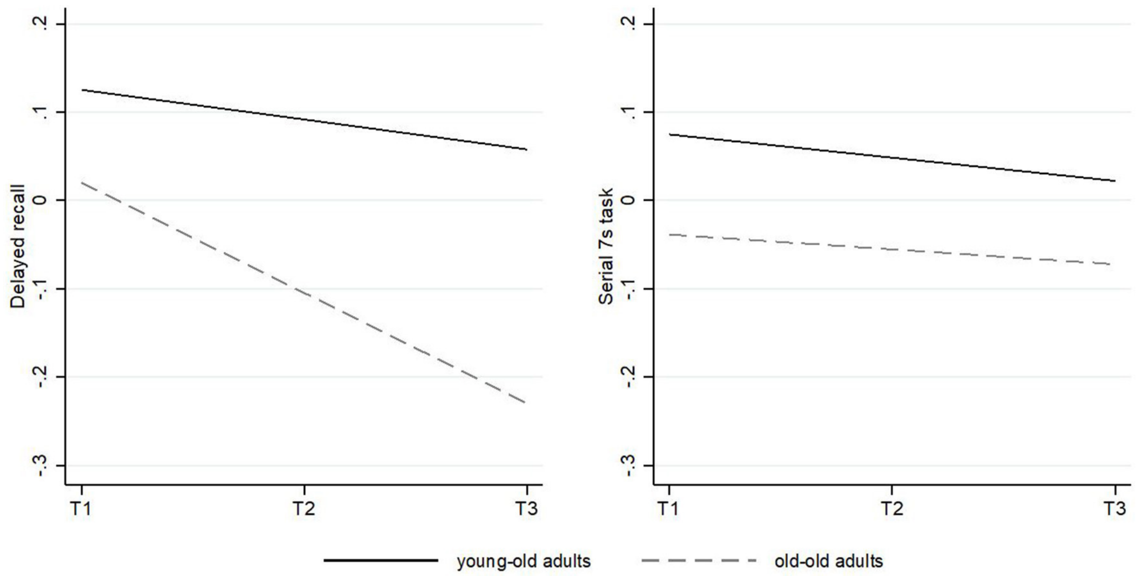

FIGURE 4
Predicted change of performance in delayed recall and the Serial 7s task in the SHARE sample over time. The solid slope shows the trajectory for young-old adults with an average age mean of 60.51 years; the dashed slope shows the trajectory for old-old adults with an average age mean of 69.59 years. Slopes are controlled for all covariates.

However, improvement in the 2-back performance was greater for women than for men between T2 and T3 ($p = 0.002$). For all other cognitive subtasks, the improvement was comparable between men and women (each $p \geq 0.06$). Mean **educational level** was 11.96 (SD 2.09) ranging from 8 to 17 years. Interaction of age, sex, and educational background was detected for the 2-back and the verbal fluency task at T3. Whereas in the 2-back task educational background was more important for men than for women (2-back $p = 0.02$), in the verbal fluency task education had only an impact on performance in women ($p = 0.03$).

Discussion

Cognitive decline in age takes many years and there is a high variability in cognitive trajectories in the general population (69). Thus, the effects of auditory rehabilitation on cognition are difficult to assess. Only a few studies analyzed CI users' long-term cognitive performance with a focus on the single subject and in the light of a suitable control group.

In the present study, CI recipients had a significantly better cognitive performance at T3 than at T1. This was most evident

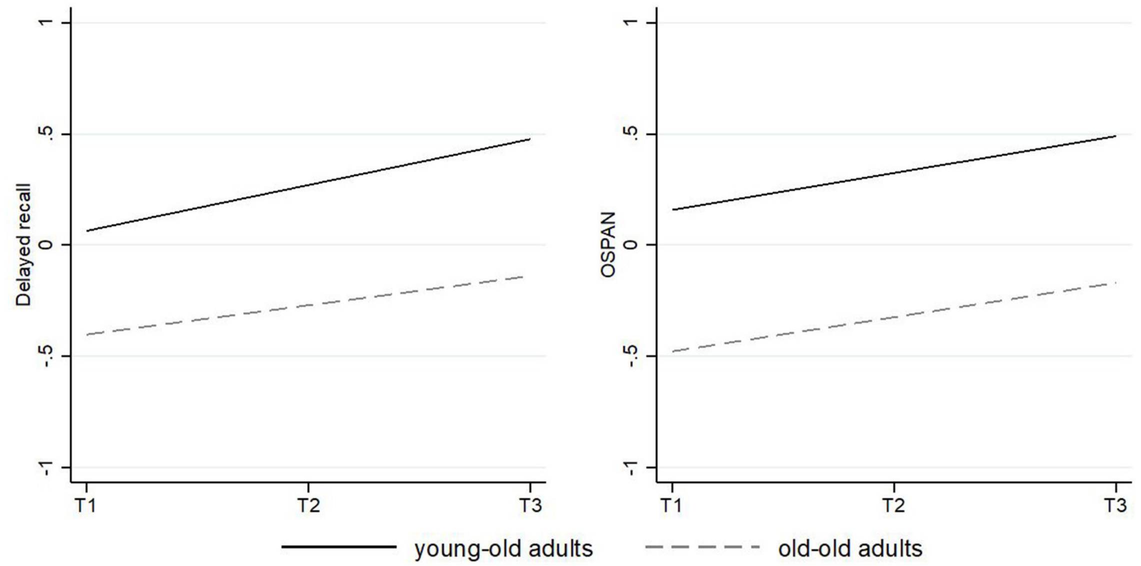

FIGURE 5
Predicted change of performance in delayed recall and the OSPAN in the cochlear implant sample over time. The solid slope shows the trajectory for young-old adults with an average age mean of 56.73 years; the dashed slope shows the trajectory for old-old adults with an average age mean of 72.50 years. Slopes are controlled for all covariates.

in delayed recall, attention, and working memory assessed by the OSPAN task; but also in verbal fluency and inhibition. Performance on other cognitive subdomains such as the 2-back also improved but were no longer significant after Bonferroni correction. In contrast, performance on the TMT A, the TMT B, and the recall task remained without change.

Improvements in attention and in the total RBANS-H score were also described by Mertens et al., whose participants were 24 CI recipients (mean age of 72 years) when assessed 14 months after cochlear implantation (31).

Cosetti et al., who reported on a long-term follow-up of 3.7 years after implantation, found an enhanced cognitive performance in 70% of the 20 cognitive tasks of which some were taken from the Wechsler Adult Intelligent Scale and from the RBANS (28). In contrast, Sarant et al. did not see any change in cognitive test scores in the Cogstate battery in 59 CI recipients (mean age of 72.3 years) after 18 months of CI use. Only the subgroup of men with lower educational achievement significantly improved in executive functions in the Groton Maze learning test (20).

In order to analyze cognitive changes in the follow-up, multiple assessments might be helpful to draw a slope (70). Multiple cognitive assessments in the follow-up after cochlear implantation have rarely been studied. In the present study, mean cognitive performance showed a significant enhancement after 12 months and remained stable at up to 5 years. Our data support those of Ohta et al., who also found a peak 12 months after implantation (in 21 CI recipients aged between 65–80 years 12 months after cochlear implantation) and a plateau which remained stable at up to 24 months. Unfortunately, no analysis was done on the different subtests of the MMSE to see which cognitive subdomain benefits the most (35). In contrast to earlier results by Mosnier et al. (23), in their latest data set no significant improvement was found after 12 months of CI use. Scores even declined in the long-term follow-up in the clock drawing test, the d2 test, the TMT tasks and in the MMSE, while scores on the 5 word-test and categorial verbal fluency remained stable (32).

Further, changes in cognitive function after auditory rehabilitation have mostly been discussed in light of whole samples rather than for individuals themselves. It is important to note that change in terms of mean-level change only refers to average increase or decrease within a specific group over time. However, lack of mean-level change does not rule out the possibility that substantial individual-level change exists. For example, individuals may increase and decrease offsetting each other's change. Given that individual variability in cognitive function is greater in the older population (71, 72), and even greater in clinical populations with chronic diseases, this needs to be considered (43, 73). So far, only two studies have analyzed subjects' individual trends. Cosetti et al. described the individual performance of each single CI recipient ($n = 7$) in any of the tests applied, by either a positive or a negative change. One subject improved in five of 15 subtests, two subjects in six or nine of 17 subtests and four subjects in seven up to 10 of 20 subtests (28). Mosnier et al. clustered their sample into MCI subjects, cognitively healthy individuals and subjects suffering from dementia. Of the 29 MCI participants 19 remained stable, 10 returned to normal cognition, and only one developed dementia at a mean follow-up of 6.8 years of CI use. At the same follow-up time amongst participants with normal

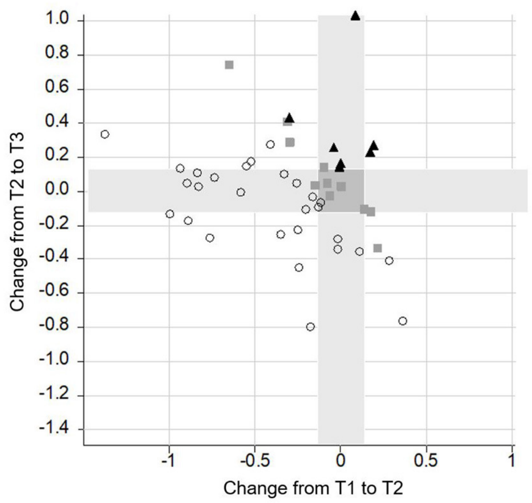

FIGURE 6
Change of performance in the **M3** task. Lower scores indicate a better performance. Each symbol represents a person according to their change from T1 to T2 (*x*-axis) and T2 to T3 (*y*-axis). The overall change of the person from T1 to T3 is indicated by different shapes (▲ = poor performance; ■ = stable performance; ○ = improved performance). All symbols right from the vertical grey bar indicate a decrease in performance from T1 to T2. All symbols above the horizontal grey bar represent a poorer performance from T2 to T3. Giving an example, the lowest dot on the right side indicates a decrease in performance from T1 to T2. In contrast, from T2 to T3 there was an increase in performance. In total, the subject improved from T1 to T3 and therefore, it was labeled by a dot. Furthermore, the highest square which you can find is on the left side of the vertical grey bar. This means that it increased from T1 to T2. From T2 to T3 performance decreased, as the square is above the horizontal grey bar. In total, this subject remained stable and therefore, it was labeled by a square.

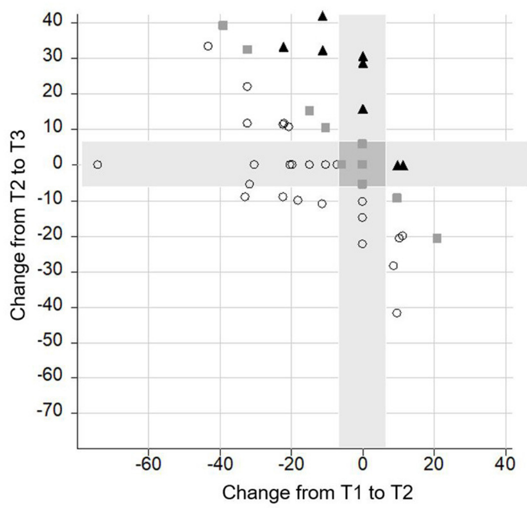

FIGURE 7
Change of performance in the **delayed recall** task. Lower scores indicate a better performance. Each symbol represents a person according to their change from T1 to T2 (*x*-axis) and T2 to T3 (*y*-axis). The overall change of the person from T1 to T3 is indicated by different shapes (▲ = poor performance; ■ = stable performance; ○ = improved performance).

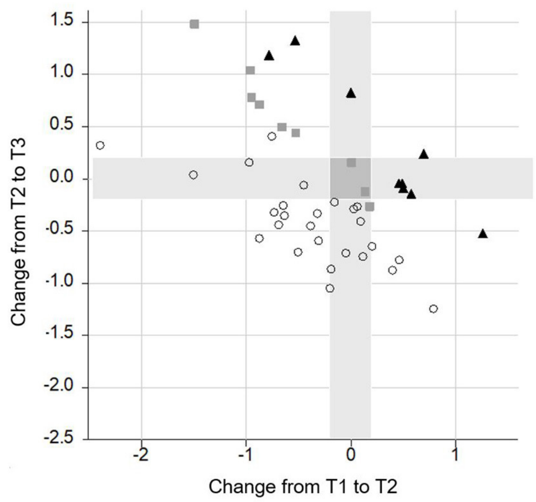

FIGURE 8
Change of performance in the **Flanker** task. Lower scores indicate a better performance. Each symbol represents a person according to their change from T1 to T2 (*x*-axis) and T2 to T3 (*y*-axis). The overall change of the person from T1 to 3 is indicated by different shapes (▲ = poor performance; ■ = stable performance; ○ = improved performance).

preoperative cognition 26 remained stable and 32% developed mild cognitive impairment. Interestingly, the proportion of subjects with preoperative mild cognitive impairment included in Mosnier et al. was 45%, which is relatively high compared to the estimated 12–15% in the general population of people aged ≥60 years and might be country- or region-specific (74, 75). In contrast, in mean cognitive test scores did not improve at 12-months post-CI and a decline in the Mini Mental Status Examination, the Clock Drawing Test, the D2 and the Trail Making Test A and B was observed in the follow-up.

Results of the present study indicate that cognitive function underlies individual variability between the test intervals and according to the different subtests. In general, the majority of the subjects showed an enhancement in overall performance, only a few a total decrease; however, some subjects increased in the first interval and decreased or remained stable later or even reversed. Subjects with a worse preoperative neurocognitive performance enhanced the most.

Other authors also claim that individuals with a poor baseline performance show the greatest improvement (18, 23, 26). Therefore, one may speculate that a CI should not be denied to people with mild cognitive impairment. Recent

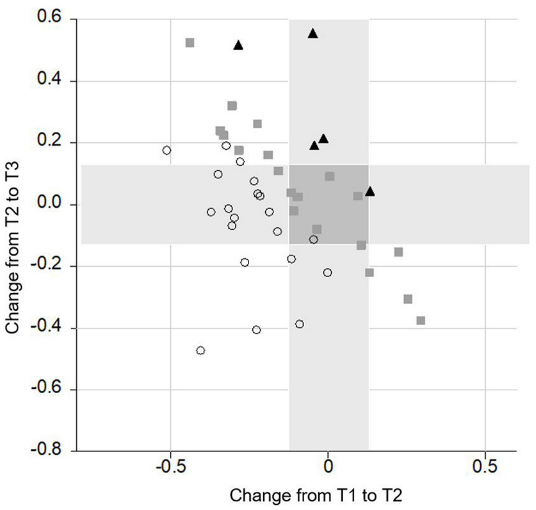

FIGURE 9
Change of performance in the **OSPAN** task. Lower scores indicate a better performance. Each symbol represents a person according to their change from T1 to T2 (*x*-axis) and T2 to T3 (*y*-axis). The overall change of the person from T1 to 3 is indicated by different shapes (▲ = poor performance; ■ = stable performance; ○ = improved performance).

studies have explored the effect of hearing device use on the cognitive function of people with cognitive impairment (76–78), nonetheless more data on this is needed.

Long-term effects of cochlear implantation and comparison

To better judge the cognitive changes in the CI group and considering the high cognitive variability in age, we included a huge control group and compared two cognitive tests, one for memory and one for working memory with similar measures from a large representative data set of the Survey of Health, Ageing and Retirement in Europe (SHARE). We also estimated multilevel growth models to explore the average cognitive change in both samples. Three key findings emerged from these analyses.

Firstly, when only focusing on the CI users, positive changes in delayed recall and working memory remained robust within a rigorous and well-controlled longitudinal design. This indicates that positive cognitive changes occurred over longer observational periods even when controlling for sociodemographic characteristics. This adds to existing research in the field that has primarily explored changes after cochlear implantation within pre-post study designs.

Secondly, positive time slopes in cognition among CI users were not dependent on chronological age. This rules out the possible explanation, that only middle-aged adults would benefit in terms of cognition. This finding is remarkable given that biomechanical cognitive abilities typically show age-related declines into later life (61). However, a robust body of knowledge has proven that cognitive plasticity occurs even until very late in life (48) and our findings suggest that cochlear implantation may play a potential role in contributing to such plasticity.

Thirdly, the importance of our findings from CI users is further underscored after comparison of this specific study population with the SHARE data. In these secondary data analyses, we found the expected age-related negative trajectories over time in memory (delayed recall task) and some degree of stability in working memory performance (Serial 7s task). In addition, the SHARE respondents showed an even steeper decline in memory with increasing age. Treating the secondary data as an approximation of a nonexperimental comparison group, we argue that these findings demonstrate the beneficial effects of CI use among older adults. This approach, however, is limited due to different cognitive base-levels and nonequivalent dependent measures between the CI and the SHARE group. Another issue pertains to the lack of objective audiometric assessments in the SHARE data to better control for the potential influence of hearing impairment on cognition over time. Supplementary analyses indicated that the overall findings were robust when including the subjective assessment of hearing which is included in the SHARE data. However, hearing loss is often underestimated in hearing-impaired especially in older subjects (79, 80). Audiometric assessments are clearly needed in future research with secondary data. Moreover, future studies would benefit from constructing propensity scores that balance treatment and control groups on potentially relevant baseline variables.

Considering that hearing loss is associated with a faster cognitive decline (16, 81), the observation that cognition improves after implantation and that such improvement is maintained at 12 months of CI use is promising. We should encourage older people to treat age-related hearing loss (82). However, the findings of the present study have to be critically discussed.

First of all, one has to keep in mind that not all subjects who were included preoperatively could be followed-up. Thus, one might argue that only subjects with an active lifestyle and better cognitive functions agreed to do the re-evaluation of the cognitive performance after 60 months. Thus, subjects who did not improve in the same way might be underrepresented although there was no statistical difference between the 50 subjects included and the total CI group. Further, this bias of nonparticipation might be the case in any study protocol.

Further, all CI users in the present study received an intensive auditory rehabilitation schedule as defined by the guidelines of the German society of Ear, Nose and Throat Medicine (83). So, the interactive effects of the behavioral speech and language therapy on cognitive aging cannot be ruled out. This has to be stressed as cognitive enhancement in the present study as well as in the literature is mainly reported during the first year after implantation, when rehabilitation usually takes place. In addition, the level of leisure activities as shown in the CRIq significantly increased. One may argue that better audibility motivates the CI recipient to take part in leisure activities more frequently. This, in turn might contribute to better cognitive abilities independently of education and occupation as shown in the Cambridge Center for Ageing and Neuroscience study (84).

Therefore, cochlear implantation might have a booster effect on cognition which might decline in the follow-up. Data by our group as well as in the literature did not show a correlation between speech perception and cognition or between the improvement in speech perception and in cognitive performance (32, 44, 85). Thus, it is not clear whether this enhancement is really direct due to an improvement in auditory abilities or whether it is indirect due to a general stimulating effect. Speech recognition alone might not be sufficient and social interaction might be crucial to enhance cognition (35, 44). Further, rehabilitative training might have also triggered the better cognitive performance after 1 year.

In addition, even if the performance in the total CI group significantly improved, cognitive changes varied greatly between the single subjects. Thereby, the number of subjects included—although being one of the largest in this field—might be too small due to the high inter-individual variability of cognitive aging. Studies with larger sample sizes need to be performed to control for the various participants' characteristics and to minimize the impact of these features on outcome measures.

What's more, we do not know to what extent laboratory-based cognitive tasks can predict real-life outcomes in older adults: older adults often function competently in complex everyday situations despite age-related deficits on laboratory-based cognitive tasks (86). Several factors have been identified as influencing everyday activities realization, including physical and cognitive functioning (87). However, there is little evidence that interventions improve performance on distantly related tasks or that training improves everyday functioning in later life (88). A classic study from Ball et al. (89) assessed the effects of cognitive training interventions on older adults and found that cognitive training did not affect daily functioning over 2 years. In their follow-up study, they explored 10-year effects of cognitive training on cognition and everyday functioning in older adults (90). Findings suggest slower declines in performing IADLs (Instrumental Activities in Daily Living) in intervention groups over 10-years; however, effects were modest and even absent with respect to performance-based everyday functioning tests.

Lastly, although the present study's follow-up time is longer than in most similar studies, it still might be too short to determine if a CI can arrest or even reverse cognitive decline. Dementia takes multiple years to develop, and cognitive decline might only be observed in studies which have a follow-up time of up to, or even longer than, 10 years.

Conclusion

Auditory rehabilitation by cochlear implantation seems to stimulate the plasticity of the brain within the first year after implantation leading to an improvement in some cognitive functions in the follow-up in the total group in comparison with data of a representative sample. However, large multicenter studies on CI recipients with a long-term follow-up of up to 10 years or even more must be undertaken to confirm the present data. To allow comparability, the development of a standard diagnostic protocol including cognitive assessment tools adapted to severe hearing-impaired will be the first step.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Ruhr-University Bochum, Germany. The patients/participants provided their written informed consent to participate in this study.

Author contributions

CV and JT designed the study. LG selected the subjects and collected a part of the data. CV, IH, SK, and LG analyzed and evaluated the data. CV wrote the manuscript with contributions from LG and critical feedback from SD and JT. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Authors CV, JT, and SD have received reimbursement of scientific meeting participation fees and accommodation expenses, as well as honoraria for preparing continuing medical education events and funding for research projects that they initiated, from MED-EL.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fneur.2022.1009087/full#supplementary-material

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Coupling of sensorimotor and cognitive functions in middle- and late adulthood

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Introduction: The present study explored age effects and the coupling of sensorimotor and cognitive functions in a stratified sample of 96 middle-aged and older adults (age 45-86 years) with no indication of mild cognitive decline. In our sensorimotor tasks, we had an emphasis on listening in noise and postural control, but we also assessed functional mobility and tactile sensitivity.

Methods: Our cognitive measures comprised processing speed and assessments of core cognitive control processes (executive functions), notably inhibition, task switching, and working memory updating. We explored whether our measures of sensorimotor functioning mediated age differences in cognitive variables and compared their effect to processing speed. Subsequently, we examined whether individuals who had poorer (or better) than median cognitive performance for their age group also performed relatively poorer (or better) on sensorimotor tasks. Moreover, we examined whether the link between cognitive and sensorimotor functions becomes more pronounced in older age groups.

Results: Except for tactile sensitivity, we observed substantial age-related differences in all sensorimotor and cognitive variables from middle age onward. Processing speed and functional mobility were reliable mediators of age in task switching and inhibitory control. Regarding coupling between sensorimotor and cognition, we observed that individuals with poor cognitive control do not necessarily have poor listening in noise skills or poor postural control.

Discussion: As most conditions do not show an interdependency between sensorimotor and cognitive performance, other domain-specific factors that were not accounted for must also play a role. These need to be researched in order to gain a better understanding of how rehabilitation may impact cognitive functioning in aging persons.

KEYWORDS

listening in noise, postural control, functional mobility, processing speed, cognitive control, healthy aging

Introduction

Currently, more than 1 billion people in the world are 60 years and older[1]. A widespread sensory impairment in this rapidly aging population is age-related hearing impairment (ARHI or presbycusis). Hearing impairment is the third leading cause of disability for people ≥ 70 years, and the largest potentially modifiable risk factor for dementia (Livingston et al., 2020). Similarly, dramatic age-related differences occur for postural control, a phenomenon that is amply documented by the increased number of falls in the older population (Fuller, 2000). Global estimates suggest that 28–35% of people over 65 fall at least once a year. This estimate rises to 32–42% in people over 70 years of age[2]. Other sensorimotor functions affected by considerable age-related differences are tactile sensitivity and walking. Common to these different modalities is the trajectory of change: initial declines emerge during middle adulthood and accelerate after the 7th decade of life. Similar age-related changes also apply to cognitive processes like overall processing speed, fluid intelligence, or cognitive control processes (Baltes et al., 1999). The similarities of trajectories across functions and the considerable shared age-related variance in cross-sectional studies have motivated different theoretical accounts, arguing that the observed correlations reflect genuine couplings of sensorimotor and cognitive functions in their adult development.

Coupling between cognitive and sensorimotor functions

Several theoretical accounts have linked age-related differences in sensory, sensorimotor, and cognitive functions (Verhaeghen and Cerella, 2002; Uchida et al., 2019), all of which depart from observations of correlations or shared age-related variance in older samples. Following earlier review papers, we distinguish between cascade models, common cause hypotheses, and compensation models (Li and Lindenberger, 2002; Kiely and Anstey, 2015; Humes and Young, 2016). Upward cascade models assume that degraded or reduced sensory information causes gradual declines in central cognitive functions. For example, age-related hearing loss may disturb the comprehension of spoken conversations and result in social isolation and reduced challenges for cognitive functioning. Reverse cascades have also been proposed in which declining central cognitive processing impairs sensory functions. For example, reduced inhibitory functions limit sustained attention necessary to identify sound sources and disambiguate auditory input. Specific versions of cascade models like the *perceptual degradation* and the *cognitive permeation* hypotheses emphasize that poor peripheral processing not only impairs higher-level cognitive processing, but that low-fidelity sensory inputs require more cognitive resources related to attention and executive functions for further processing. As a result, cognitive resources may not be available for their original purpose, which impinges on higher-level processing. An important implication of upward cascade models is that cognitive impairment should be reduced if the source of sensory malfunction is remedied or compensated for by, for example, cataract removal or a hearing aid. Positive evidence along these lines is far from equivocal(for reviews, see Schneider and Pichora-Fuller, 2000; Kiely and Anstey, 2015).

Common-cause explanations are resource accounts of behavioral aging, which assume that age-related differences within and across domains reflect, in part, a common set of senescent alterations (Lindenberger and Ghisletta, 2009). The differences between common-cause accounts refer to the type of central resource that is postulated and the causes of its deterioration in later adulthood. Precursors of modern common-cause theories emphasized the role of processing speed and its general age-related slowing (Cerella, 1985; Myerson et al., 1990; Salthouse, 1996). Slowing itself was conceptually linked to age-related changes in the brain, for example, impaired quality of axonic myeline and its presumed effects on signal conduction. The key idea was that processing speed, as assessed by, for example, simple reaction time or the digit-symbol substitution test from the WAIS, mediates age differences in cognitive functioning, including non-speeded tasks. Evidence for this "speed-mediation of cognitive aging" hypothesis in later adulthood was provided by Lindenberger et al. (1993) using the first wave sample from the Berlin Aging Study (BASE, age range 70-103 years). The authors found that speed fully accounted for common and specific age-related variances in reasoning, memory, knowledge, and fluency. Later, Lindenberger and Baltes (1994) included sensory (hearing and vision) and sensorimotor (balance-gait) variables in their mediation analyses of the same sample and found that vision and hearing together accounted for 93.1% of the age-related variance in the five intelligence factors in BASE. This includes the four factors mentioned above, but also the speed factor itself. Balance-gait added another 4.7% of the variance to the sensory variables and turned out to be as effective a predictor of age-related differences in intellectual functions as vision and hearing. Lindenberger and Baltes (1994) argued that age differences in intellectual and cognitive functions are the outcome of a third common factor or ensemble of factors that they attributed to age-related differences in the physiological state of the brain. Thus, unlike cascade models, common-cause accounts refrain from postulating a temporal order of age-related differences.

The cognitive compensation hypothesis proposed by Li and Lindenberger (2002) assumes that the aging brain tries

1 www.who.int

2 https://www.nice.org.uk/guidance/cg161

to compensate for declines in sensorimotor functions by permanently recruiting cognitive resources (Li et al., 2001; Li and Lindenberger, 2002). This account is motivated by compensation accounts in neuropsychology (Cabeza et al., 1997; Reuter-Lorenz et al., 2000), and it also accommodates ideas from cascade models like the cognitive permeation hypothesis described earlier. An important difference with the latter approach is that the diversion of cognitive resources from their original purposes is seen as permanent. Li and Lindenberger based their proposition on the same correlational evidence as the common cause hypothesis; however, they also considered experimental evidence from two relevant approaches, notably simulations of auditory and visual decline and dual-task studies combining cognitive and sensorimotor tasks.

Most authors agree that the different accounts are not mutually exclusive and that a combination of mechanisms contributes to the coupling of cognitive and sensorimotor functions. For the described example of age-related hearing loss, one might imagine that peripheral damage causes reduced sociability resulting in central processing declines, accelerating listening difficulties or adapting to the handicap. Li and Lindenberger (2002) argued that a combination of common cause and compensation accounts would provide the best account of various findings. This argument is plausible from the perspective that (general) deterioration of functions precedes and triggers compensation. A second implication is that accelerated decline at advanced ages heightens the need for compensation, leading to even stronger correlations between sensorimotor and cognitive functions. While theories differ in the causal mechanisms or the direction of causality they emphasize, most models agree that the link between cognitive and sensorimotor functions becomes stronger with the advancing ages of the individuals (cf. reviews Boisgontier et al., 2013; Johannsen et al., 2022).

Sensorimotor and cognitive functions with age

Loss of hearing sensitivity, often captured by pure tone audiometry, only partially explains difficulties in speech understanding. Damage to the inner ear also leads to distortion of (incoming) sound (e.g., Plomp, 1978) and loss of spectral and temporal resolution (e.g., Moore et al., 2012). Aging affects structures across the central auditory pathway (Profant et al., 2020) due to the reduction of neurons and inhibitory neural transmitters (Gao and Wehr, 2015; Jayakody et al., 2018). The loss of neural fibers, also caused by deterioration of ribbon synapses ("cochlear synaptopathy" Kujawa and Liberman, 2015; Parthasarathy and Kujawa, 2018), has consequences for listening in noise. Even without hearing impairment speech perception in noise declines by middle age (Goossens et al., 2017). The degrading effect of age is mediated by deficiencies in temporal processing and cognitive control and is also observed in persons without indication of cognitive decline. Aging as well as hearing impairment affect the neural encoding of speech cues in both subcortical and cortical structures (Anderson et al., 2012, 2021; Presacco et al., 2016; Goossens et al., 2018a,b), and these deficits in central auditory temporal processing have consequences for binaural processing (Vercammen et al., 2018b; Koerner et al., 2020), and the ability to separate a target speech message from a competing speech message (e.g., Helfer and Freyman, 2008). Given the abovementioned we wished to capture listening difficulties with a measure of speech understanding instead of the (predominantly) peripheral pure tone measure.

Aging also affects our ability to acquire and maintain a stable state of balance. Changes in the proprioceptive, visual and vestibular systems reduce the peripheral sensory reliability. In addition, postural control is constrained by central changes such as the reduction of white and gray matter integrity, affecting multisensory integration and motor execution at a (supra)spinal level. Together these developments negatively impact our sense of body position and coordination (Michalska et al., 2021). Measurements of postural control during upright stance are frequently recorded with a force plate which registers fluctuations in the participant's center of pressure (COP) across time. Conventionally, these fluctuations are quantified using the total displacement or the area in which COP movement occurs. Using these metrics, Abrahamová and Hlavacka (2008) showed substantial age-related differences in performance starting around 60 years of age.

Even though these metrics are sensitive enough to address age-related differences in sway behavior, more elaborate methods have gained popularity because of their potential to address the neuromuscular mechanisms underlying postural control (Lacour et al., 2008). Based on Einstein's theory of Brownian motion, the stabilogram diffusion analysis (SDA) analyzes mean squared C0P displacement at different timescales. The short timescale behavior reflects an open-loop control scheme tempering the inherently unstable body. Once a critical threshold is reached, long-term closed-loop mechanisms come into effect resulting in anti-persistent corrective feedback motion (Collins and De Luca, 1993). Previous age-comparative studies applying the SDA have consistently found pronounced increases in short timescale displacement with age (Collins and De Luca, 1995; Laughton et al., 2003; Norris et al., 2005). A common explanation for this is the elevated level of muscle activity found in older age (Laughton et al., 2003; Finley et al., 2012). Some authors argue that these processes induce a shift, going from automatic to more cognitive processing of movement (Heuninckx et al., 2008, 2010; Goble et al., 2010).

Mobility tests are essential to assess function and ambulation in a frail elderly population (Butler et al., 2009). While standard medical examinations aim to screen and diagnose diseases/injuries, they do not provide sufficient info regarding the patient's daily living capabilities (Tinetti et al., 1988).

Functional mobility is a person's ability to move around safely and independently while accomplishing everyday activities (Bouça-Machado et al., 2020). These activities include basic mobility skills such as rising from a chair, walking, turning and bending over and are significant predictors for falls, ongoing disability, and nursing home admission (Guralnik et al., 1994). Multiple tests have been designed to assess functional mobility, including self-reported questionnaires and laboratory-based assessments. The timed up-and-go test (TUG) provides an easy-to-use alternative showing reliable results that correlate highly with other gold-standard assessments such as the Barthel index and the Berg Balance Scale (Podsiadlo and Richardson, 1991). Studies have shown a moderate correlation between TUG and age (Khant et al., 2018). Additionally, age can predict TUG performance even when cognitive status is controlled for (Ibrahim et al., 2017).

Among other modifications, a declining receptor density and skin elasticity reduce our capacity to perceive touch pressure and vibration (Stevens et al., 2003; Wells et al., 2003). This is encompassed by significant changes in brain recruitment, mainly reflected by over-activation of the somatosensory network to compensate for impaired brain functions (Brodoehl et al., 2013). Perry (2006) investigated tactile age-related alterations in plantar sensitivity and found pronounced differences between young and older adults from the seventh decade onward.

Studies investigating common causes for age-related differences in cognitive and sensorimotor functions typically used measures from IQ tests, emphasizing latent constructs for processing speed of fluid intelligence. In the present study, we took a different approach. Although we included a measure of general processing speed, we focused on the three core cognitive control functions, working memory/updating, inhibitory control, and cognitive flexibility (Miyake and Friedman, 2012). While many multisensory integration processes occur automatically in association cortices, cognitive control processes involve frontal lobe circuitry (D'Esposito and Postle, 2015; Gerver et al., 2020), which is most sensitive to aging. The following paragraphs summarize age-related differences in our cognitive measures and discuss how sensorimotor processes draw on processing speed, working memory, inhibitory control, and cognitive flexibility.

Older adults need more time to process information in the same tasks than younger ones (Salthouse, 1996, 2009, 2019), and this has consequences for the comprehension and recall of speech (Wingfield, 1996, Gordon-Salant and Fitzgibbons, 1999; Goy et al., 2013) and temporal processing, such as the detection of gaps and binaural hearing (Strouse et al., 1998, Füllgrabe et al., 2015). Age-related differences in processing speed also significantly affect gait speed (Soumaré et al., 2009; Lowry et al., 2012, Desjardins-Crépeau et al., 2014; Killane et al., 2014) and mobility (Rosano et al., 2005).

Working memory (WM) is defined as a limited-capacity system by which we store, process, and manipulate information. Crucial functions are updating, replacing stored information with new incoming information, and maintaining the stored information in memory (Gajewski et al., 2018). Listening, especially in noise, draws heavily on working memory. When the peripheral and/or central encoding of speech sounds is distorted, a listener relies on implicit (or automatic) and explicit cognitive processing mechanisms to enable a fast retrieval from memory or knowledge to fill in the missing information, ignore the irrelevant noise and selectively focus attention on the spoken message (e.g., Rönnberg et al., 2013). While hearing impairment seems to be the main factor underlying speech perception problems in background noises, age explains a significant part of the communicative impairment (Gordon-Salant and Cole, 2016). WM is highly influenced by age, and reduced WM capacity makes a person more susceptible to reverberation and echoes (Reinhart and Souza, 2016). Age-related cognitive decline is also a leading cause of the decline in motor performance (Krampe, 2002; Li and Lindenberger, 2002). Behaviorally, performance in both the working memory and motor task decline with increasing task difficulty (Lindenberger et al., 2000; Li et al., 2001; for a review Yogev-Seligmann et al., 2008), although resource allocation is flexible and can change over the lifespan to compensate for age-related decline in sensorimotor and cognitive processing.

Inhibition, the ability to suppress irrelevant information (Miyake et al., 2000), is also susceptible to aging and, consequently, affects different sensory and sensorimotor functions. As poor inhibition increases susceptibility to background noise (Janse, 2012), persons with poor inhibition will find it increasingly difficult to understand speech in noise as noise increases (Knight and Heinrich, 2017). For instance, older adults are more influenced by the semantic content of a to be ignored voice when different persons are speaking than younger adults (Tun et al., 2002).

Suppressing irrelevant information is also crucial for postural control/mobility/balance (see Kwag and Zijlstra, 2022 for a recent scoping review). Mirelman et al. (2012) report that executive functioning, including inhibition, predicted falls over the five years following cognitive assessment. A more recent study shows that participants who are better at inhibiting their responses in the stop signal task were better at inhibiting an unwanted leg response than grasping a supportive handle (England et al., 2021).

Cognitive flexibility, the ability to switch between tasks or mental sets (Kray and Lindenberger, 2000), is crucial for listening, whether needed to monitor multiple simultaneous voices (Kidd et al., 2005), to focus auditory spatial attention (Singh et al., 2013), to process unattended speech (Perrone-Bertolotti et al., 2017). Whether task switching is compromised in healthy aging remains somewhat unclear because of its interdependence with inhibitory control. Using a binaural-listening paradigm, Oberem et al. (2017) studied age-related differences in the ability to intentionally switch auditory selective attention between two speakers. Significantly higher reaction times and error rates were observed for older participants than for younger ones. Previously, Lawo and Koch (2014) also reported that the ability to switch auditory attention in a selective listening task intentionally does not seem to be compromised in healthy aging. Mobility also taxes cognitive flexibility. For example, faster individuals during the timed-up-and-go task demonstrate better cognitive flexibility (Berryman et al., 2013). An increased congruency effect when standing compared to sitting is observed in an auditory cue task-switching paradigm with different postural control demands (Stephan et al., 2018).

Outline of current study

Over and beyond the expected age-related differences in sensorimotor and cognitive functioning, this study examined whether age-related individual differences in processing speed and cognitive control processes (working memory, inhibition, task switching) were coupled with differences in performance in sensorimotor processes during middle- and late adulthood. Our study design was guided by four considerations that differ from most of the earlier work. First, we deviate from earlier research which used psychometric intelligence tests as a general measure of cognitive ability. Instead, we chose for core cognitive control measures, notably inhibition, working memory updating and switching to determine which candidate mechanisms drive the age-related coupling of sensory and cognitive functions. In addition, we included processing speed, which is closely related but not identical to fluid intelligence. Second, we focused on listening in noise, postural control, functional mobility and tactile sensitivity on the sensorimotor side, as these functions become more challenging with age and have not been researched before in the same population. Hearing ability has been assessed by the 'pure tone average' in previous studies. We argue that a measure of speech understanding in noise is better suited to capture the influence of cognitive processes and also much closer to the ecological reality of aging listeners. Third, we targeted the transition between middle- and late adulthood to pick up early and potentially subtle changes in sensorimotor and cognitive skills. From perspectives of prevention and intervention this is also the most critical period to investigate. Fourth, we exclusively tested individuals who had passed cognitive screening to minimize confounding effects of accelerated cognitive decline.

Following the reasoning of common-cause accounts, we first asked whether processing speed or our measures of sensorimotor performance mediated age effects in the three cognitive control variables. We then asked whether individuals who had poorer (or better) than median cognitive performance for their age group also performed relatively poorer (or better) on sensorimotor tasks. Our driving hypotheses were that individuals with poor processing speed, inhibitory control, cognitive flexibility, and working memory updating also perform relatively poorly on the sensory and sensorimotor measures. We expected the coupling to emerge during middle age and to intensify in later adulthood.

Materials and methods

Participants

Four age cohorts, two middle-aged and two older-age, were defined, i.e., (46-55), (56-65), (66-75), and (76-86). A hundred and twelve healthy participants were recruited through campus, market advertisements, and e-mail. Prior to testing, a brief questionnaire assessed health-related issues, i.e., whether participants smoked, wore one or two hearing aid(s), had been hospitalized, had experienced falls within the last year, had a knee or hip prosthesis, had suffered chronic ear infections or undergone ear operations, had ever had physical therapy. Six participants, mainly in the two older categories, had hearing aids (5 bilateral, one unilateral), and six participants had experienced falls and wore knee or hip prostheses (see **Supplementary material**). All participants performed the modified version of the CODEX (Ziso and Larner, 2019). The Cognitive Disorders Examination or Codex is a 3-min test with high sensitivity and specificity for dementia diagnosis (Belmin et al., 2007). A participant is assigned 1 of 4 levels of the CODEX (A = very low, B = low, C = high, and D = very high probability of dementia). Only data of persons with scores A or B were included. Eight persons with scores of C or D were excluded, and eight women of the two youngest categories were randomly excluded to analyze an equal number of participants per age category (n = 24). No difference was observed between the A and B scores of the CODEX (χ^2 (3) = 7.18, p = 0.066).

Table 1 lists the demographics of the remaining 96 participants, including educational level and estimated total IQ per group. A Kruskal-Wallis chi-square test yielded statistical significance for education level (ranked in years, (H(3):11.149, p = 0.01). *Post hoc* Dunn tests showed that only the 46-55 and the 66-75 age groups differed significantly from each other (p = 0.03). The total IQ was based on the sum of the scaled scores of the performance and verbal IQ according to the norm values of the Dutch version of the Wechsler Adult Intelligence Scale (Wechsler, 2001). Scaled scores for each domain were estimated based on the digit symbol substitution (performance IQ) and the digit span task (verbal IQ). All participants provided informed consent to the study, which the Medical Ethical Committee approved of KU Leuven/UZ Leuven. They received 11€ for participating.

TABLE 1 Sample characteristics.

Age	Mean age	Sd age	N	Gender		Education level			IQ	Sd IQ
				Male	Female	Low	Average	High		
46–55	51.8	2.29	24	9	15	1	2	21	118	16.2
56–65	61.6	3.05	24	12	12	1	4	19	119	20.3
66–75	71.3	2.37	24	12	12	2	11	11	116	20.2
76–86	80.8	3.54	24	12	12	5	5	14	104	19.0

Education: low = obligatory schooling not completed, average = obligatory schooling completed, high = higher education.

Procedure

Each participant was tested individually at the lab or at home. Testing took, on average, 1.5 h and always started with listening in noise. All other tests were randomized. In addition to the tests mentioned below, we also performed a posture verbal fluency dual-task test, and we asked participants to fill out the 12-item Speech, Spatial and Qualities of hearing questionnaire (Noble et al., 2013). These data did not belong to the scope of this paper.

Listening in noise

Listening in noise was assessed with the Flemish version of the digits in noise test *(DiN)*. This paradigm has high sensitivity and specificity for detecting sensorineural hearing loss (Jansen et al., 2013; Smits et al., 2013). Three speech digits were presented in noise via a Samsung tab A tablet and calibrated Peltor H7A headphones to both ears (without hearing aids for the six persons mentioned in the **Supplementary material**). The level of the speech was fixed at 65 dB A, and the first triplet was presented at a –2 dB signal-to-noise ratio. Speech reception thresholds (SRT) in broadband noise were determined utilizing an adaptive procedure using triplet and digit scoring (Denys et al., 2019).

Postural control

In the static balance, postural control task, participants are asked to stand as still as possible for 30 seconds on a Nintendo® Wii Balance Board (Nintendo, Kyoto, Japan) while looking at a black dot placed 1 meter in front of them at the eye level. Feet are positioned parallel close to each other in the center of the board, with the toes pointed forward. At the start of each trial, the instructor provides a cueing signal "ready" and a starting signal "start" when the time measurement commences. After a warm-up trial, four test trials are assessed. For each trial, the center of pressure (COP) is calculated based on four load sensors positioned at the corners of the Wii balance board using a bluetooth connected computer with CU BrainBLoX software (Cooper et al., 2014). This data is then linearly interpolated to a 100 Hz frequency and low-pass filtered with a fourth-order 13 Hz Butterworth filter using a custom-written script in R (R Core Team, 2021). Evaluation of postural control included the stabilogram diffusion analysis (SDA) proposed by Collins and De Luca (1993). The SDA is based on Einstein's theory of Brownian motion and analyzes mean squared CoP displacement at different timescales. The short timescale behavior reflects an open-loop control scheme tempering the inherently unstable body. Once a critical threshold is reached, long-term closed-loop mechanisms result in anti-persistent corrective feedback motion. The slopes of the linear regressions fit on short- and long-timescale regions were used to quantify these mechanisms, i.e., the short-term diffusion coefficient and the long-term diffusion coefficient, respectively. Additionally, the critical time interval represents the time interval separating both regions.

Functional mobility: Timed up and go

The ability to rise from a chair is a critical mobility component and was assessed with the timed-up-and-go (TUG, Podsiadlo and Richardson, 1991), a widely used clinical test and screening tool. Participants were instructed to rise from a chair, walk 3 m straight, turn around, walk back and return to the same sitting position as fast and safely as possible (Schoene et al., 2013). Running was not allowed, and the 3-m distance was indicated on the floor. After a warm-up trial, three test trials were conducted. At the start of each trial, the instructor presented a cueing signal "ready" and a starting signal "start," after which the time measurement commenced. Timing stops when the participants' shoulder blades touch the chair's backrest (Vereeck et al., 2008). The outcome measure was the average time (s) required to finish the three test trials.

Tactile sensitivity

A monofilament test measures a participant's cutaneous perceptual threshold by applying light touch pressure to the skin. This is often done with Von Frey filaments, i.e., 20 nylon filaments with ascending stimulus intensity. The filament must be placed perpendicular to the skin, and force is gradually increased until the filament bends, thereby regulating the stimulus intensity of a given filament. Participants were asked to sit in a chair and take off their right sock. A dot was placed lateral to the fifth metatarsophalangeal joint of the right foot. Pressure was applied to the dot with filaments of different intensities, and participants were instructed to close their eyes and answer with "Yes" or "No" when asked whether they felt something. An interlacing adaptive staircase method was used with staircases A, for odd-numbered stimuli, and B, for even-numbered stimuli. The task included 18 trials in staircase A, 17 trials in staircase B, and five-catch trials (Berquin et al., 2010). A negative response to a filament yielded a filament of higher intensity in the subsequent trial and vice versa. Each time the response within a staircase differed from the preceding response (turnaround point), the step size was adjusted according to the 4, 2, and 1 stepping algorithm (Dyck et al., 1993). A custom-written software was used to register the responses and indicate the stimulus intensity. The average stimulus intensity of the turnaround points with step size one was registered for each staircase. The average of these stimulus intensities served as an outcome measure.

Processing speed/Digit symbol substitution

The digit symbol substitution is a paper and pencil test (Wechsler, 2001) used to proxy processing speed (Jaeger, 2018). The test consisted of a key grid of digits and matching symbols. The participant was instructed to fill out the empty boxes with the symbol that matches each digit as quickly and accurately as possible. This task requires planning and strategizing, updating digit-symbol matches, and filtering out irrelevant information (e.g., symbols that may look alike). First, participants were instructed to fill all digit-symbol associations up to the bold black line. Once the practice section was completed and corrected if necessary, participants were asked to continue filling in the digit-symbol associations as fast as possible without skipping any. The score reflects the number of correct digit–symbol matches within 120s.

Working memory updating/2-back task

Given that auditory input is constantly changing in daily life, updating information is a critical component of speech understanding in noise (e.g., Sussman and Winkler, 2001). The 2-back task taps into working memory updating (Gajewski et al., 2018). Letters appear consecutively on a 17′ monitor for 300 ms. Participants were instructed to press the space bar if a letter was identical to the second-last letter. The task required updating incoming information. A computerized version was used (OpenSesame 3.1, Mathôt et al., 2012). First, participants performed a short warm-up trial of 20 letters in which oral feedback was provided. Later, a test trial of 156 letters was presented, including 20% target and 80% non-target letters. Each stimulus was presented for 300 ms and the interstimulus time was 1,400 ms. During that period, a response could be provided. The outcomes were the responses and the reaction times (RT) of the correct scores (hits). RTs less than 100 ms and more than 1,200 ms were scored as misses. Subsequently, d' was determined from the responses for further analyses.

Inhibitory control/Stroop task

The Stroop task assesses inhibitory control (Scarpina and Tagini, 2017) by requiring participants to identify the color in which a symbol or word is presented while ignoring the word's meaning. Two conditions were presented together via OpenSesame 3.1 (Mathôt et al., 2012): a neutral condition in which the letters contained four or five X's or an incongruent condition in which the colored shape contained a written word, consisting of a written color that is different from the color in which the word was written. Participants responded with four keys on an external keyboard corresponding to the letters (f, k, d, j). The participant was asked to only respond to the color of the word/X's. A practice trial was offered before testing with four neutral and eight incongruent trials. Participants were instructed to keep their fingers on the respective keys of the keyboard. The actual test contained 48 trials, of which half were neutral and half incongruent. Reaction times were registered. Preprocessing the data was according to Gajewski et al. (2020). The first trial was deleted, as well as all response times shorter than 100 ms and response times longer than 2 SD of the mean response time (per age group and condition). We used the inverse efficiency score (IES) for further analysis, reflecting an overall performance index while accounting for speed and accuracy trade-off. The IES was calculated by dividing the mean reaction times of the correct trials by the overall accuracy. Afterward, Stroop interference (MacLeod, 1991) was calculated by subtracting the IES in the neutral condition from the IES in the incongruent condition ($SI = IES_{incongruent} - IES_{neutral}$).

Task switching/Color-shape switch task

Participants are asked to switch between two or more task sets in a task-switching paradigm. Performance on the color-shape switch task reflects global cognitive control, cognitive flexibility, and working memory (Sicard et al., 2020). The color-shape switch task is also administered with OpenSesame 3.1 (Mathôt et al., 2012). It consists of three non-verbal parts: in the first part, participants indicate the color of a shape (A), either blue or yellow, in a fixed (non-switch) block (n = 24, AA AA AA AA AA). In the second part, another fixed block is presented, namely the shape of the form, either round or square (B, n = 24, BB BB BB BB BB). In the third part, a mixed (switch) block is presented, and the participant must alternatively focus on the shape or color (n = 48, AA BB BB BB). For the latter condition, participants are instructed to focus twice on the shape, then twice on the color, and then twice on the shape. The background color (black/gray) is presented on the screen to indicate whether to focus on the shape or the color. Similar to the Stroop task, within each block, the first trial was deleted, as well as reaction times shorter than 100ms and reaction times longer than two SD of the mean response time. The general switch costs (also known as mixing costs) reflect the ability to maintain and select among different task sets in working memory (AA AA AA vs. AA BB AA). General switch costs are calculated by subtracting the IES of the fixed block from the IES of the mixed block. Specific switch costs are calculated by subtracting the IES of the repetition trials in the mixed block (AA or BB) from the switch trials in the mixed block condition (AB or BA).

Digit span

The digit span test was used to estimate verbal IQ (**Table 1**). This test was taken from the Wechsler Adult Intelligent Scale (Wechsler, 2008). A list of digits is presented verbally at a rate of one per second. The participant must either repeat the list in the same order (digit span forward, short-term memory) or the reverse order (digit span backward, working memory). All digits must be in the correct order for the list to be marked correct. The lists start at a length of two digits (maximum 8 for the forward digit span, maximum 7 for backward digit span), and two lists of each length are presented. The test is stopped when two lists of a certain number of digits are recalled incorrectly. The outcome is the number of correct sequences.

Statistical analyses

Statistical analyses were conducted with R (R Core Team, 2021). Each variable was transformed to obtain normality using either a log transformation or a Box-Cox negative power transformation (Fox and Weisberg, 2019). This was done across age groups. The effects of age group on sensorimotor processes, processing speed, and cognitive control processes were analyzed using linear models (LMs). Three orthogonal age group contrast were specified *a priori*, comparing (a) the mean of the two middle-aged groups with the mean of the two older adult groups; (b) the two middle-aged groups with one another; and the two oldest groups against each other. Following the approaches by Lindenberger et al. (1993) and Lindenberger and Baltes (1994), we assessed the degree to which age-related variance in cognitive control measures was mediated by processing speed and the four sensorimotor functions. To this end, we performed a causal mediation analysis using the package Mediate in R (Tingley et al., 2014). The R package "Mediate" uses a non-parametric bootstrapping method to estimate the significance of the causal mediation effects in a linear model. Finally, we determined the coupling between cognitive and sensorimotor functions by applying median splits within each age group to identify individuals with high and low levels of performance. Median group was added as a fixed effect to the LM described earlier. *Post hoc* tests were performed through Bonferroni-corrected t-tests unless unequal variances were detected, in which case Bonferroni-corrected Welch t-tests were used.

Results

The current study aimed to examine whether age-related individual differences in processing speed and cognitive control processes (working memory, inhibition, task switching) were coupled with differences in performance in sensorimotor processes during middle- and late adulthood. We present our results in three parts. We established age-related differences for sensorimotor and cognitive functions in the first part. We then applied two different approaches toward determining whether and how aging of sensorimotor and cognitive processes mutually constrain each other. First we walk on the trails of common cause hypotheses by assessing to what degree processing speed and sensorimotor functions mediate age-related variance in cognitive control measures. Second, we turned our perspective around by asking whether high and low performance levels in processing speed or cognitive control functions coincided with better or worse performances in sensorimotor tasks. In our analyses, we included gender as a fixed factor. Given that it did not improve the model fit significantly, gender was further excluded from the analyses reported below.

Age-group differences in sensorimotor and cognitive functions

Figures 1A-E illustrate age-related differences in sensory and sensorimotor functions. For listening in noise (**Figure 1A**), the younger groups performed systematically better than their older counterparts. This was reflected by reliable differences between middle-aged and older adults (β = 0.19, SE = 0.02, $t = 9.02$, $p < 0.0001$) and between the age groups of 46-55 and 56-65 (β = 0.05, SE = 0.01, $t = 3.56$, $p = 0.001$), 66-75 and 76-86 (β = 0.05, SE = 0.01, $t = 3.67$, $p = 0.001$). Speech in noise thresholds decreased, on average, by 0.15 dB SNR per annum.

Postural control performance showed reliable age effects for path length (**Figure 1B**). Middle-aged adults performed better compared with older adults (β = 0.32, SE = 0.064, $t = 5.03$, $p < 0.0001$), and the 66-75 age group performed better when compared with the 76-86 one (β = 0.11, SE = 0.04, $t = 2.48$, $p = 0.0015$). **Figure 1C** illustrates the component processes (SDA parameters) of postural control. Only the short-term diffusion coefficient, i.e., the early time-scale slope, yielded reliable age differences. Short-term diffusion coefficients of middle-aged adults were lower than those of older adults (β = 0.58, SE = 0.12, $t = 4.99$, $p < 0.0001$), while the long-term diffusion coefficient and the critical time interval did not differ significantly between age groups.

With increasing age significantly more time was needed for the timed-up-and-go test (**Figure 1D**). Functional mobility was significantly different between the middle aged and older adults (β = 0.03, SE = 0.003, $t = 6.02$, $p = 0.0001$), between 56-65 and 76-86 (β = 0.01, SE = 0.002, $t = 2.24$, $p < 0.03$), and between 46-55 and 56-65 year olds (β = 0.01, SE = 0.002, $t = 3.17$, $p = 0.005$).

Different from the other sensorimotor functions, our measure of tactile sensitivity turned out to be less sensitive to age (**Figure 1E**) and only showed a reliable difference between

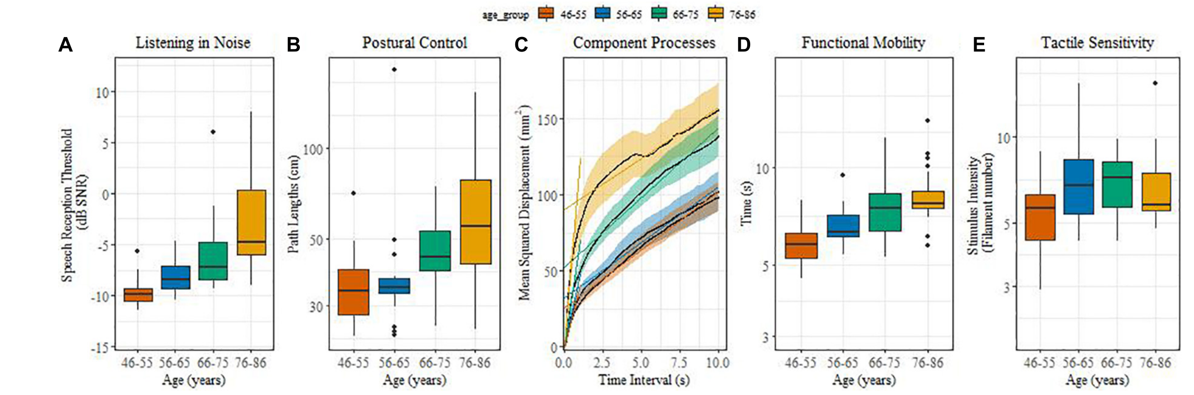

FIGURE 1
(A–E) (boxplots): Effect of age on sensory and sensorimotor processes. **(A)** Listening in noise in noise; **(B)** Postural control; **(C)** Component processes; **(D)** Functional mobility; **(E)** Tactile sensitivity.

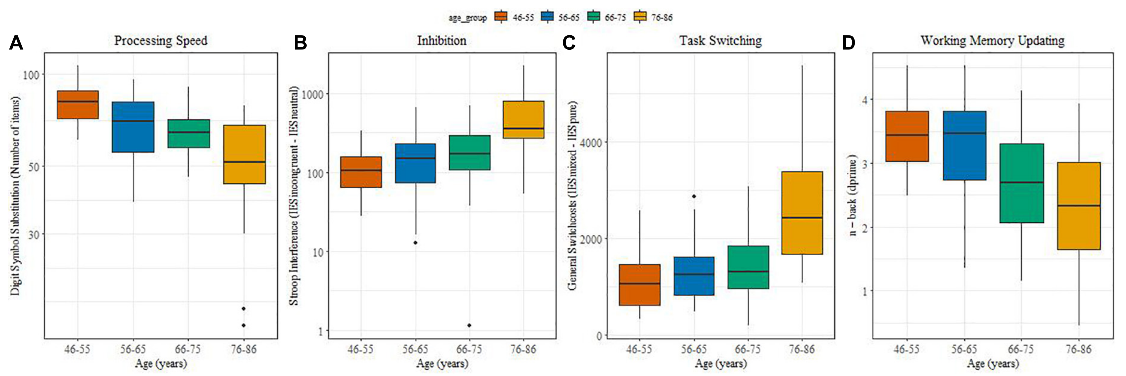

FIGURE 2
(A–D) (boxplots): Associations between age and performance on cognitive measures. **(A)** Processing speed; **(B)** Inhibition; **(C)** Task switching; **(D)** Working memory updating.

the middle-age groups of 46-55 and 56-65 (β = 0.11, SE = 0.03, t = 3.4, p = 0.001).

Figures 2A–D illustrate potential changes in processing speed, inhibitory control, task switching and working memory updating with age. Processing speed (Figure 2A) differed significantly between the two middle aged and the older groups (β = −33.25, SE = 0.35, t = 3.72, $p < 0.0001$), between the 66-75 and 76-86 group (β = −11,58, SE = 0.25, t = 3.29, p = 0.0065) and between 46-55 and 56-65-75 (β = −10,91, SE = 0.25, t = 1.26, p = 0.01). With advancing ages inhibiting information became more difficult. Stroop interference values (Figure 2B) increased significantly between the middle-aged groups and the older groups (β = 1.09, SE = 0.22, t = 4.84, p = 0.001 0.05), and between the 66-75 and 76-86 group (β = 0.53, SE = 0.15, t = 2.18, p = 0.00070.05).

Regarding cognitive flexibility, general switch costs also increased with age (Figure 2C) and they were significantly higher for older adults in comparison with middle-aged adults (β = 7.31, SE = 1.6, t = 4.57, $p < 0.0001$) as well as between the 66-75 and 76-86 groups (β = 5.95, SE = 1.13, t = 5.26, $p < 0.0001$). Variability in performance was pronounced in the oldest age group. Specific switch costs did not yield an effect of age (not shown).

Working memory updating (Figure 2D) showed a reliably lower d' for older compared with middle-aged individuals (β = −1.55, SE = 0.33, t = −4.63, $p < 0.00015$).

Processing speed and sensorimotor functions as mediators of age-related variance in cognition

We used causal mediation analysis to determine how much of the age-related variance (ARV) in three cognitive control measures was mediated by processing speed or sensorimotor functions. Results are shown in Table 2. The average causal mediation effect (ACME) reflects the mediation effect of age

TABLE 2 Causal mediation analysis.

Dependent variables	Task switching	Inhibitory control	Working memory updating
Processing speed			
Mediation effect of age effect through processing speed (ACME)	0.12***	**0.01****	−0.01
Direct effect of age on the dependent variable when controlling for processing speed (ADE)	**0.11***	**0.01***	**−0.03***
Total effect (ADE + ACME)	**0.24*****	**0.02***	**−0.04***
Proportion mediated	**0.52*****	**0.41****	0.25
Listening in noise			
Mediation effect of age effect through listening in noise (ACME)	0.04	−0.004	−0.001
Direct effect of age on the dependent variable when controlling for listening in noise (ADE)	**0.20****	**0.02*****	**−0.04****
Total effect (ADE + ACME)	**0.24*****	**0.02*****	**−0.04*****
Proportion mediated	0.16	−0.23	0.04
Functional mobility			
Mediation effect of age effect through functional mobility (ACME)	**0.09***	**0.01*****	−0.01
Direct effect of age on the dependent variable when controlling for functional mobility (ADE)	**0.14***	**0.01***	**−0.03*****
Total effect (ADE + ACME)	**0.23*****	**0.02*****	**−0.04*****
Proportion mediated	**0.42***	**0.41*****	0.22
Postural control			
Mediation effect of age effect through postural control (ACME)	−0.01	−0.0001	−0.004
Direct effect of age on the dependent variable when controlling for postural control (ADE)	**0.25*****	**0.02*****	**−0.04*****
Total effect (ADE + ACME)	**0.24*****	**0.02*****	**−0.04*****
Proportion mediated	−0.04	−0.01	0.10

The table lists the ACME, ADE, total effect and the proportion mediated for each mediator (processing speed and the sensorimotor measures) and each dependent variable (task switching, inhibitory control and working memory updating). Education: low = obligatory schooling not completed, average = obligatory schooling completed, high = higher education. Statistically significant results are indicated in bold with an asterisk (*$p < 0.05$, **$p < 0.01$, ***$p < 0.005$).

through processing speed or the sensorimotor measures. The average direct effect (ADE) reflects the direct effect of age on the cognitive control measures when controlled for the mediator. The total effect is the sum of the ADE and ACME, which reflects both the direct and indirect effect of age on the dependent variable (cognitive measures). The proportion mediated describes the proportion of age on the cognitive measure that passes through the mediator. Our results show a reliable mediation effect of age through processing speed and functional mobility on task switching and inhibitory control, with proportions varying from 41% to 52%. None of the other variables show a reliable mediation effect.

Coupling of cognitive and sensorimotor functioning: Median splits

As a final assessment of coupling between cognitive and sensorimotor functions, we performed median splits based on cognitive ability within each age group (processing speed and the three cognitive control variables). The high-low performance distinction, so derived, was used in the LM model with the three age-group contrasts as an additional predictor. Analyses were conducted separately for cognitive variables and three sensorimotor functions (listening in noise [DiN], functional mobility [TUG], and the postural data assessed through the short-term diffusion coefficient). The long-term diffusion coefficients and the critical time interval in posture tasks, specific switch costs and tactile data were not further analyzed because they did not show reliable age effects to begin with. Main effects related to the median-split factor indicated that individuals with low performance on a certain cognitive measure also differed reliably from high-performing individuals in the sensorimotor function in question. In other words, they point to a coupling of the cognitive and the sensorimotor function under consideration. Interactions between the three age-group contrasts and the median-split factor indicated that coupling strength (i.e., the differences in sensorimotor functioning between high- and low cognitively performing individuals) depended on age group.

From top to bottom, **Figures 3A,D,G,J** illustrate the coupling between listening in noise thresholds for individuals with high (green bars) versus low (red bars) cognitive ability

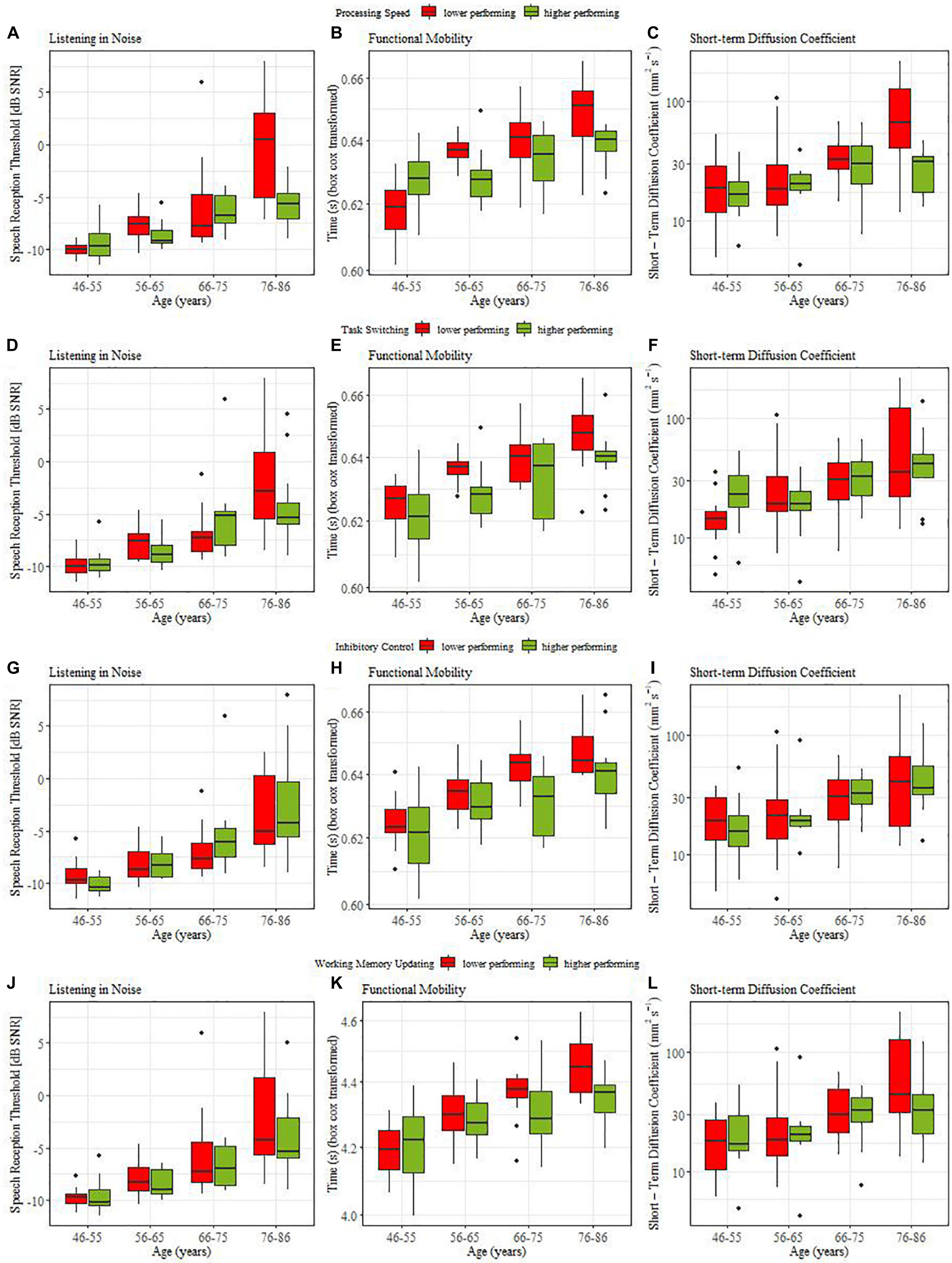

FIGURE 3
Coupling between sensorimotor and cognitive functions for lower (red) and higher (green) performing participants.

(assessed by processing speed, task switching, inhibitory control, and working memory updating, respectively). None of the median splits based on cognitive abilities induced a main effect. However, when processing speed was used to distinguish high and low cognitive performers, we obtained a significant interaction with the contrast comparing young vs. oldest old ($\beta = -0.004$, SE = 0.14, $t = 2.71$, $p = = 0.008$). *Post hoc* analysis showed that only the oldest age group (76-86 yr) yielded a reliable coupling in that older adults with slower processing speed also required reliably higher thresholds during listening in noise ($\Delta M = 0.07$, $t(22) = 3.45$, $p = 0.002$).

Figures 3B,E,H,K illustrate the coupling between functional mobility (TUG) and the four cognitive variables. For all cognitive abilities we obtained main effects of median split: processing speed ($\beta = -0.002$, SE = 0.009, $t = 2.30$, $p = 0.032$), for task switching ($\beta = -0.003$, SE = 0.001, $t = 3.06$, $p = 0.004$), for inhibitory control ($\beta = -0.003$, SE = 0.001, $t = 3.255$, $p = 0.002$ 0.05), and for working memory updating ($\beta = -0.002$, SE = 0.002, $t = 2.55$, $p = 0.026$). For processing speed and working memory updating significant interaction effects with age group contrasts were obtained. For processing speed this involved middle-aged versus old ($\beta = -0.008$, SE = 0.004, $t = 2.17$, $p = 0.021$), and young middle-aged (46-55yr.) vs. older middle-aged (56-65 yr) individuals ($\beta = -0.008$, SE = 0.002, $t = 2.96$, $p = 0.002$). *Post hoc* t-tests showed that in the 56-65yr ($\Delta M = 0.008$, $t(18.5) = 2.85$, $p = 0.012$) and 76-86yr old groups ($\Delta M = 0.01$, $t(17) = 2.62$, $p = 0.018$) individuals with higher processing speed also showed better functional mobility. For working memory updating the interaction ($\beta = -0.009$, SE = 0.004, $t = 2.26$, $p = 0.026$) indicated that in middle-aged individuals, cognition was not coupled to functional mobility while older adults with better working memory had higher functional mobility ($\Delta M = 0.01$, $t(46) = 2.96$, $p = 0.017$). In sum, we found strong evidence for a coupling between cognitive abilities and functional mobility. This coupling was similar across age groups for switching and inhibition while coupling increased with age when processing speed or working memory updating were considered.

Figures 3C,F,I,L illustrate the coupling between postural control (short-term diffusion coefficient) and cognitive ability. Only processing speed yielded significant coupling effects, namely interactions of median split with the middle-aged versus old contrast ($\beta = -0.26$, SE = 0.11, $t = 2.34$, $p = 0.033$), and the young-old (66-75yr) versus old-old (76-86yr) contrast, ($\beta = -0.16$, SE = 0.07, $t = 2.34$, $p = 0.034$ 0.05). *Post hoc* t-tests confirmed that older adults with faster processing speed had better postural control ($\Delta M = 0.23$, $t(41.2) = 2.7$, $p = 0.008$) and that this coupling relation was pronounced for the comparison within older age groups ($\Delta M = 0.40$, $t(17.1) = 3.25$, $p = 0.005$).

Discussion

The present study explored age effects and the coupling of sensorimotor and cognitive functions during middle- and late adulthood in individuals from four age groups with no indication of even mild cognitive decline. In a first step, we aimed to establish negative age-related differences for cognitive as well as sensorimotor functions, as could be expected based on extensive earlier research. Naturally, such demonstration is a prerequisite to exploring the coupling of sensorimotor and cognitive functions and their age-related intensification. Following the different theoretical accounts (common cause, cascade, compensation), we expected this coupling to emerge during late middle adulthood and to increase in the older age groups.

Except for tactile sensitivity, all measures yielded substantial age effects consistent with those reported in the literature. The median value of the SRT in the 46-55 group, −10 dB SNR, corresponds to the normative value for good hearing in young and middle-aged adults (Jansen et al., 2013; Vercammen et al., 2018a). The decline in speech in noise by about 0.15 dB per annum is comparable to the 0.18 dB SNR reported by Pronk et al. (2013) for persons between 57 and 93 years of age using a similar digits-in-noise task. Like in their study, the rate accelerated with age in our sample (0.16, 0.19, 0.32 dB SNR between the four age cohorts), caused by alterations in peripheral auditory, central auditory and cognitive changes.

For postural control, we found relative age-graded stability until late middle adulthood with substantial performance decrements in later decades of life. This is in line with normative data from Abrahamová and Hlavacka (2008) and Goble and Baweja (2018), who demonstrated strong age effects from the seventh decade onward. In our study, the short-term diffusion coefficient was the only variable among the SDA parameters sensitive to the balance system's age-related differences. This suggests that open-loop control processes are most affected by this age-related deterioration. Surprisingly, no differences were found for short-term diffusion coefficients when we compared the two oldest age groups. One potential explanation for this is the relatively low complexity of the postural control task; studies have indicated that age effects in postural control become more pronounced with increasing task complexity (Boisgontier et al., 2013; Carr et al., 2020). In line with Laughton et al. (2003) and Norris et al. (2005), no age-related differences were observed for the long-term diffusion coefficient. The critical time interval also did not show any age-related differences. This is in contrast with earlier studies that found a substantial increase in the critical time interval with increasing age (Collins and De Luca, 1995; Norris et al., 2005). As these studies compared young to older adults and averaged the mean squared displacement of 10 trials to calculate their SDA variables, methodological discrepancies are most likely responsible for these differences.

For functional mobility, we observed, on average, an increase in TUG-times similar to the 0.6-0.8 second increase per decade reported by Vereeck et al. (2008). Our assessment of tactile sensitivity only revealed reliable differences between young and older middle-age and age-graded stability in later phases. Most studies found an accelerated decrease in tactile perception with advanced age. As Berquin et al. (2010) observed significant effects of age only in the upper limbs but not in the lower limbs, we believe that our method, which measures at the feet, may be suboptimal for capturing changes in the older cohorts.

Processing speed and measures of cognitive control also showed robust age effects except for specific switch costs. It is well known that older adults need more time to process information than younger ones (Salthouse, 1996, 2009), that interference control changes with increasing age using the Stroop task (Gajewski et al., 2020), and that working memory updating is subject to age (De Beni and Palladino, 2004). Absence of age effects in specific task-switching costs was also reported by Verhaeghen and Cerella (2002) when reviewing the results of a series of meta-analyses examining age-related differences in selective attention (e.g., Stroop task) and divided attention (task switching).

We took two different approaches to explore sensorimotor coupling and its age-related intensification. The first approach was inspired by earlier common cause research investigating how much age-related variance (ARV) in cognitive functions could be explained by processing speed or sensorimotor functions. In line with the results presented by Lindenberger et al. (1993), we found that most of the age-related variance in cognitive control measures was mediated by processing speed. Mediator effects were generally much lower for working memory updating. Functional mobility turned out to be almost as successful as a mediator of ARV, in line with the findings presented by Lindenberger and Baltes (1994). Different from our expectations, the other two sensorimotor functions listening in noise and short-term diffusion in postural control, were poor mediators of ARV in cognitive functions.

For our second approach to coupling, we split individuals in the four age groups into high- and low-ability subgroups based on their performances in four markers of domain-general cognitive functioning. Subsequently, we asked whether high vs. low cognitive ability corresponded to better vs. poor performance levels in three sensorimotor functions. Like before, we found the strongest evidence for sensorimotor-cognition coupling when processing speed was used to identify subgroups with high vs. low cognitive abilities. Processing speed accounted for individual differences in all three sensorimotor functions, and this coupling increased with advancing ages for listening in noise, functional mobility, as well as postural control. For markers of cognitive control (inhibition, switching, working memory updating), the evidence was mixed. For all three markers, we demonstrated significant coupling with individual differences in functional mobility and working memory updating also showed increased coupling strength with age, as expected. At the same time, no indication of coupling was evident for cognitive control functions and listening in noise or postural control.

In sum, except for tactile sensitivity, we found substantial age-related differences in the sensorimotor and cognitive tasks, which was perfectly in line with previous studies and sufficient grounds for our investigation of sensorimotor-cognitive coupling and its age-related intensification. Different from our expectations and earlier studies we found that only processing speed and functional mobility reliably showed coupling and age-related increases thereof in combination with different cognitive or sensorimotor variables. When we extended the functions considered to cognitive control on the one hand and posture or listening in noise on the other, evidence for coupling was weak. The bottom line is that individuals with poor cognitive control do not necessarily have poor listening-in-noise skills or poor postural control.

Limitations and associations

Our study was explorative by its correlational and cross-sectional design, as is the bulk of the evidence accumulated to support cascade models, common-cause or cognitive compensation hypotheses. For some time, researchers have recognized that a solid evaluation and comparison of the different accounts require longitudinal data and sophisticated approaches (Ghisletta and Lindenberger, 2005; Kiely and Anstey, 2015). Nevertheless, even more sophisticated approaches yield moderate correlations between sensory and cognitive declines (Lindenberger and Ghisletta, 2009.

Key differences with earlier studies relate to our choices for sensorimotor and cognitive functions and how we assessed performance. While most studies compared young and old individuals, we narrowed the age range to periods where functional decline has been demonstrated to accelerate and during which the coupling of sensorimotor and cognitive functions is assumed to become stronger. In our study, the coupling in middle-aged is not very pronounced, perhaps because only 7% of our participants wore hearing aids (compared to 16.7% in the study by Lindenberger and Baltes, 1994). Analyses of 165.000 persons between 49-69 years showed that 10.7% of adults had significant hearing impairment based on a similar digits-in-noise task (Dawes et al., 2014). In our sample the prevalence of HI is 4% for 46-55 years, 21% for 56-65 years, 46% for 66-75 years and 83% for 76-86 years based on a cut-off of −7 dB SNR. This cut-off is lower than the reference value at −8.6 dB SNR for middle-aged persons (Vercammen et al., 2018a), indicating that these persons are likely to have HI.

Our mixed results as far as coupling between different cognitive and sensorimotor abilities go is not an exception in the literature. For example, Dryden et al. (2017) reported variable associations between cognition and speech in noise understanding. Their systematic study showed that the overall association between cognitive performance and speech understanding in noise was in the order of r = 0.31. More recently, Danielsson et al. (2019) showed that the association between age, auditory function, and cognition looked different depending on the type of variable used to represent auditory function and cognition. In our study listening in noise was assessed with a speech-weighted noise task which is cognitively less demanding than an informational masker (e.g., Goossens et al., 2017). In a similar vein, no significant correlations were observed between amplitude modulation detection thresholds for diotic tones and cognitive abilities (Füllgrabe et al., 2015), while strong correlations were observed between spatial audition and performance on the trail-making task in older persons with HI (Strelcyk et al., 2019), presumably because spatial cues are coded centrally. A modality-general spatial processing deficit and/or individual differences in global processing speed could lie at the basis of this relationship. Previously, significant correlations were also observed between the temporal fine structure of the signal and cognitive factors (Rönnberg et al., 2016; Ellis and Rönnberg, 2022).

Implications for hearing rehabilitation

Although more than 70% of listeners with self-reported hearing problems mention having consulted a medical professional about their hearing health (Laureyns et al., 2016), hearing aid uptake in this group ranges from 20-40% only (Abrams and Kihm, 2015; Hougaard et al., 2016; Laureyns et al., 2016). This is unfortunate as hearing aid use is associated with better cognition, independently of social isolation and depression (Dawes et al., 2015). Hearing aids may improve cognitive performance, presumably because of improvement in audibility or associated increases in self-efficacy. Similarly, improvements in working memory and processing speed were reported for persons over 70 years with bilateral hearing impairment following unilateral cochlear implantation (Knopke et al., 2021). Besides technological intervention, auditory training involving cognitive processes may also improve working memory and other cognitive factors (Ferguson and Henshaw, 2015). As the sensorimotor-cognitive coupling was strongest in the older age groups it may be that training processing speed improves listening skills and indirectly other sensorimotor skills like keeping posture and walking.

Conclusion

We demonstrated robust age effects for cognitive and sensorimotor functions emerging in middle adulthood and accelerating in late adulthood. Processing speed and functional mobility reflected sensorimotor-cognition coupling and its age-related intensification. However, this was not true for other domain-general cognitive abilities and sensorimotor functions. A major implication is that domain-specific factors must also play a major role in cognitive and sensorimotor aging. While this might complicate theorizing, it portrays an optimistic perspective in our view in that it "does NOT go altogether when it goes" (Rabbitt, 1993). Further research is needed to establish the relationship between the cognitive constructs and sensorimotor functioning in aging individuals in order to develop targeted interventions for persons with HI.

Data availability statement

The raw data supporting the conclusions of this article will be made available upon request.

Ethics statement

The studies involving human participants were reviewed and approved by Medical Ethical Committee of UZ Leuven/KU Leuven. The patients/participants provided their written informed consent to participate in this study.

Author contributions

MV and NV prepared the materials, collected the data, and preprocessed the data. MV performed the data analysis. All authors have contributed to the study conception and design, each wrote parts of the manuscript, and provided critical revision and feedback.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnins.2022.1049639/full#supplementary-material

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Cognitive and linguistic abilities and perceptual restoration of missing speech: Evidence from online assessment

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When speech is clear, speech understanding is a relatively simple and automatic process. However, when the acoustic signal is degraded, top-down cognitive and linguistic abilities, such as working memory capacity, lexical knowledge (i.e., vocabulary), inhibitory control, and processing speed can often support speech understanding. This study examined whether listeners aged 22–63 (mean age 42 years) with better cognitive and linguistic abilities would be better able to perceptually restore missing speech information than those with poorer scores. Additionally, the role of context and everyday speech was investigated using high-context, low-context, and realistic speech corpi to explore these effects. Sixty-three adult participants with self-reported normal hearing completed a short cognitive and linguistic battery before listening to sentences interrupted by silent gaps or noise bursts. Results indicated that working memory was the most reliable predictor of perceptual restoration ability, followed by lexical knowledge, and inhibitory control and processing speed. Generally, silent gap conditions were related to and predicted by a broader range of cognitive abilities, whereas noise burst conditions were related to working memory capacity and inhibitory control. These findings suggest that higher-order cognitive and linguistic abilities facilitate the top-down restoration of missing speech information and contribute to individual variability in perceptual restoration.

KEYWORDS

perceptual restoration, interrupted speech, cognition, linguistic, online assessment

Introduction

When conditions are optimal, understanding speech for normal-hearing listeners is a relatively simple and automatic process. High-fidelity speech information is rapidly transmitted through the peripheral and central auditory systems to the primary auditory cortex, acoustic cues are matched to stored lexical representations, and meaning can be extracted with little to no conscious reappraisal (Marslen-Wilson and Welsh, 1978). However, in everyday communication, background noise or interruptions are common. Background noise can interfere with the perception of target speech (Gordon-Salant and Fitzgibbons, 2004; Neuman et al., 2010; Smith et al., 2019), and if the interruptions become more intense than the speech itself, segments may be masked entirely. Despite this obfuscation of the speech signal by background noise, many listeners with normal hearing remain able to understand speech relatively well. In difficult conditions, listeners are thought to piece together the remaining speech fragments to "fill in the gaps," integrating and organizing them perceptually across time. For example, listeners may rely on spectrotemporal cues, such as the fundamental frequency, that are less affected by background noise and can bridge the gaps to assist with perceptual grouping (Li and Loizou, 2007; Oxenham, 2008). This idea is often referred to as "glimpsing," "dip listening" (Cooke, 2006; Akeroyd, 2008), or "perceptual restoration" when segments of speech information are intentionally absent or removed (Warren, 1970).

This process can be investigated using an interrupted speech paradigm wherein segments of a speech signal are periodically removed, as pioneered by Miller and Licklider (1950). Periodic removal of speech allows for an investigation into which factors may aid in the recovery of the remaining proportion of speech information. Speech intelligibility improves when the periodic interruption is a rectangular burst of broadband noise instead of a silent gap (Powers and Wilcox, 1977; Bashford and Warren, 1987; Bashford et al., 1992; Bologna et al., 2019). This effect is particularly salient when the intensity of the noise burst is greater than the speech signal. The negative signal-to-noise ratio is thought to give the listener the impression of perceptually continuous speech occurring behind the noise, aiding perceptual organization and grouping (Bashford and Warren, 1987; Bashford et al., 1996).

Most perceptual restoration research has emphasized signal-level factors, such as speech spectrotemporal fidelity, rate, and length; interruption length, density, and type; and interruption/signal intensity that affect how much speech information can be restored (Miller and Licklider, 1950; Warren, 1970; Bashford et al., 1996; Başkent et al., 2009; Chatterjee et al., 2010; Jin and Nelson, 2010; Benard et al., 2014; Clarke et al., 2016; Shafiro et al., 2016). Furthermore, most of the perceptual restoration literature focuses on group differences (e.g., age, hearing status) (Başkent, 2010; Kidd and Humes, 2012; Fogerty et al., 2015; Başkent et al., 2016; Bologna et al., 2018; Jaekel et al., 2018). While signal-level factors clearly play a role in the ability to restore missing speech, individuals within the same group still vary substantially in their perceptual restoration ability.

We suggest that individual variability during the perceptual restoration of missing speech information may be driven by individual differences in higher-order processing abilities, such as cognitive and linguistic abilities. Cognitive abilities differ substantially from one person to the next, and while abilities such as working memory and inhibitory control do tend to vary together within one person, they are not always aligned (e.g., an individual can have high working memory with low inhibitory control) (Carroll and Maxwell, 1979; Boogert et al., 2018). Linguistic abilities also vary across individuals, with lexical knowledge, or vocabulary, increasing with advancing age (Verhaeghen, 2003). The Ease of Language Understanding (ELU) model takes these higher-order processes into account, proposing a model where cognitive and linguistic abilities interact to support degraded speech understanding. The ELU model accounts for cognitive abilities, such as working memory, which allows speech to be temporarily held in an episodic buffer for later reprocessing; and linguistic knowledge, which allows context and vocabulary to identify possible lexical candidates for speech which was not automatically recognized (Rönnberg et al., 2013). This model provides an explanation whereby individuals may restore missing or interrupted speech differently based on their cognitive and linguistic abilities, as follows.

First, the reconstruction of missing speech requires the reprocessing of available speech fragments which are temporarily held in an episodic buffer. Temporarily holding speech fragments tasks a listener's working memory capacity. Some evidence suggests that an individual's working memory capacity mediates the ability to restore missing speech (Benard and Başkent, 2014; Millman and Mattys, 2017; Nagaraj and Magimairaj, 2017) while other data are less definitive (Nagaraj and Knapp, 2015; Shafiro et al., 2015; Bologna et al., 2018). Second, reprocessing is informed by a listener's lexical knowledge and how quickly that information can be accessed to accurately identify lexical candidates when filling the gap. Current literature indicates that lexical knowledge (i.e., vocabulary) plays a role during perceptual restoration (Benard and Başkent, 2014; Nagaraj and Magimairaj, 2017). However, existing literature has not captured an aspect of speech perception that may be important during perceptual restoration: lexical access speed, or the rate at which stored lexical representations can be activated or matched by speech information. Third, irrelevant information, such as unlikely lexical candidates, noise-burst interruptions, and other cognitive processes that may be competing for attention must be inhibited, which relies on a listener's inhibitory control. Current evidence suggests that an individual's inhibitory control is predictive of his/her ability to perform other degraded speech recognition tasks, such as speech-in-noise (Dey and Sommers, 2015; Dryden et al., 2017; Stenbäck et al., 2021; Perron et al., 2022). Bologna et al. (2018) investigated inhibitory control using interrupted speech and found null results for both younger and older adults, albeit at a very difficult signal-to-noise ratio. Last, working memory reprocessing, lexical processing, and inhibitory control require processing time to complete. Thus, these abilities depend on processing speed, or the rate at which cognitive tasks are completed by an individual (Salthouse, 1992; Morrison and Gibbons, 2006; Rozas et al., 2008). Processing speed has shown predictive value in previous research on degraded speech recognition (Ellis et al., 2016; Dryden et al., 2017; Yumba, 2017) and perceptual restoration (Bologna et al., 2018), but data exist only for young normal-hearing and older hearing-impaired adults.

Taken together, we predict that listeners who have a higher working memory capacity, greater lexical knowledge, faster lexical access speed, better inhibitory control, and faster processing speed will be more successful when restoring missing speech information, especially for high context, predictable sentences. Building from previous work, we used a periodically interrupted speech paradigm to force listeners into an explicit processing loop as outlined in the ELU model (Rönnberg et al., 2013), and we separately measured the cognitive and linguistic processes supporting explicit processing. To further explore the role of lexical processing during perceptual restoration, we chose to include both high- and low-context sentences in addition to a sentence set that resembles everyday speech. Because in-person testing capacity was restricted as a result of the COVID-19 pandemic, this experiment was conducted using online assessments for listeners ranging from young to middle-aged adults.

Materials and methods

Participants

Prior to data collection an *a priori* power analysis was performed based on the relationship between perceptual restoration and cognitive data from Nagaraj and Magimairaj (2017). For a medium effect size of 0.3, an alpha level of 0.05, a power level of 0.9, and four predictors, the projected sample size necessary was 57 participants. Sixty-three participants (22 males, 36 females, five other or prefer not to answer) completed this experiment (Age range = 22–63 years, Mean = 42.0 years, SD = 12 years); they represented an age range captured in only a small set of perceptual restoration data (Millman and Mattys, 2017). To be eligible, participants needed to self-report normal hearing and cognitive status, speak English as their primary language, be between 18 and 65 years of age, and be a current resident of the United States. Because participation was virtual, hearing thresholds were not assessed. The Institutional Review Board of Northwestern University approved the study, all participants signed an informed consent form on the secure data collection platform REDCap (Harris et al., 2009), and participants were compensated at an hourly rate for taking part in the study.

Stimuli

Speech stimuli consisted of three sentence sets: the Revised Speech in Noise (RSPIN) low- and high-context sentences (Bilger et al., 1984) and the Perceptually Robust English Sentence Test: Open Set (PRESTO) (Tamati et al., 2013). The RSPIN sentences were designed to determine the role of top-down and bottom-up processes during speech recognition and were selected from a corpus of 200 sentences that were highly predictable (e.g., "the witness took a solemn *oath*"), where top-down resources can inform final word choice, or 200 sentences that were unpredictable but syntactically correct (e.g., "he has a problem with the *oath*") which relies more on the fidelity of the bottom-up signal to the auditory cortex. Following Jenstad and Souza (2007), the entire sentence was scored (see Section "General procedure"). RSPIN sentences were produced by a male talker. High context sentences had an average of 5.1 content words per sentence, and low context sentences had an average of 4.8 content words per sentence. The PRESTO is a high-variability sentence set designed to be sensitive to individual differences and is thought to access both central cognitive and perceptual abilities during speech recognition, including current theories of lexical organization and automatic encoding of lexical components. The PRESTO sentence set is balanced for talker gender, number of keywords (average of 4.2 content words per sentence), word frequency, and word familiarity.

Both silent gap sentences and noise burst sentences were constructed using a common method for interrupted speech stimuli development which is known to induce perceptual restoration. This method also avoids both floor and ceiling effects, as follows.

All sentences

Six sentence conditions consisting of sixty sentences each were tested: two interruption conditions (silent gap versus noise burst) by three sentence conditions (RSPIN low context, RSPIN high context, and PRESTO), resulting in 240 RSPIN sentences and 120 PRESTO sentences. First, the 360 sentences were gated with a 50% duty cycle square wave at a rate of 2.0 Hz using a custom MATLAB R2020a script, creating interrupted speech stimuli with alternating 250 ms segments of speech and silence. Second, a separate set of 360 noise-burst stimuli were created where the noise bursts aligned with the silent segments of the interrupted speech stimuli. The speech-shaped noise bursts were generated using the combined Fourier transform of all 360 sentences, where the phases of all spectral components were randomized before being converted back into the time domain using an inverse Fourier transform. The overall lengths of the noise-burst stimuli were the same as the overall lengths of the interrupted speech segments because the noise bursts would later be interleaved with the interrupted speech segments (i.e., creating alternating 250 ms segments of speech and noise bursts). To minimize spectral splatter and distortion, 10 ms cosine on- and off-ramps were applied to both the remaining interrupted speech segments and noise burst stimuli. The RMS of the interrupted speech stimuli and the noise burst stimuli were normalized. Because the amount of speech information restored improves with the addition of a noise burst when the noise burst is louder than the remaining speech segments (Bashford et al., 1996), the level of the noise burst stimuli was raised by 10 dB (–10 dB SNR) relative to all interrupted speech segments. The RMS of interrupted speech segments and the noise bursts was then normalized. By processing the stimuli this way, the level of the speech is always the same for both the silent-gap and noise-burst sentences, while the level of the noise burst will be 10 dB higher than the speech for the noise-burst sentences after processing.

Silent gap sentences

Silent gap sentences consisted of half of the original 360 sentences (120 RSPIN high- and low-context and 60 PRESTO sentences). The preceding procedure resulted in a set of silent gap interrupted speech stimuli with alternating segments of 250 ms of speech and 250 ms of silence with 10 ms cosine on- and off-ramps with a normalized RMS; no further signal processing was required.

Noise burst sentences

For the remaining half of the sentences (120 RSPIN high- and low-context and 60 PRESTO sentences), a periodic noise burst filled the silent gap. To do this, the interrupted speech segment stimuli and the noise-burst stimuli were added linearly to one another, including their individual 10 ms on- and off-ramps eliminating distortion and spectral splatter.

General procedure

Testing was carried out using the online recruitment and experimental testing platforms Prolific and Gorilla, respectively. Pre-screening criteria (see Section "Participants") was entered into Prolific to identify potential eligible participants, who, after indicating interest, were directed to REDCap (Harris et al., 2009), a secure data collection platform, to complete the consent form, enter demographic data, complete a brief hearing health questionnaire, and to complete the Speech and Spatial Qualities questionnaire (see Section "Questionnaires"). From there, participants were directed to the experimental platform, Gorilla, where they completed cognitive and linguistic tasks (see Sections "Cognitive tasks and Linguistic task"), a headphone screening task, and the interrupted speech task (see Section "Stimuli").

Questionnaires

First, participants completed a simple demographic questionnaire, followed by a hearing health questionnaire that included self-report of hearing loss and cognitive or memory concerns (participants were excluded if they answered "yes"). Last, participants completed the 49-item Speech and Spatial Qualities of Hearing questionnaire (SSQ) in which participants self-assessed their hearing ability in specific contexts and situations on a numerical scale of 0–10 (Gatehouse and Noble, 2004). Questions address self-perceived function in three domains: speech hearing (*"SSQ—Speech")*, spatial hearing (*"SSQ—Spatial"*), and quality of hearing (*"SSQ—Quality"*). Participants were asked to rate their ability to hear and understand speech in different settings (speech hearing domain), their ability to listen in different environments, which includes distance, direction, and movement (spatial hearing domain), and their perceived abilities for everyday sounds, including music listening, ease of listening, clarity, and naturalness of sound (quality of hearing domain).

Cognitive tasks

To assess listeners' working memory capacity, inhibitory control, and processing speed, participants completed several automated, virtual assessments in the visual modality: the Reading Span Task (RST; complex working memory capacity), the Digit Span Forward and Backward (DST; simple working memory capacity), the Stroop Task (Stroop; processing speed and inhibitory control), and the Flanker Task (Flanker; processing speed and inhibitory control).

Reading span task

The reading span task (RST) is a task that measures a listener's complex working memory capacity, or the simultaneous storage and reprocessing of complex information, requiring additional processing beyond simple repetition or reversal of information (see Section "Digit span forward and backward"). The current version of the RST was described by Rönnberg et al. (1989), which was modified from the original version first introduced by Daneman and Carpenter (1980). The current version was modified so that the assessment could be completed virtually and without supervision. In this task, listeners were asked to first read and comprehend sentences presented on a screen and to determine whether or not the sentence makes sense. Half of the sentences were absurd (e.g., "The fish drove a car") and the other half were normal sentences (e.g., "The ball bounced away"). Each content word and any accompanying articles (e.g., "the ball" or "a car") were presented sequentially on the screen each for 800 ms. Listeners were then asked to respond "yes" by pressing a button on the screen if the sentence made sense or "no" if the sentence was absurd.

If listeners did not respond within 3,000 ms, the program advanced automatically. Participants were presented with 2–5 sentences per sequence. Listeners were then asked to recall either the first content word or the last content word from each sequence. They were not made aware beforehand whether they will be expected to recall the first or the last word, and thus must maintain both streams of information simultaneously. Using their keyboard, listeners typed their content word responses into a box on the screen and the number of correctly recalled words (not in correct serial order) out of the number of possible words was scored. Because participants were not supervised during this task, practice trials with feedback were provided. First, participants practiced only responding whether or not the sentence made sense. Next, they practiced recalling the first words of a two-sentence sequence, then the last words of a two-sentence sequence. Last, they practiced responding by recalling either the first or the last words of a two-sentence sequence before beginning the actual task. The percent correct of first or last words correctly recalled in any order ("*RST Percent Correct*") reflects a participant's complex working memory capacity.

Digit span forward and backward

The digit span task represents a traditional neuropsychological measure of a listener's short-term memory (digit forward), such as the storage of a phone number (Jones and Macken, 2015), and simple working memory capacity (digit backward). Digit span backwards requires that the participant store and later invert the serial presentation of numerical information, similar to the storage and reprocessing of information during more demanding working memory tasks like the RST. Digit span forward and backward then may represent reduced processing demands compared to the RST (Daneman and Merikle, 1996) or different processes of working memory, with digit span forward and backward tapping into the simple rehearsal of visual stimuli during working memory and RST tapping into more complex rehearsal and reprocessing of visual information in the current study (Millman and Mattys, 2017). However, these complex working memory tasks correlate weakly with digit span backwards and the role of the digit span task as an assessment of working memory has been questioned (Hilbert et al., 2015). The digit span forward and backward task was chosen in addition to the RST to assess a range of memory capacities, from simple to complex, and their relationship to restoration of missing speech across participants. The current digit memory test was designed and revised by Turner and Ridsdale (2004). Participants were presented with a sequence of 2–9 digits and were afterwards asked to type them into the computer, either in the same order for digit span forward, or in reverse order for digit span backward. Each digit was presented on the screen for 1,000 ms. If participants typed in an incorrect response for both trials of a given sequence length, the task would end. Prior to administration of digit span forward and digit span backward, participants had two practice trials in which they received feedback for each task. Percentiles were calculated from norms and were based on the total number of correct trials for digit span forward and digit span backward together ("*DST Percentile*") (Turner and Ridsdale, 2004).

Stroop task

The Stroop task measures a participant's inhibitory control, or their ability to suppress task-irrelevant information. The ability to inhibit irrelevant verbal information, such as unlikely lexical candidates, may allow some listeners to restore more missing speech than others. In the Stroop task, participants named color words (*W*, 25 items) (e.g., "blue"), color hues of "XXXX" to eliminate any reading component (*C*, 25 items), and color words printed in an incongruent color hue (*CW*, 25 items) (e.g., "blue" written in green ink). For the incongruent trials, the participant was asked to name the color of the ink that the word is printed in, not the word itself. The task–naming color words–captures processing speed in milliseconds ["*Stroop Processing Speed (ms)*"], while the final task captures a participant's interference score, with higher interference scores indicating reduced inhibitory control and poorer performance (Jensen, 1965). This assessment was based on the method developed by Golden (1976); however, rather than the number of items completed within a specified time limit, each participant completed the same number of items and correct/incorrect and reaction time for each item were captured. For each item, the participant pressed a key on their keyboard that corresponded with the first letter of the color (e.g., "b" for blue). Reminders for the keys were present on the screen. Interference was calculated as the ratio of the average time in milliseconds to correctly identify a CW trial divided by the average time taken to correctly identify a C trial (i.e., *CW/C*), a method common in neuropsychology literature ["*Stroop Interference (ms)*"] (Lansbergen et al., 2007; Scarpina and Tagini, 2017).

Flanker task

The Flanker task measures a participant's response inhibition, or the ability to suppress responses that are irrelevant or inappropriate for a given task. The Flanker task requires participants to inhibit irrelevant non-verbal information, such as noise bursts, which may allow some listeners perform better on some perceptual restoration tasks than others. During this task, participants completed a computerized version of the Eriksen flanker task (Eriksen and Eriksen, 1974). During this task, participants were presented with five black arrows against a white background and were asked to press a key ("e" for left-facing arrows and "i" for right-facing arrows) to indicate the direction of the arrow in the middle. Participants were asked to respond as quickly and as accurately as possible. There was no time limit for responding on each trial. Half of the 90 items were congruent (e.g., >>>>> or <<<<<) and half were incongruent (e.g., >><>> or <<><<). The interstimulus interval was 750 ms. Before the scored trials, participants had eight practice trials in which they received feedback. Reaction time for congruent and incongruent items were captured as well as task accuracy. Interference was calculated by subtracting the mean reaction time for correct congruent items from the mean reaction time for correct incongruent items in milliseconds [“*Flanker Interference (ms)*”] (Sanders et al., 2018).

Linguistic task

To assess listeners’ lexical access accuracy and lexical access speed, participants completed an automated virtual assessment in the visual modality, the Lexical Test for Advanced Learners of English (LexTALE; lexical knowledge and lexical access speed).

Lexical test for advanced learners of English

The English version of the LexTALE task (Lemhöfer and Broersma, 2012) estimates English vocabulary size (i.e., lexical knowledge) and the speed at which lexical decision-making occurs (i.e., lexical access speed). This measure was originally developed to assess lexical knowledge for intermediate to advanced learners of English as a second language. However, participants who speak English as their first language do not necessarily produce ceiling effects (Lorette and Dewaele, 2015) because factors such as age can influence lexical knowledge over time (Keuleers et al., 2015). Participants were presented with 60 items, 40 of which are real English words and 20 of which are orthographically permissible, pronounceable non-words. Participants were asked to press the “j” key if the word is a real word or the “k” key if it was a non-word and to respond as quickly and as accurately as possible. Reminders for the keys were present on the screen. Participants had 2,000 ms to respond before the program automatically advanced, scoring the missed item as incorrect. Participants did not receive practice trials or feedback prior to task administration. Lexical knowledge was the average of correct responses for real English words and non-words [*“LexTALE Non-word Accuracy (ms)”*] while lexical access speed was measured using the reaction time (“*LexTALE Word RT*”) of correctly identified real words.

Screening task

Participants were asked to wear headphones and to set the volume on their computer to a “loud, but not uncomfortable” level while listening to a recorded excerpt from the Discourse Comprehension Test (Brookshire and Nicholas, 1984). Listeners were also asked to complete a headphone screening procedure to ensure headphone use [see Woods et al. (2017) for more detail]. Briefly, the headphone test required the listener to listen to three tones and pick the softest one out of three correctly at least 4/6 times. Over a loudspeaker setup (e.g., laptop), one of the three tone presentations suffers from destructive interference resulting from two tones presented out of phase at each loudspeaker, making it difficult to differentiate from the tone that is 6 dB below the standard tone. With headphones, the phase differences do not result in destructive interference, making one of the three tones easier to pick out as the softest. Failing the headphone screening twice resulted in exclusion.

Interrupted speech task

Participants listened to and practiced typing in uninterrupted sentences, followed by those same sentences interrupted by both silent gaps and noise bursts. Feedback was not provided. Participants then listened to the experimental interrupted stimuli. The order of the silent gap sentences and the noise burst sentences were blocked and counterbalanced to prevent order effects. Within each (silent gap or noise burst) block, sentences were not blocked by sentence type and were presented in a random order. After one RSPIN or PRESTO sentence was presented, listeners were asked to type in what they heard into a box on the computer screen. The number of keywords correctly identified was scored using Autoscore (Borrie et al., 2019). Autoscore is an open-source tool for scoring listener transcripts, where the researcher specifies the scoring rule and under which circumstances that rule should be applied. Strict criterion were applied in this experiment. Only the double-letter rule was applied, which scores a word as correct if a double letter is omitted within a word (e.g., “atack” is considered correct for “attack”). Additionally, a custom acceptable spelling list was created that included common misspellings of all keywords in the RSPIN and PRESTO sentences including the following: single letter transpositions within a single word during typing, inclusion/omission of an apostrophe for keywords with a contraction, and any entry of a double space (e.g., spacebar was accidentally hit twice). Traditionally, only the last word of the RSPIN is scored; however, we were interested in how participants restored speech across the entire interrupted sentence, not just the word in the final position. Therefore, content words across the entire sentence were scored using the same method and number of keywords as Jenstad and Souza (2007).

Statistical approach

All data were analyzed using the open source RStudio statistical program version 4.0.5 (R Core Team, 2013), using the *tidyverse* library (Wickham et al., 2019) including the library *dplyr* for data manipulation (Wickham et al., 2022) prior to statistical analysis. The library *ggplot2* was also used for data visualization and figure preparation (Wickham, 2016). For the analysis of variance, the library *rstatix* was utilized

(Kassambara, 2021). For the linear models, the libraries *MASS* and *lmtest* were used to assess homoscedasticity and the distribution of residuals (Venables and Ripley, 2002; Zeileis and Hothorn, 2002). First, outliers in the data were identified and adjusted, followed by descriptive analysis for participant data, cognitive and linguistic measures, and interrupted speech conditions. Next, an analysis of variance (ANOVA) tested for significant differences between the six sentence conditions and Pearson correlations between cognitive and linguistic variables and interrupted sentence conditions were determined. Last, a set of linear regression analyses was performed using cognitive and linguistic variables as predictors for the six sentence conditions.

Results

Prior to analysis, outliers were identified and adjusted, and a fence was determined. All values within any single measure that were outside three times the interquartile range (IQR) were identified as outliers and were adjusted to the nearest fence boundary (i.e., the first or third quartile) to minimize regression toward the mean. Three times the IQR was chosen as a conservative fence in order to avoid unnecessary adjustment given the unsupervised, online nature of the data collected. In total, nine of 1,071 observations across the seventeen reported measures fell outside of the IQR fence and were adjusted. Of the nine adjusted observations, six occurred in the linear models that follow. Descriptive statistics for the 63 participants in this study are presented in **Table 1** and results for cognitive and linguistic measures and interrupted speech conditions are available in **Table 2**. After addressing outliers, measures were normally distributed with skewness and kurtosis under accepted values (Kline, 2015). Participants in this sample performed slightly better but within one standard deviation on the RST compared to existing data (Friedman and Miyake, 2005; Füllgrabe et al., 2015), performed above average on the digit span task with an average percentile score of 72.6 (Turner and Ridsdale, 2004), were consistent with existing Stroop data with regard to reaction time but slightly better with regard to interference scores (Langenecker et al., 2004; Van der Elst et al., 2006), Flanker interference scores were within one standard deviation of existing data (Paap et al., 2020), and participants were highly consistent with published data for English monolinguals on the LexTALE task (Dijkgraaf et al., 2016).

Perceptual restoration differences across experimental conditions

Number of keywords correctly identified across the six sentence conditions were analyzed using an analysis of variance (ANOVA) with the sentence conditions as factor levels and

TABLE 1 Descriptive statistics for participants.

Measures	Mean (SD)	Range	Skew	Kurtosis
Age	42.0 (12.0)	[22, 63]	−0.04	−1.2
Education	15.4 (2.8)	[8, 24]	0.27	0.79
SSQ–speech	8.4 (1.4)	[10, 3]	−1.25	2.11
SSQ–spatial	7.7 (1.5)	[10, 4]	−0.4	−0.48
SSQ–qualities	8.6 (1.2)	[10, 5]	−1	0.39

the percent of keywords correctly identified as the dependent variable. The normality assumption was checked and met using quantile-quantile (Q-Q) plots rather than a Shapiro-Wilk test, as the sample size is greater than 50 participants (D'Agostino, 1971). Levene's test for the homogeneity of variances assumption necessary for the ANOVA was significant, indicating the variances for the six sentence conditions were not equal $F_{(5,372)} = 2.45$, $p = 0.03$ (Levene, 1960). To account for this violation, a Welch one-way test was used which does not require homogeneity of variance (Moder, 2007).

The perceptual restoration of missing speech information differed by sentence condition (**Figure 1**), $F_{(5,372)} = 99.7$, $p = < 0.001$. *Post-hoc* pairwise *t*-tests with no assumption of equal variances using a Benjamini-Hochberg correction for multiple comparisons revealed that all pairwise differences between the six conditions were statistically significant ($p < 0.05$) and different from one another, except PRESTO Noise and RSPIN Low Silent conditions ($p = 0.58$) and RSPIN High Silent and RSPIN Low Noise conditions ($p = 0.18$) (Benjamini and Hochberg, 1995).

Relationships between perceptual restoration and higher-order, cognitive and linguistic variables

Correlations between the six sentence conditions and cognitive and linguistic variables are presented in **Table 3** and **Figure 2** (note that *p*-values have not been adjusted for multiple comparisons). Complex working memory capacity measured with the Reading Span Task was moderately correlated with simple working memory measured using the digit span task, a traditional measure working memory thought to be less taxing than complex working memory tasks ($r = 0.28$, $p = 0.02$). This is consistent with previous research (Daneman and Merikle, 1996) and with similar construct validity between complex working memory, or tasks requiring substantial information storage and reprocessing, and simple working memory, or tasks requiring more straightforward repetition or reversal of information (Lehto, 1996), though the digit span task was not correlated with interrupted speech performance and may not necessarily represent working memory performance (Jones and Macken, 2015). Furthermore, working memory capacity had a moderate,

TABLE 2 Descriptive data for experimental tasks.

	Measures	Mean (SD)	Range	Skew	Kurtosis
Cognitive measures	RST percent correct	73.5 (14.3)	[96.7, 34]	−1.31	1.66
	DST percentile	72.6 (28.6)	[99.9, 0.8]	−1.22	0.42
	Stroop interference (ms)	1.35 (0.26)	[2.29, 0.95]	1.07	1.33
	Stroop processing speed (ms)	804.9 (156.9)	[1,337, 472]	0.84	1.41
	Flanker interference (ms)	41 (23.7)	[100, −12.5]	0.52	0.21
Lexical tasks	LexTALE percent correct	88.7 (9.4)	[100, 66.3]	−1.13	0.45
	LexTALE word RT (ms)	754.3 (125.5)	[1,110, 476]	0.52	0.4
Interrupted speech conditions	RSPIN high silent	48.3 (8.7)	[64, 26]	−0.55	−0.32
	RSPIN high noise	60.1 (9.1)	[77, 31]	−0.97	1.28
	RSPIN low silent	42.4 (5.9)	[57, 30]	0.2	0.01
	RSPIN low noise	50.4 (7.7)	[65, 25]	−0.66	0.84
	PRESTO silent	27.6 (8.3)	[47, 3]	−0.03	0.46
	PRESTO noise	43.1 (8.7)	[57, 21]	−0.3	−0.54

RSPIN, revised speech in noise test; PRESTO, perceptually robust English sentence test open-set; High refers to high context sentences; Low refers to low context sentences; Silent refers to sentences interrupted by a silent gap; and Noise refers to sentences interrupted by a noise burst.

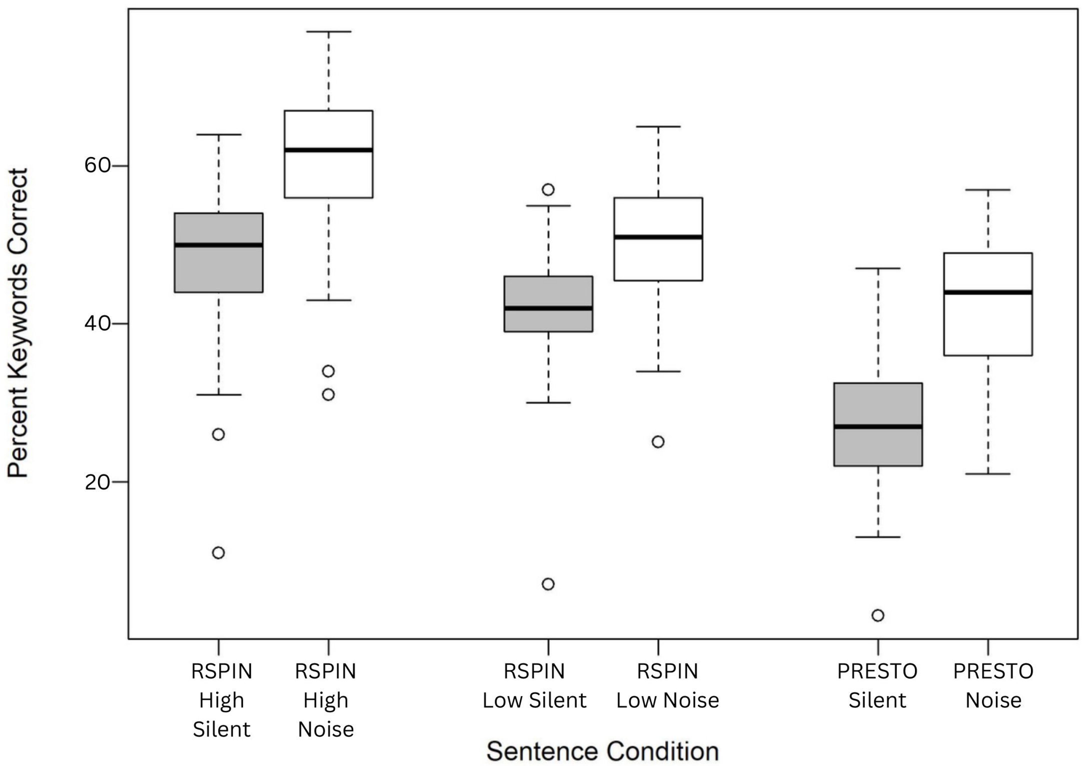

FIGURE 1
Box plot representing perceptual restoration, or the percent of keywords correctly identified for the six sentence conditions.

negative correlation with inhibitory control measured using the Flanker task ($r = -0.28$, $p = 0.02$), which was the only significant correlation with the Flanker task across all measures, making it a weak predictor overall. Lexical processing speed recorded using the LexTALE word reaction time in milliseconds was positively and significantly correlated with inhibitory control measured using the Stroop Interference score ($r = 0.29$, $p = 0.02$) and processing speed measured using the Stroop word-only item reaction time, or processing speed ($r = 0.29$, $p = 0.02$). This result is consistent with both processing speed and the calculation of inhibitory control both relying on reaction time. Working memory measured using the Reading Span Task significantly

TABLE 3 Pearson correlation coefficients across cognitive, linguistic, and interrupted speech measures.

	Measures	1	2	3	4	5	6	7	8	9	10	11	12
	Cognitive measures												
1	RST percent correct	1											
2	DST percentile	**0.28 (0.02)**	1										
3	Stroop interference (ms)	0.005 (0.96)	0.003 (0.98)	1									
4	Stroop processing speed (ms)	−0.15 (0.25)	0.07 (0.55)	−0.07 (0.60)	1								
5	Flanker interference (ms)	**−0.28 (0.025)**	−0.12 (0.38)	0.08 (0.51)	0.13 (0.30)	1							
	Linguistic measures												
6	LexTALE percent correct	0.04 (0.74)	−0.10 (0.43)	−0.19 (0.12)	−0.13 (0.29)	−0.15 (0.21)	1						
7	LexTALE word RT (ms)	−0.22 (0.08)	−0.02 (0.86)	**0.29 (0.02)**	**0.29 (0.02)**	0.08 (0.51)	−0.18 (0.17)	1					
	Interrupted speech measures												
8	RSPIN high silent	**0.38 (0.002)**	−0.03 (0.82)	−0.12 (0.36)	−0.22 (0.08)	−0.11 (0.40)	**0.32 (0.009)**	−0.12 (0.37)	1				
9	RSPIN high noise	**0.40 (0.001)**	−0.05 (0.68)	−0.16 (0.22)	−0.13 (0.32)	−0.01 (0.94)	0.10 (0.39)	−0.18 (0.15)	**0.63 (<0.001)**	1			
10	RSPIN low silent	0.18 (0.16)	−0.1 (0.43)	**−0.27 (0.03)**	**−0.32 (0.01)**	0.001 (0.99)	**0.34 (0.006)**	−0.13 (0.31)	**0.73 (<0.001)**	**0.47 (<0.001)**	1		
11	RSPIN low noise	**0.32 (0.01)**	−0.04 (0.74)	**−0.27 (0.03)**	−0.21 (0.11)	−0.04 (0.74)	0.13 (0.30)	−0.22 (0.08)	**0.62 (<0.001)**	**0.83 (<0.001)**	**0.55 (<0.001)**	1	
12	PRESTO silent	**0.32 (0.01)**	−0.07 (0.59)	−0.06 (0.64)	**−0.38 (0.002)**	−0.08 (0.56)	**0.35 (0.004)**	−0.21 (0.09)	**0.80 (<0.001)**	**0.48 (<0.001)**	**0.80 (<0.001)**	**0.57 (<0.001)**	1
13	PRESTO noise	**0.38 (0.002)**	0.006 (0.96)	**−0.27 (0.03)**	**−0.26 (0.04)**	−0.05 (0.67)	**0.26 (0.03)**	**−0.27 (0.03)**	**0.78 (<0.001)**	**0.79 (<0.0001)**	**0.63 (<0.001)**	**0.79 (<0.001)**	**0.67 (<0.001)**

Correlation strength is followed by statistical significance, and bolded cells are statistically significant without correction for multiple comparisons ($p < 0.05$).

and positively correlated with five of the six sentence conditions. Lexical knowledge measured using the LexTALE percent correct score correlated with four of the six sentence conditions. Both inhibitory control measured using the Stroop interference score and processing speed measured using the Stroop word-only item reaction time correlated with three of the six sentence conditions. After correcting for multiple comparisons using the Bonferroni method for 24 comparisons (six conditions times four measures of interest), reducing the α level to 0.00208, only RST was significantly correlated with RSPIN High Silent ($r = 0.38$, $p = 0.002$), RSPIN High Noise ($r = 0.40$, $p = 0.001$), and PRESTO Noise ($r = 0.38$, $p = 0.002$).

Some measures had few or no correlations with the interrupted sentence conditions. For example, lexical access speed measured using the LexTALE correctly identified word reaction time in milliseconds correlated only with the PRESTO noise-burst interrupted sentence condition. Simple working memory measured using the digit span task and inhibitory control measured using the Flanker task did not correlate with any of the sentence conditions. These latter three variables were considered poor predictors and were excluded from further analysis. Age was significantly correlated with only the PRESTO silent gap interrupted sentence condition ($r = -0.4$, $p = 0.001$) and correlated with only the Stroop processing speed cognitive measure ($r = 0.35$, $p = 0.004$). Age was not significantly correlated with perceptual restoration performance or performance on the cognitive and linguistic measures overall and was excluded from further analysis.

Linear regression analysis was performed using normalized predictors and word recognition percent correct outcome data. Separate models were conducted for each sentence condition. Predictors for the models for the sentence conditions were selected using an *a priori*, hypothesis-driven approach. This approach was informed by the results of **Table 3** to minimize Pearson correlation coefficients between predictors during linear model design (Bursac et al., 2008; Hosmer et al., 2013). Last, *a priori* model design was checked against a quantitative approach to minimize the number of predictors while maximizing numerical stability and ease of interpretation [i.e., purposeful selection (Zhang, 2016)]. This approach removes predictors, one by one, from a full, saturated model when their *p*-values are less than 0.25, unless they are assumed to be related to the hypothesis (Mickey and Greenland, 1989). During this process, predictors such as age, education, the SSQ, DST, and Flanker were not significantly associated with the six interrupted speech conditions and were systematically removed from the model. This method then creates a new, smaller model which can be compared to the saturated model to ensure that the change in coefficients (Δβ) is not greater than 20%, which would indicate that these predictors should be added back into the model given their strong adjustment effect. Last, potential interactions among remaining predictors are checked one-by-one and removed if non-significant before goodness of fit (GOF)

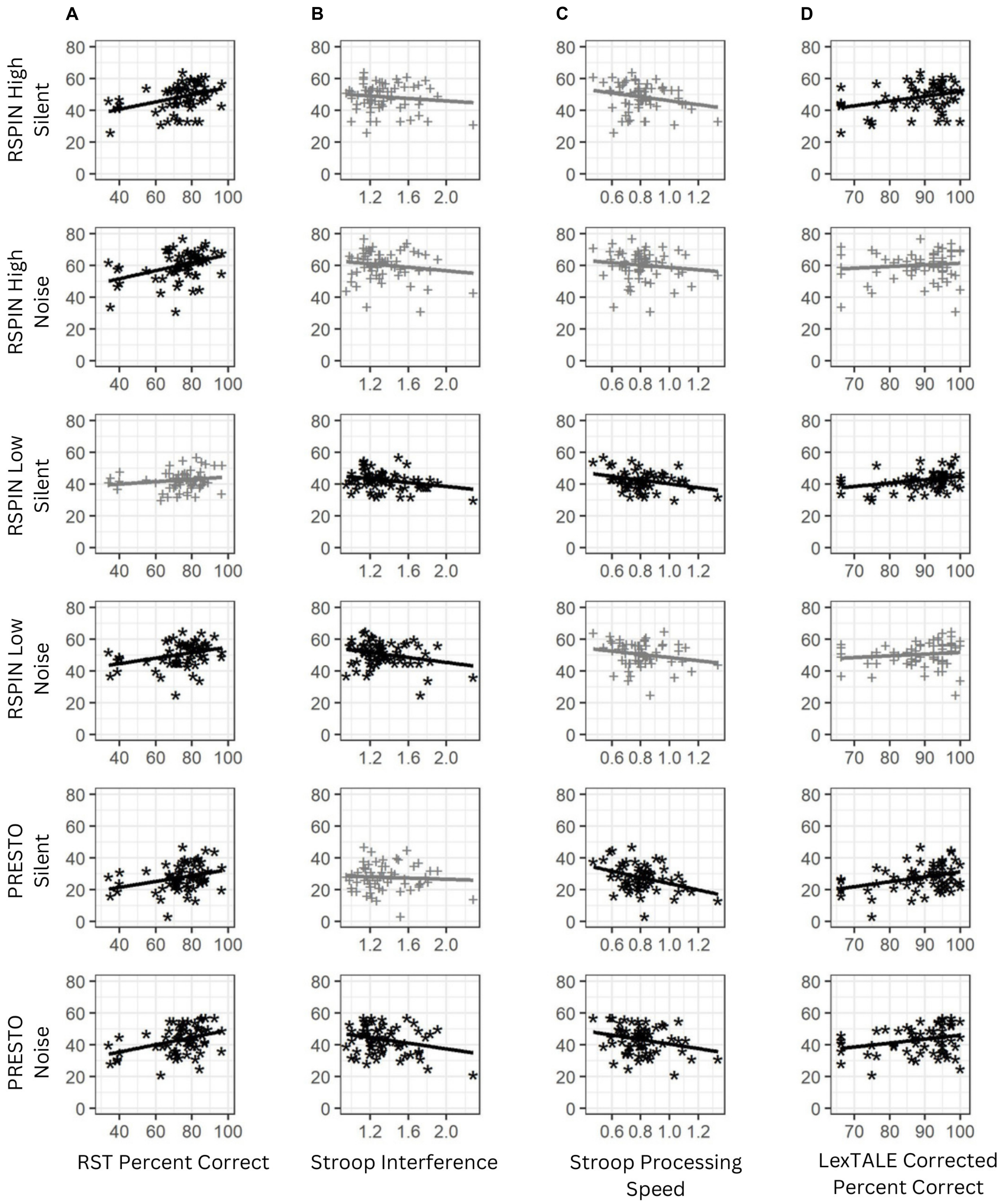

FIGURE 2
Scatter plots of perceptual restoration scores for interrupted speech conditions with working memory capacity measured using the reading span test (RST) **(A)**, inhibitory control measured using the Stroop task **(B)**, processing speed measured using Stroop reaction time **(C)**, and lexical accuracy measured using the LexTALE Percent Correct score **(D)**. Higher scores on RST Percent Correct and LexTALE Percent Correct indicate better performance, while lower scores on Stroop Interference and Stroop Processing Speed indicate better performance. Scatter plots in black with asterisk symbols are statistically significant without correction for multiple comparisons ($p < 0.05$) and scatter plots in gray with plus symbols are not statistically significant. Refer to **Table 3** for correlation strength and statistical significance for each of these measures.

is checked visually using plots of residual values versus fitted values and Q-Q plots. This purposeful selection approach was completed for each sentence condition using the percent of words correctly identified as outcome. This process resulted in an overall standard model with the same four predictors used in each model for ease of interpretation: RST Percent Correct, LexTALE Percent Correct, Stroop Interference, and Stroop Processing Speed. Multicollinearity was deemed acceptable among these predictors with the highest variance inflation factor value being 1.06, very close to the minimum value of 1 and well below 2.5, which may indicate multicollinearity, or 10, which is problematic (Mansfield and Helms, 1982; Vittinghoff et al., 2006; Thompson et al., 2017; Johnston et al., 2018). All six models meet the assumption of homoscedasticity necessary for linear model design using a studentized Breusch-Pagan test (Breusch and Pagan, 1979). Three (RSPIN Low Silent, PRESTO Silent, and PRESTO Noise) models met the assumption that the residuals are normally distributed using a Wilk-Shapiro test of normality, while the remaining three models (RSPIN High Silent, RSPIN High Noise, RSPIN Low Noise) have a non-normal distribution of residuals and should be interpreted with caution.

The overall linear models for all six conditions were statistically significant ($p < 0.05$). All six models are reported without correction for multiple comparisons (see Table 4) as there is not a strong consensus regarding correction when considering multiple separate models. However, a Bonferroni correction for six comparisons reduces the α level to 0.008 and five of the six models remain significant, with only RSPIN High Noise losing significance ($p = 0.01$) Adjusted R^2 values ranged from 13.6 for RSPIN High Noise to 25.5 for PRESTO Silent. Working memory capacity measured using the RST was a significant predictor in five of the six models: RSPIN High Silent ($\beta = 3.01$, $p = 0.004$), RSPIN High Noise ($\beta = 3.51$, $p = 0.002$), RSPIN Low Noise ($\beta = 2.28$, $p = 0.015$), PRESTO Silent ($\beta = 2.16$,

TABLE 4 Linear regression analysis models predicting perceptual restoration by sentence condition.

Condition	Predictors	R^2 (%)/Adjusted R^2 (%)	*F* (*p*-value)	β	Confidence intervals	*T*-score (*p*-value)
RSPIN high silent		**25.8/20.7**	**5.05 (0.001)**			
	RST percent correct			**3.01**	**1.01–5.01**	**3.02 (0.004)**
	Stroop interference			−0.66	−2.69–1.36	−0.66 (0.51)
	Stroop processing speed			−1.21	−3.23–0.81	−1.2 (0.24)
	LexTALE percent correct			**2.40**	**0.36–4.44**	**2.36 (0.022)**
RSPIN high noise		**19.2/13.6**	**3.45 (0.01)**			
	RST percent correct			**3.51**	**1.33–5.69**	**3.22 (0.002)**
	Stroop interference			−1.42	−3.63–0.79	−1.28 (0.2)
	Stroop processing speed			−0.69	−2.90–1.51	−0.63 (0.53)
	LexTALE percent correct			0.47	−1.75–2.69	0.42 (0.67)
RSPIN low silent		**26.3/21.3**	**5.18 (0.001)**			
	RST percent correct			0.76	−0.59–2.12	1.13 (0.26)
	Stroop interference			**−1.45**	**−2.82–−0.08**	**−2.12 (0.04)**
	Stroop processing speed			**−1.67**	**−3.04–−0.30**	**−2.44 (0.02)**
	LexTALE percent correct			**1.47**	**0.09–2.85**	**2.14 (0.04)**
RSPIN low noise		**21/15.5**	**3.84 (0.007)**			
	RST percent correct			**2.28**	**0.46–4.1**	**2.51 (0.015)**
	Stroop interference			**−2.09**	**−3.93–−0.25**	**−2.27 (0.027)**
	Stroop processing speed			−1.35	−3.19–0.5	−1.46 (0.15)
	LexTALE percent correct			0.34	−1.52–2.19	0.36 (0.72)
PRESTO silent		**30.3/25.5**	**6.3 (0.0002)**			
	RST percent correct			**2.16**	**0.33–4.00**	**2.36 (0.02)**
	Stroop interference			−0.18	−2.04–1.68	−0.19 (0.84)
	Stroop processing speed			**−2.48**	**−4.34–−0.62**	**−2.67 (0.01)**
	LexTALE percent correct			**2.48**	**0.61–4.35**	**2.65 (0.01)**
PRESTO noise		**29.8/24.9**	**6.14 (0.0003)**			
	RST percent correct			**2.98**	**1.05–4.92**	**3.09 (0.003)**
	Stroop interference			**−2.17**	**−4.13–−0.21**	**−2.22 (0.03)**
	Stroop processing speed			−1.74	−3.69–0.22	−1.78 (0.08)
	LexTALE percent correct			1.55	−0.42–3.52	1.58 (0.12)

Significant predictor titles are italicized with bolded statistics ($p < 0.05$).

p = 0.02), and PRESTO Noise (β = 2.98, *p* = 0.003). Lexical knowledge measured using the LexTALE task was a significant predictor for restoring missing speech for silent conditions, but not noise conditions: RSPIN High Silent (β = 2.40, *p* = 0.022), RSPIN Low Silent (β = 1.47, *p* = 0.04), and PRESTO Silent (β = 2.48, *p* = 0.01). On the other hand, inhibitory control measured using the Stroop task was a significant predictor for the majority of noise burst conditions and one silent gap condition: RSPIN Low Silent (β = −1.45, *p* = 0.04), RSPIN Low Noise (β = −2.09, *p* = 0.027), and PRESTO Noise (β = −2.17, *p* = 0.03). Finally, processing speed significantly predicted perceptual restoration ability in only two of the six models, but in most of the silent gap conditions: RSPIN Low Silent (β = −1.67, *p* = 0.02), and PRESTO Silent (β = −2.48, *p* = 0.01).

Discussion

The current study was designed to investigate the role of higher-order cognitive and linguistic abilities, such as working memory capacity, lexical knowledge (i.e., vocabulary), lexical access speed, inhibitory control, and processing speed during the perceptual restoration of missing speech information in adults. Of the measures tested, working memory capacity was the most predictive cognitive ability and lexical knowledge was the most predictive linguistic ability during the restoration of missing speech information. The strength of contribution depended on the type of interruption and on sentence material. In the silent gap conditions, a larger set of cognitive and linguistic abilities predicted the restoration of missing speech information. In the noise burst conditions, only working memory capacity and inhibitory control predicted perceptual restoration ability. For high context sentences, working memory capacity and linguistic knowledge predicted the restoration of missing speech, whereas, in the low context and everyday speech conditions, a larger set of cognitive and linguistic abilities predicted perceptual restoration.

Perceptual restoration of missing speech by interruption type and sentence type

In line with previous research, listeners restored more missing speech when sentences were interrupted with noise bursts rather than silent gaps, regardless of sentence type (Miller and Licklider, 1950; Warren, 1970; Powers and Wilcox, 1977; Bashford et al., 1992; Bologna et al., 2019). This result is thought to occur because of gestalt properties of perceptual organization supporting the percept of continuous speech occurring behind the noise bursts, as long as the noise burst itself would be considered an effective masker of the target signal (Warren and Obusek, 1971; Bashford et al., 1992). The noise bursts may also mask the accidental perception of word boundary that might occur during silent gap interrupted sentences. This occurs when a word is interrupted by a silent gap and that same silent gap is misinterpreted as the end of a word, resulting in the percept of a non-word. However, the noise burst may override this challenging effect by creating illusory continuity and improving degraded speech recognition (Clarke et al., 2016).

Listeners were also able to benefit from sentence context, attaining better scores for RSPIN High sentences when compared to RSPIN Low sentences, a result that is in line with existing perceptual restoration literature (Bashford and Warren, 1987; Bashford et al., 1992; Kidd and Humes, 2012). However, the benefit of context may be limited by the constraints of the RSPIN sentences themselves. Originally, the RSPIN sentences were designed so that only the last word of each sentence would be scored as either correct or incorrect (Bilger et al., 1984). In our data the entire sentence was periodically interrupted and participant performance was scored across all key words in the sentence. Scoring only the last word may reduce individual differences in the ability to compensate across an entire sentence, because sentence context effects take place across an entire sentence (Stanovich and West, 1983; Kutas et al., 2019), the effect builds over time when sentences are predictable (Brothers and Kuperberg, 2021), and high predictability increases the benefit from glimpses of target speech across an entire sentence (Schoof and Rosen, 2015). However, it should be noted that the RSPIN High Silent, RSPIN High Noise, and RSPIN Low Noise sentences had a non-normal distribution of residuals in the current data set and thus these results should be interpreted with caution and RSPIN High Noise did not survive a Bonferroni correction for multiple comparisons.

The highest variability across listeners and poorest performance occurred for PRESTO sentences. This increase in variability and decrease in performance may have occurred for several reasons. First, the PRESTO sentences were designed to incorporate multiple factors during speech recognition: talker characteristics, dialect, and the role of higher order processes. The PRESTO sentences also vary in length and syntactic complexity. Taken together, these factors make PRESTO sentences less constrained than the RSPIN sentences and, thus, more representative of everyday speech (Cole et al., 2010). Second, the PRESTO sentences used here contain 455 unique words, which exceeds both the RSPIN High (421 words) and RSPIN Low (218 words) conditions. Therefore, the variability in the results may follow simply from the increased variability in the number of unique words in the PRESTO sentence set. Third, many of the key words in the PRESTO sentence set are longer and contain additional syllables (average of 7.96 syllables per sentence for PRESTO sentences compared to 6.14 syllables per sentence for the RSPIN High and 6.29 for the RSPIN Low context sentence sets). While the silent gap and noise burst interruptions in the current experiment were designed to be shorter than the average syllabus nuclei duration in American English (Peterson and Lehiste, 1960), minimizing the obliteration of syllables entirely (Miller and Licklider, 1950), additional syllables in a key word may provide listeners with multiple glimpses at one word, which may improve or support perceptual restoration ability. This wider range of syllabic structure may contribute to the increased variability in the PRESTO sentences compared to the RSPIN sentences.

The role of working memory capacity in perceptual restoration

Working memory capacity measured using the Reading Span Task was significantly correlated with or acted as a significant predictor for interrupted speech recognition in five of the six sentence conditions. The significance of working memory capacity is in line with some previous literature for noise burst interrupted sentences using low-context, QuickSIN stimuli and a similar interruption paradigm, indicating the importance of working memory capacity for noise burst sentences (Millman and Mattys, 2017; Nagaraj and Magimairaj, 2017). However, previous literature has also found that working memory capacity does not play a role during perceptual restoration of PRESTO sentences using a very similar interruption process (Bologna et al., 2018). Bologna and colleagues used a zero signal-to-noise ratio (SNR) for the noise burst stimuli so that the speech was the same overall intensity as the noise bursts. This design may reduce the percept of speech continuity behind the noise burst, which may impede or interfere with the reprocessing role of working memory capacity during perceptual restoration, making the task more difficult than a noise burst condition with a negative SNR as in the current study. This would fall in line with existing literature that indicates few significant correlations between working memory capacity and silent gap interrupted sentences (Nagaraj and Knapp, 2015; Shafiro et al., 2015; Jaekel et al., 2018). A unique aspect of the current study is the wider range of participant age compared to most existing data, which tested only younger participants (Nagaraj and Knapp, 2015; Nagaraj and Magimairaj, 2017) or utilized group comparisons between older and younger adults, largely missing middle-aged listeners (Shafiro et al., 2015; Millman and Mattys, 2017; Bologna et al., 2018; Jaekel et al., 2018). Given the changing role that working memory capacity plays with increasing age (Wingfield et al., 1988), its effect on language comprehension (Caplan and Waters, 2005), and its possible task dependent nature (Turner and Engle, 1989), this may explain why the current data set found significant working memory capacity correlations for the majority of difficult silent gap conditions.

Lexical knowledge, lexical access speed, and perceptual restoration

The current data add to the evidence that lexical knowledge is important during perceptual restoration (Benard et al., 2014; Nagaraj and Magimairaj, 2017; Bologna et al., 2018; Jaekel et al., 2018). Under the ELU model, lexical knowledge is thought to support explicit working memory reprocessing within the episodic buffer (Rönnberg et al., 2013). This explicit reprocessing identifies likely and unlikely lexical candidates for the missing speech segments and attempts to reconcile segments into a cohesive, logical whole across the entire utterance (Bashford et al., 1992; Zhang and Samuel, 2018). In this way, the most lexically and contextually appropriate candidate can then be chosen by comparing options at the sentence level rather than just the gap level, thereby improving perceptual restoration across the entire utterance (Bashford and Warren, 1987).

For the silent gap interrupted conditions where lexical knowledge was strongly predictive, it is feasible that for listeners with greater lexical knowledge that a larger set of possible lexical candidates might be identified in the silent gap conditions than for listeners with poorer vocabularies. For the noise burst sentences where lexical knowledge was less predictive, it is possible that the noise burst itself may create enough illusory perceptual continuity that the correct lexical candidate can be more easily identified for all listeners, regardless of vocabulary size (Bashford et al., 1996). Alternatively, listeners with greater lexical knowledge may be less susceptible to misidentification of word boundaries in the silent gap conditions, making them better able to activate appropriate lexical candidates despite incomplete lexical neighborhood activation (Clarke et al., 2016). This alternative hypothesis follows the Neighborhood Activation Model, which suggests that listeners with greater lexical knowledge, even without priming, are better able to activate lexical neighborhoods with incomplete information, and that this effect is only detectable in the silent gap interrupted conditions because the noise burst sentences facilitate enough lexical neighborhood activation for all listeners (Luce and Pisoni, 1998; Luce et al., 2000).

To date, no known data have been reported on the relationship between lexical access speed, or the rate at which lexical candidates are identified and selected, and perceptual restoration. The current data do not support a significant role of lexical access speed. The lack of results for lexical access speed may stem from the LexTALE task itself, which was not designed to assess lexical access speed but rather to assess English language proficiency for English second language learners (Lemhöfer and Broersma, 2012), though it does have predictive value as a rapid task of proficiency assessment in English first language learners (Lorette and Dewaele, 2015). Although a computerized assessment does allow for the capture of reaction time for real words, non-words, and correct and incorrect items, the upper time limit of 2,000 ms may artificially limit lexical access speed. Future studies of perceptual restoration and lexical access speed should include measures designed to capture this time-sensitive measure.

Inhibitory control, processing speed, and perceptual restoration

Inhibitory control was significantly correlated with and acted as a significant model predictor for three of the six sentence conditions: RSPIN Low Silent, RSPIN Low Noise, and PRESTO Noise. These results contrast those by Bologna et al. (2018), who found that inhibitory control did not significantly improve model fit for perceptual restoration in either silent gap or noise burst sentences. One possibility for the discrepancy between the current data and the results from Bologna et al. (2018) is the administration of the Stroop task. In the current data, the Stroop task was administered using an online platform, and listeners were asked to press a corresponding color key (e.g., "g" for green) when responding and do so as rapidly as possible. Remembering key location, key correspondence, and the motor control necessary to complete the task may have engaged working memory beyond what occurs during the process of responding verbally in the traditional administration of the Stroop task. Our Stoop task was correlated with and a significant predictor for most of the noise burst sentence conditions. This may indicate that inhibitory control plays an active role in inhibiting the irrelevant noise bursts when reprocessing speech fragments during perceptual restoration, and that listeners who are better able to inhibit the noise bursts are better able to focus on cognitive tasks that restore missing speech. However, RSPIN High Noise and RSPIN Low Noise conditions had a non-normal residuals distribution and this result should be interpreted with caution and RSPIN High Noise did not survive a Bonferroni correction for multiple comparisons.

Potential limitations of this experiment include the inability to measure audiometric thresholds from participants in this study, relying on self-report measures of "normal hearing." Because auditory thresholds decline with increasing age (Gates and Mills, 2005; Huang and Tang, 2010) it is possible that hearing acuity may have had an unmeasured impact on the results, despite the lack of significant correlations with both age and SSQ on cognitive/linguistic data and restoration of missing speech. Next, it should be noted that the cognitive/linguistic measures in this study were all in the visual modality while the outcome measures of interest were in the auditory modality. While many of the cognitive and linguistic measures included in this study are often thought of as domain-general (i.e., they are not modality specific), there is evidence that modality differences may affect how signals are processed cortically (Salthouse and Meinz, 1995; Crottaz-Herbette et al., 2004; Roberts and Hall, 2008) which may influence these results. Furthermore, the scoring method chosen for cognitive/linguistic measures can often yield different results and the results from this study should be compared only to other measures administered in a similar fashion (Knight and Heinrich, 2017). Last, because the noise burst conditions are generally perceived as being less difficult than the silent gap conditions and the sentence types (e.g., RSPIN High, RSPIN Low, and PRESTO) differ from one another with regard to sentence and word length, these conditions may differ from one another with regard to overall task difficulty which can affect overall response accuracy (Robinson, 2001).

In the current experiment, processing speed, or the rate at which cognitive tasks are completed, was significantly correlated with RSPIN Low Silent, PRESTO Silent, and PRESTO Noise conditions and acted as a significant predictor in the RSPIN Low Silent and PRESTO Silent conditions. These results are similar to those found by Bologna et al. (2018) who found that interrupted key word recognition improved with faster processing speed when measured using the connections line making test (Salthouse, 2000). Given that processing speed was significant in two of three silent gap conditions, it is possible that these conditions are more difficult compared to the noise burst conditions and listeners who are able to reprocess and reanalyze the information more rapidly might be better able to restore missing speech information.

Conclusion

In this study, we hypothesized that higher-order cognitive and linguistic abilities would facilitate the restoration of missing speech information using the ELU model framework (Rönnberg et al., 2013). The interrupted speech paradigm was utilized to explore this hypothesis, which in this case removed 50% of the speech signal in order to encourage participants to explicitly reprocess and reanalyze the incomplete speech signal. We predicted that listeners with stronger cognitive and linguistic abilities measured using validated cognitive measures would restore more missing speech information than those with weaker cognitive and linguistic abilities. Working memory capacity and lexical knowledge (i.e., vocabulary) played the most consistent and unique role in perceptual restoration across the sentence conditions, followed by inhibitory control and processing speed. In general, silent gap conditions appeared to be related to a broader range of cognitive and linguistic abilities whereas noise burst conditions were predicted by and correlated with working memory capacity and inhibitory control. Furthermore, sentences that had limited context cues and lacked predictability or were more like those encountered in everyday listening were significantly correlated with and predicted by a wider range of cognitive and linguistic abilities than those that contained additional context cues and had higher levels of predictability. The differences between silent gap and noise burst conditions as well as the context, predictability, and everyday speech conditions may be related to task-dependent difficulties that recruit different constellations of cognitive and linguistic abilities to facilitate the restoration of missing speech information. In sum, perceptual restoration of speech is a complex process that relies on an individual's ability to store and reprocess, to identify potential lexical candidates, to inhibit irrelevant information, to contextually consider several options simultaneously, and to complete these cognitive tasks rapidly, and listeners vary considerably in these abilities (Carroll and Maxwell, 1979; Reuter-Lorenz et al., 2000; Cabeza et al., 2002; George et al., 2007; Rudner et al., 2008; Boogert et al., 2018).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Northwestern University Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

Author contributions

Both authors contributed to study design, data collection, management, analysis, and manuscript preparation and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Associations of audiometric hearing and speech-in-noise performance with cognitive decline among older adults: The Baltimore Longitudinal Study of Aging (BLSA)

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Background: Established associations between hearing loss and cognitive decline were primarily defined by pure-tone audiometry, which reflects peripheral hearing ability. Speech-in-noise performance, which reflects central hearing ability, is more limited in prior literature. We examined the longitudinal associations of audiometric hearing and speech-in-noise performance with cognitive decline.

Methods: We studied 702 participants aged ≥60 years in the Baltimore Longitudinal Study of Aging 2012–2019. Global and domain-specific (language, memory, attention, executive function, visuospatial ability) cognitive performance were assessed by the cognitive assessment battery. Hearing thresholds at 0.5, 1, 2, and 4 kilohertz obtained from pure-tone audiometry were averaged to calculate better-ear pure-tone average (PTA) and participants were categorized as having hearing loss (>25 decibels hearing level [dB HL]) or normal hearing (≤25 dB HL). Speech-in-noise performance was assessed by the Quick Speech-in-Noise (QuickSIN) test, and participants were categorized as having below-median (worse) or above-median performance. Linear mixed effects models with random intercepts and slopes were used to assess baseline cognitive performance and cognitive decline by hearing status. Models adjusted for demographic, lifestyle and disease factors.

Results: Participants with audiometric hearing loss showed similar baseline cognitive performance but faster decline in global cognitive function, language, executive function, and attention. Participants with below-median QuickSIN score showed worse baseline cognitive performance in all domains and faster decline in global cognitive function, language, memory, executive function and attention.

Conclusions: Audiometric hearing might be targeted to delay cognitive decline. Speech-in-noise performance might be a novel marker and might be more sensitive to memory decline.

KEYWORDS

aging, hearing loss, audiometry, speech perception, cognition

Introduction

Approximately 6.2 million U.S. older adults currently live with Alzheimer's disease and related dementias and this number is expected to rise with population aging (1). Living with cognitive impairment poses challenges for older adults, their families, and societies. Despite the complexity of underlying pathologies and the unmodifiable nature of certain pivotal dementia risk factors like age, emerging evidence indicates that many modifiable factors, including hearing loss, are important in the prevention of dementia (2).

Hearing loss, as defined by pure-tone audiometry, is common among older adults: its prevalence increases from 45% among adults in their 60s to nearly 90% among adults 80 years and older (3). Audiometric hearing loss has been identified as the largest potentially modifiable risk factor for dementia, accounting for up to 8% of dementia cases (2). Previous studies have reported both cross-sectional associations between hearing loss and poorer cognitive performance (4, 5) and longitudinal associations between hearing loss and accelerated cognitive decline among U.S. older adults (6–9). Plausible mechanisms have been proposed linking hearing loss and cognitive decline, including increased cognitive processing effort, structural and functional changes in the brain, and social isolation (10). However, studies in population-based cohorts with pure-tone audiometry and longer follow-up periods are needed to further clarify the associations and understand how cognitive domains might be differentially affected.

Although pure-tone audiometry is the gold standard for hearing evaluation that has long been used for defining hearing loss, pure-tone audiometry is primarily a measure of peripheral auditory function, reflective of the initial encoding of auditory signals. Other hearing evaluations like speech-in-noise tests, which characterize central auditory function (the decoding of auditory signals), instead rely on higher-level cognitive processing. Difficulties understanding speech in the presence of noise are common among older adults and significantly impact daily living. Cognitive functions like working memory and attention have been related to speech-in-noise performance (11), suggesting that speech-in-noise performance might be a marker for cognitive deficits. However, prior evidence investigating speech-in-noise performance and cognitive decline in large population-based cohorts is limited (12, 13).

To bridge the gaps in longitudinal evidence that examines and compares the impacts of peripheral and central aspects of hearing on cognition in well-established aging cohorts, this study aims to investigate associations of both audiometric hearing and speech-in-noise performance with global and domain-specific (language, memory, attention, executive function, visuospatial ability) cognitive decline over follow-up among adults aged 60 years and older using data from the Baltimore Longitudinal Study of Aging (BLSA). We hypothesize that worse audiometric hearing and speech-in-noise performance are both associated with accelerated rates of cognitive decline.

Materials and methods

Study population

The Baltimore Longitudinal Study of Aging (BLSA) is an ongoing cohort study of aging conducted by the National Institute on Aging since 1958. BLSA enrolls community-dwelling healthy U.S. adults aged 20 years and older continuously. Enrolled participants are followed for life. Participants undergo comprehensive health assessments during study visits every 1–4 years depending on age (20–59 years: every 4 years; 60–79 years: every 2 years; ≥80 years: every year). Details of the BLSA design have been published previously (14, 15). Written informed consent was obtained from all participants and the Institutional Review Board of the Intramural Research Program approved the study protocol.

Hearing evaluations were performed in the BLSA from 2012 onwards. This study included BLSA participants aged 60 years and older with hearing and cognitive measures between 2012 and 2019. We identified 738 participants aged 60 years or older with complete data on pure-tone audiometry and speech-in-noise performance at ≥1 study visit and defined their first visit as the baseline in this analysis. We further excluded 3 participants

TABLE 1 Description of the cognitive tests in the Baltimore Longitudinal Study of Aging 2012–2019.

Domain	Cognitive test	Interpretation
Language	Letter fluency test	Number of words generated in 60 s
	Category fluency test	Number of words generated in 60 s
	Boston naming test	Number of pictures identified
Memory	California verbal learning test immediate recall	Number of words recalled
	California verbal learning test long-delay recall	Number of words recalled
Attention	Trail making test part A	Time to completion (seconds)
	Digit span forward test	Maximum length of digits recalled
Executive function	Trail making test part B	Time to completion (seconds)
	Digit span backward test	Maximum length of digits recalled
	Digit symbol substitution test	Number of symbol/digit pairs completed in 90 s
Visuospatial ability	Card rotations test	Number classified correctly—number classified incorrectly
	Benton visual retention test	Number of errors

missing all cognitive assessments and 33 participants with missing data on covariates, leaving a final analytical sample of 702 participants.

Cognitive performance

Global and domain-specific cognitive performance, as our outcomes of interest, were assessed by a battery of neurocognitive tests at each study visit between 2012 and 2019. Descriptions of the cognitive tests are presented in Table 1. A total of five cognitive domains were constructed using factor analysis methods:

(1) Language was represented by Letter Fluency Test (16), Category Fluency Test (16), and Boston Naming Test (17);
(2) Memory was represented by immediate and long-delay free recall from the California Verbal Learning Test (18);
(3) Attention was represented by Trail Making Test Part A (19) and Digit Span Forward Test (20);
(4) Executive function was represented by Trail Making Test Part B (19), Digit Span Backward Test (20), and Digit Symbol Substitution Test (21);
(5) Visuospatial ability was represented by Card Rotations Test (22) and Benton Visual Retention Test (23).

Global cognitive performance was represented by all the tests mentioned above. Scores from Benton Visual Retention Test and Trail Making Test Parts A and B were reversed (multiply by −1) so that higher scores for all the cognitive tests reflect better performance. Individual cognitive tests were standardized by converting to Z scores using the baseline mean and standard deviation (SD) for comparison across tests. Corresponding standardized test scores in each cognitive domain were then used to derive global and domain-specific cognitive factor scores using structural equation modeling for confirmatory factor analysis, where observed covariation in the manifest variables (cognitive test scores) was explained by the latent variables (cognitive factor scores) (24, 25).

Global cognitive factor score served as our primary outcome of interest and five domain-specific cognitive factor scores (language, memory, attention, executive function, visuospatial ability) served as our secondary outcomes of interest.

Hearing measures

Pure-tone audiometry, as our measure of peripheral auditory function, was conducted using Interacoustics AD629 audiometer with ER3A insert earphones in a sound-attenuating booth according to best-practice procedures (26). Participants were presented with pure-tone signals at frequencies between 0.5 and 8 kilohertz (kHz) and were instructed to raise hands when they heard the signal. The intensities of the signals were decreased until the participants no longer responded to determine the quietest sound participants indicated they heard the signal (hearing threshold) at each frequency. Air-conduction hearing thresholds in each ear were obtained and expressed in decibels hearing level (dB HL). Pure-tone average (PTA) was calculated by averaging hearing thresholds at 0.5, 1, 2, and 4 kHz for each ear, higher PTA indicates worse audiometric hearing. PTA in the better-hearing ear was analyzed continuously (per 10 dB HL worse) and categorically comparing participants having hearing loss (PTA $>$25 dB HL) to those with normal hearing ($\leq$25 dB HL) according to common clinical cut-points (27).

The Quick Speech-in-Noise (QuickSIN) test assesses participants' ability to understand speech in the presence of background noise (28). Participants were presented with two lists of six sentences at a fixed presentation level (70 dB HL) first in quiet and then under successively higher levels of background noise. Participants were instructed to repeat as much of the sentences as they could. Each sentence has five target words and the scoring of the test is based on the correct identification of target words. Scores of two lists were averaged to represent mean number of target words correctly identified, ranging from 0 to 30. These raw QuickSIN scores (higher = better performance) were used directly for analysis instead of converting to signal-to-noise ratio (SNR) loss as in clinical settings, which lacks age-specific norms for performance and interpretability in statistical analysis. QuickSIN score was analyzed continuously as per 5-point worse and categorically (below vs. above median) based on statistical distribution in our study population.

Other covariates

Demographic information was collected *via* self-report, including age (continuous in years), sex (Male; Female), race (White; Black; Other [Combining American Indian or Alaska Native, Chinese, Filipino, Japanese, Other Asian or Pacific Islander, Other non-White, and Not classifiable]) and years of education. Education was categorized as high school or less (≤12 years), any college (12–16 years) and beyond college (>16 years). Self-reported smoking status was collected as current, former and never and was combined as ever/never smoker for analysis due to the small number of participants identified as current smokers. Body mass index (BMI) was calculated from measured height and weight and was analyzed continuously in kg/m^2. Hypertensive status was defined based on measured systolic blood pressure (SBP) and diastolic blood pressure (DBP): Hypertension was considered present if SBP was ≥140 mmHg or DBP ≥90 mmHg; Prehypertension was considered present if SBP was between 120 and 139 mmHg or DBP was between 80 and 89 mmHg (29). Diabetes was defined as glycated hemoglobin (HbA1c) ≥6.5%. Elevated cholesterol was defined as having total cholesterol ≥200 mg/dL (30). The 20-item Center for Epidemiological Studies-Depression Scale (CES-D) was used to assess depressive symptoms. Participants were asked to report the frequency of each symptom (0: Rarely or none of the time; 1: Some or little of the time; 2: Moderately or much of the time; and 3: Most or almost all the time) and responses were summed to yield total CES-D score (31). Total scores range from 0 to 60 and higher scores indicate greater level of depressive symptoms. All the covariates were defined at the baseline visit.

Statistical analysis

Baseline characteristics of the participants were summarized and compared by hearing status (Better-ear PTA >25 vs. ≤25 dB HL and QuickSIN score below vs. above median) using ANOVA for continuous variables and Pearson's chi-squared test for categorical variables.

Linear mixed effects models with random intercepts, random slopes, unstructured covariance matrix and robust standard errors were fitted to estimate the longitudinal associations between hearing status at baseline and longitudinal trajectories of cognitive performance. To test whether rates of change in cognitive performance vary by baseline hearing status, models included an interaction term between time since baseline and hearing status. Model assumptions were checked using residual diagnostic plots. For each cognitive factor score (global, language, memory, attention, executive function, visuospatial ability), which is the outcome of interest, we fit separate models for each hearing measure (Better-ear PTA; QuickSIN score) as the main exposure of interest. Non-linear trajectories of cognitive performance were explored by graphical representation and were found for QuickSIN score. We therefore included a liner spline term with a knot at 20 points, which assumes different linear relationships between QuickSIN score and cognitive performance among those with QuickSIN score <20 vs. ≥20 points.

To explore interactions of hearing status with demographic characteristics predicting cognitive decline, 3-way interaction terms (time since baseline × hearing status × age/sex/race) were included in the models to test whether the longitudinal associations between hearing and cognitive performance vary by demographic characteristics. For exploration of interactions, age was categorized as >75 vs. ≤75 years, race was categorized as White vs. Black (excludes 46 participants in other categories), and sex was still analyzed as males vs. females.

Models with better-ear PTA as the main exposure were adjusted for age, sex, race, education, smoking, body mass index, hypertension, diabetes, elevated cholesterol, and depressive symptoms. Models with QuickSIN score as the main exposure were additionally adjusted for better-ear PTA since speech perception in noise depends on the integrity of the auditory signals from the peripheral auditory system.

Analyses were conducted using Stata, version 15.1 (StataCorp LLC, College Station, Texas). A two-sided *P*-value <0.05 was considered statistically significant.

Results

Characteristics of the participants

A total of 702 participants (Baseline mean age: 75 years; 45% male; 68% White) were included in our study. Participants were followed for a mean of 3.5 years (Range: 0–7 years) over a mean number of 3 visits (Range: 1–7). Among 702 participants, 258 (37%) had normal audiometric hearing (Better-ear PTA ≤25 dB HL) and above-median (>23) QuickSIN score, 292 (42%) had both audiometric hearing loss (Better-ear PTA >25 dB HL) and below-median (≤23) QuickSIN score, 65 (9%) had normal audiometric hearing but below-median QuickSIN score,

TABLE 2 Baseline characteristics of participants by audiometric hearing in the Baltimore Longitudinal Study of Aging 2012–2019.

	Total $N = 702$	Better-ear pure-tone average[a]		P-value[b]
		Normal hearing $N = 323$	Hearing loss $N = 379$	
	N (%)	N (%)	N (%)	
Male	317 (45.2)	113 (35.0)	204 (53.8)	<0.001
Race				<0.001
White	474 (67.5)	179 (55.4)	295 (77.8)	
Black	182 (25.9)	120 (37.2)	62 (16.4)	
Other	46 (6.6)	24 (7.4)	22 (5.8)	
Education				0.47
High school or less	50 (7.1)	19 (5.9)	31 (8.2)	
Any college	259 (36.9)	123 (38.1)	136 (35.9)	
Beyond college	393 (56.0)	181 (56.0)	212 (55.9)	
Ever smoker	285 (40.6)	120 (37.2)	165 (43.5)	0.09
Hypertension				0.30
Normal	415 (59.1)	201 (62.2)	214 (56.5)	
Prehypertension	230 (32.8)	98 (30.3)	132 (34.8)	
Hypertension	57 (8.1)	24 (7.4)	33 (8.7)	
Diabetes	98 (14.0)	51 (15.8)	47 (12.4)	0.20
Elevated cholesterol	202 (28.8)	103 (31.9)	99 (26.1)	0.09
	Mean (SD)	Mean (SD)	Mean (SD)	
Age (years)	75.1 (8.3)	70.7 (6.7)	78.7 (7.8)	<0.001
Body mass index (kg/m^2)	27.3 (4.7)	28.0 (5.0)	26.6 (4.2)	<0.001
CES-D score	4.7 (4.9)	4.6 (4.6)	4.8 (5.1)	0.60
Number of visits	3.0 (1.4)	2.7 (1.1)	3.2 (1.5)	<0.001

SD, standard deviation; CES-D, Center for Epidemiologic Studies Depression Scale.

[a]Better-ear pure-tone average was calculated using hearing thresholds at 0.5, 1, 2, and 4 kilohertz obtained from pure-tone audiometry. Participants were categorized as having hearing loss (>25 decibels hearing level [dB HL]) or normal hearing (≤25 dB HL).

[b]P-values were calculated by ANOVA for continuous variables and Pearson chi-squared test for categorical variables.

and 87 (12%) had audiometric hearing loss but above-median QuickSIN score. 697 of 702 participants had data on hearing aid use and 117 of them had any hearing aid use (6 with normal audiometric hearing and 111 with audiometric hearing loss).

Baseline characteristics of participants by audiometric hearing are presented in Table 2. 379 (54%) participants had audiometric hearing loss and 323 (46%) had normal hearing. When compared to participants with normal hearing, participants with audiometric hearing loss were older (Mean age: 79 vs. 71 years), more likely to be male (54 vs. 35%) and White (78 vs. 55%) and had lower BMI (Mean: 27 vs. 28 kg/m^2). We also compared baseline characteristics of participants with QuickSIN score below median (worse performance) to those with QuickSIN score above median (Table 3). Participants with QuickSIN score below median were older (Mean age: 79 vs. 71 years), more likely to be male (54 vs. 37%) and White (69 vs. 66%), were less educated (≤High School: 10 vs. 5%), had lower BMI (Mean: 27 vs. 28 kg/m^2) and greater level of depressive symptoms (Mean CES-D: 5 vs. 4).

Associations with audiometric hearing

Baseline cognitive performance comparing participants with audiometric hearing loss to participants with normal audiometric hearing did not differ significantly. However, participants with audiometric hearing loss had faster annual rates of decline in global (Estimate = −0.09 SD, 95% confidence interval [CI]: −0.11, −0.06), language (Estimate = −0.04 SD, 95% CI: −0.06, −0.02), executive function (Estimate = −0.04 SD, 95% CI: −0.07, −0.02) and attention (Estimate = −0.04 SD, 95% CI: −0.07, −0.02) cognitive factor scores when compared to participants with normal hearing (Table 4). Neither group of participants had significant declines in memory domain during

TABLE 3 Baseline characteristics of participants by speech-in-noise performance in the Baltimore Longitudinal Study of Aging 2012–2019.

	Total $N = 702$	Speech-in-noise performance[a]		*P*-value[b]
		Above median $N = 345$	Below median $N = 357$	
	N (%)	*N* (%)	*N* (%)	
Male	317 (45.2)	126 (36.5)	191 (53.5)	<0.001
Race				<0.001
White	474 (67.5)	228 (66.1)	246 (68.9)	
Black	182 (25.9)	105 (30.4)	77 (21.6)	
Other	46 (6.6)	12 (3.5)	34 (9.5)	
Education				0.04
High school or less	50 (7.1)	16 (4.6)	34 (9.5)	
Any college	259 (36.9)	129 (37.4)	130 (36.4)	
Beyond college	393 (56.0)	200 (58.0)	193 (54.1)	
Ever smoker	285 (40.6)	140 (40.6)	145 (40.6)	0.99
Hypertension				0.55
Normal	415 (59.1)	211 (61.2)	204 (57.1)	
Prehypertension	230 (32.8)	108 (31.3)	122 (34.2)	
Hypertension	57 (8.1)	26 (7.5)	31 (8.7)	
Diabetes	98 (14.0)	55 (15.9)	43 (12.0)	0.14
Elevated cholesterol	202 (28.8)	101 (29.3)	101 (28.3)	0.77
	Mean (SD)	**Mean (SD)**	**Mean (SD)**	
Age (years)	75.1 (8.3)	70.7 (6.6)	79.2 (7.6)	<0.001
Body mass index (kg/m^2)	27.3 (4.7)	27.6 (4.8)	26.9 (4.5)	0.04
CES-D score	4.7 (4.9)	4.2 (4.3)	5.2 (5.3)	0.003
Number of visits	3.0 (1.4)	2.7 (1.1)	3.2 (1.5)	<0.001

SD, standard deviation; CES-D, Center for Epidemiologic Studies Depression Scale.
[a]Total score of the Quick Speech-in-Noise test ranges from 0 to 30. Lower score indicates worse speech-in-noise performance. The continuous score was categorized as below (≤23) vs. above median (>23).
[b]P-values were calculated by ANOVA for continuous variables and Pearson chi-squared test for categorical variables.

follow-up, and no differences in annual rates of decline were observed. Participants in both groups demonstrated significant decline in visuospatial ability, but no differences in rates of decline were found. When PTA was modeled continuously as per 10 dB HL worse, similar results were found.

Associations with speech-in-noise performance

Participants with QuickSIN scores below the median (worse) showed significantly lower cognitive factor scores at baseline across all domains when compared to participants with QuickSIN scores above the median (Table 5). Participants with QuickSIN scores below the median had faster annual rates of cognitive decline (Global: Estimate = −0.08 SD, 95% CI: −0.11, −0.06; Language: Estimate = −0.03 SD, 95% CI: −0.05, −0.01; Memory: Estimate = −0.03 SD, 95% CI: −0.05, −0.00; Executive function: Estimate = −0.04 SD, 95% CI: −0.06, −0.01; Attention: Estimate = −0.04 SD, 95% CI: −0.06, −0.02). For visuospatial ability, both groups had significant decline during follow-up, but the difference in annual rates of change was not significant. When QuickSIN score was modeled continuously as per 5-point worse, no differences in annual rates of decline were found across all the domains when QuickSIN score is below 20. Significant differences in rates of decline when QuickSIN score is above 20 were similarly observed in global (Estimate = −0.09 SD, 95% CI: −0.13, −0.04), memory (Estimate = −0.04 SD, 95% CI: −0.07, −0.00), executive function (Estimate = −0.04 SD, 95% CI: −0.08, −0.00) and attention (Estimate = −0.04 SD, 95% CI: −0.08, −0.01), while the language domain (Estimate = −0.02 SD, 95% CI: −0.05, 0.00) showed borderline significance (Table 5).

TABLE 4 Multivariable-adjusted associations[a] of audiometric hearing with cognitive performance in the Baltimore Longitudinal Study of Aging 2012–2019 ($N = 702$).

Cognitive factor score[b]	Baseline differences: >25 vs. ≤25 dB HL	Annual rate of change			
		≤25 dB HL (Ref.)	>25 dB HL	Differences: >25 vs. ≤25 dB HL	Differences: Per 10 dB HL Worse
Global	−0.03	**−0.04**	**−0.13**	**−0.09**	**−0.03**
	(−0.16, 0.10)	**(−0.05, −0.03)**	**(−0.15, −0.10)**	**(−0.11, −0.06)**	**(−0.04, −0.02)**
Language	0.02	**−0.02**	**−0.06**	**−0.04**	**−0.01**
	(−0.09, 0.14)	**(−0.03, −0.01)**	**(−0.07, −0.04)**	**(−0.06, −0.02)**	**(−0.02, −0.01)**
Memory	−0.04	0.01	−0.02	−0.02	−0.01
	(−0.18, 0.10)	(−0.01, 0.03)	(−0.04, 0.00)	(−0.05, 0.00)	(−0.01, 0.00)
Executive function	0.01	**−0.03**	**−0.07**	**−0.04**	**−0.01**
	(−0.11, 0.12)	**(−0.04, −0.01)**	**(−0.09, −0.05)**	**(−0.07, −0.02)**	**(−0.02, −0.00)**
Attention	−0.05	−0.01	**−0.05**	**−0.04**	**−0.02**
	(−0.16, 0.06)	(−0.02, 0.00)	**(−0.07, −0.04)**	**(−0.07, −0.02)**	**(−0.03, −0.01)**
Visuospatial	0.04	**−0.03**	**−0.05**	−0.01	−0.00
	(−0.08, 0.15)	**(−0.04, −0.02)**	**(−0.06, −0.03)**	(−0.03, 0.00)	(−0.01, 0.00)

dB HL, decibels hearing level; CI, confidence interval; Ref, reference.

[a] Linear mixed effects models with random intercept, random slope, unstructured covariance structure and robust standard errors. Models adjusted for age, sex, race, education, smoking, body mass index, depression, hypertension, diabetes and elevated cholesterol.

[b] Cognitive test scores were standardized to baseline mean and standard deviation and were used to derive global and domain-specific cognitive factor scores using factor analysis. Lower scores indicate worse performance.

The bold values indicate the value of $p < 0.05$ which are statistically significant.

TABLE 5 Multivariable-adjusted associations[a] of speech-in-noise performance with cognitive performance in the Baltimore Longitudinal Study of Aging 2012–2019 ($N = 702$).

Cognitive factor score[b]	Baseline differences: below vs. above median	Annual rate of change				
		Above median (Ref.)	Below median	Differences: below vs. above median	Differences: per 5-point worse	
					QuickSIN <20	QuickSIN ≥20
Global	**−0.46**	**−0.05**	**−0.13**	**−0.08**	−0.02	**−0.09**
	(−0.63, −0.29)	**(−0.06, −0.03)**	**(−0.15, −0.10)**	**(−0.11, −0.06)**	(−0.06, 0.02)	**(−0.13, −0.04)**
Language	**−0.30**	**−0.03**	**−0.05**	**−0.03**	−0.01	−0.02
	(−0.44, −0.17)	**(−0.04, −0.01)**	**(−0.07, −0.04)**	**(−0.05, −0.01)**	(−0.03, 0.01)	(−0.05, 0.00)
Memory	**−0.23**	0.01	−0.02	**−0.03**	0.02	**−0.04**
	(−0.40, −0.07)	(−0.01, 0.03)	(−0.04, 0.00)	**(−0.05, −0.00)**	(−0.00, 0.04)	**(−0.07, −0.00)**
Executive function	**−0.36**	**−0.04**	**−0.07**	**−0.04**	0.02	**−0.04**
	(−0.51, −0.20)	**(−0.05, −0.02)**	**(−0.09, −0.05)**	**(−0.06, −0.01)**	(−0.00, 0.04)	**(−0.08, −0.00)**
Attention	**−0.31**	**−0.01**	**−0.05**	**−0.04**	−0.01	**−0.04**
	(−0.43, −0.19)	**(−0.03, −0.00)**	**(−0.07, −0.03)**	**(−0.06, −0.02)**	(−0.04, 0.01)	**(−0.08, −0.01)**
Visuospatial	**−0.31**	**−0.04**	**−0.04**	0.00	0.01	−0.00
	(−0.43, −0.18)	**(−0.05, −0.03)**	**(−0.05, −0.02)**	(−0.01, 0.02)	(−0.01, 0.03)	(−0.03, 0.02)

CI, confidence interval; Ref, reference.

[a] Linear mixed effects models with random intercept, random slope, unstructured covariance structure and robust standard errors. Models adjusted for age, sex, race, education, smoking, body mass index, depression, hypertension, diabetes, elevated cholesterol and better-ear pure-tone average.

[b] Cognitive test scores were standardized to baseline mean and standard deviation and were used to derive global and domain-specific cognitive factor scores using factor analysis. Lower scores indicate worse performance.

The bold values indicate the value of $p < 0.05$ which are statistically significant.

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Interaction by demographic characteristics

We did not detect an interaction between hearing status and age (>75 vs. ≤75 years), sex (Males vs. Females) or race (White vs. Black) (Supplementary Figures 1–6). Only the association between QuickSIN score and memory cognitive factor score varied by race, such that differences in rates of change comparing participants with QuickSIN score below the median to those above the median were not significant among White participants (Estimate = −0.01 SD, 95% CI: −0.04, 0.02), but were significant among Black participants (Estimate = −0.08 SD, 95% CI: −0.14, −0.03).

Discussion

Among 702 BLSA participants aged 60 years or older with up to 7 years of follow-up between 2012 and 2019, after adjusting for demographic, lifestyle and disease factors, we found longitudinal associations of both audiometric hearing and speech-in-noise performance with global and domain-specific cognitive decline. Participants with worse speech-in-noise performance but not audiometric hearing, already showed worse cognitive performance at baseline. Specifically, audiometric hearing loss was associated with faster rates of decline in global cognitive function as well as declines in language, executive function and attention. Participants with speech-in-noise performance below the median (worse) had faster rates of decline in global cognitive function, language, memory, executive function and attention compared to those with scores above the median. In our exploration of interaction, we found an interaction between speech-in-noise performance and race for memory performance, such that the association of speech-in-noise performance with cognitive decline was driven largely by Black participants but not White participants.

Hearing relies on both peripheral and central auditory systems: the peripheral auditory system captures sound signals and converts them into electrical signals in the cochlea; the central auditory system carries these electrical signals to the brainstem and cortex for recognition, integration and understanding of the information. As the gold standard, pure-tone audiometry is widely used in prior literature to define hearing loss and is recognized as a risk factor for cognitive decline and dementia (2). However, pure-tone audiometry does not assess all functions of the hearing system. Using an umbrella term "hearing loss" based solely on the pure-tone audiometry is not sufficient for characterizing the associations. Speech-in-noise performance involves the interplay of peripheral auditory input, central auditory processing, and cognitive functions and is reflective of brain health. Additionally, the speech-in-noise test, as a quick and clinically useful tool, is a vital component of auditory assessment. Therefore, it is important to incorporate multiple aspects of hearing to clarify potential differential associations with cognitive decline and inform hearing health care.

Though inconclusive, prior evidence has documented associations of both worse audiometric hearing and speech-in-noise performance with smaller brain volumes and worse white matter integrity cross-sectionally (32–34) as well as greater brain atrophy and decline in white matter integrity longitudinally (35, 36). The brain structures impacted are directly or indirectly involved in auditory processing, but some also play a role in cognitive processes. The observed associations might thus be explained causally by the reduced neural stimulation of the brain structures for auditory processing caused by degraded auditory signals (10, 35). With the extensive involvement of brain regions and higher-order cognitive processing, speech-in-noise performance is more likely to be a marker instead of a risk factor for cognitive decline.

Our finding that participants with normal hearing and hearing loss, as defined by pure-tone audiometry, had similar cognitive performance at baseline was consistent with the cross-sectional finding of a previous study among 313 participants in BLSA using study years 2012–2015 (9), but was inconsistent with a smaller cross-sectional study among 347 participants in BLSA using years 1990–1994 where a cross-sectional association between worse audiometric hearing and poorer cognitive function was found (5). This could be explained by characteristics of the participants, where the BLSA 1990–1994 cohort was younger (Mean age: 71 years) and had higher proportion of males (65%) and White participants (93%). As with previous longitudinal analyses, our study again demonstrates that audiometric hearing loss is associated with a faster rate of cognitive decline (6–9). Notably, although previous studies showed accelerated decline in the memory domain (6, 9), our study showed borderline differences in rates of decline comparing the hearing loss group to normal hearing group (Estimate = −0.02 SD, 95% CI: −0.05, 0.00, $P = 0.08$). It is possible that we were underpowered to detect a difference in memory decline, given our overall sample is healthy older adults.

Our study found associations between worse speech-in-noise performance and worse cognitive performance at baseline as well as faster decline in cognitive performance over time. These significant associations between speech-in-noise performance and cognition remained robust after adjusting for audiometric hearing levels. The limited prior research investigating associations between speech-in-noise performance and cognitive decline demonstrates inconsistent results. One study conducted among 837 participants (Mean baseline age = 65 years) from the Rotterdam Study found baseline differences in cognitive performance, but no significant differences in rates of change associated with speech-in-noise performance after a mean follow-up of 4.4 years (12); another study reported associations between worse baseline word recognition in competing messages and faster decline in Trail Making Test

Part B over 10-year follow-up among 1,274 participants aged 49 years at baseline in the Beaver Dam Offspring Study (13). The inconsistencies might result from characteristics of the study participants and different cognitive tests and speech-in-noise tests (recognizing digit triplets/words instead of sentences in noise) used.

When comparing the results regarding audiometric hearing and speech-in-noise performance, baseline differences in cognitive performance were only found for speech-in-noise performance. The observed associations between speech-in-noise performance and cognitive decline were driven by those with relatively intact speech perception function at baseline. Differences in the findings might reflect underlying brain pathologies not yet captured by audiometric hearing. Moreover, in terms of cognitive domains being impacted by these two hearing measures, both audiometric hearing and speech-in-noise performance are associated with accelerated decline in language, executive function and attention, but memory domain is significantly impacted by worse speech-in-noise performance instead of audiometric hearing. Though there is no well-supported hypothesis, memory, especially those aspects that required learning new materials, might decline earlier with advancing age (37). Audiometric hearing might fail to capture the decline in memory function in our study population with a mean age of 75 years. And speech-in-noise performance, as a surrogate marker of brain health, involves remembering and understanding sentences to repeat them back during the test, might thus be more sensitive to memory decline.

Our examination of interaction by age, sex and race showed an interaction between speech-in-noise performance and race in the memory domain, where Black participants showed accelerated decline in memory with worse speech-in-noise performance while White participants showed no difference in rates of decline. The observed differential associations among Black and White participants might be explained by health disparities across the lifespan. For example, White participants might have higher cognitive reserve due to positive psychosocial and lifestyle factors and are thus more resilient to cognitive aging and have compensatory strategies (38). However, our examination of interaction is still exploratory, and we cannot draw conclusions regarding interaction. More research is needed to examine differential relationships between hearing and cognition by demographic factors.

Our study has a number of strengths: First, in this well-established cohort of community-dwelling older adults, the comprehensive battery of neurocognitive tests measured over a mean follow-up time of 3.5 years enabled longitudinal investigation of global and domain-specific cognitive performance. Second, in addition to pure-tone audiometry that primarily measures peripheral auditory function, we also included speech-in-noise performance assessed using the QuickSIN test, which is a reliable measure of central auditory function. The QuickSIN test is commonly used in clinical settings and more applicable to clinical practices as it is easy and quick to administer. Additionally, we are able to capture both peripheral and central aspects of hearing and compare our findings, which can provide more insights into the underlying pathways. Last, in exploratory analysis, we investigated interactions by a set of demographic characteristics to investigate potential differences by sub-groups who might experience accelerated cognitive decline. Although our study still has a relatively limited sample size and follow-up period, we have expanded upon previous works in the BLSA cohort and added to the currently limited body of literature by investigating speech-in-noise performance and cognition longitudinally. Also, the BLSA cohort consists of healthy adults and our results might not be generalizable to the general U.S. older adult population. In addition, because magnetic resonance imaging (MRI) measures are associated with both hearing and cognition, future studies with MRI measures might consider the roles of brain structure and function.

In conclusion, our study demonstrated longitudinal associations of both audiometric hearing and speech-in-noise performance with accelerated decline in cognition among a sample of community-dwelling older adults. Moreover, participants with worse speech-in-noise performance, but not audiometric hearing loss, had worse baseline cognitive performance. Audiometric hearing, primarily as a measure of peripheral auditory function, might be a risk factor for cognitive decline and might be targeted to delay cognitive decline. Comparatively, speech-in-noise performance, as it involves higher-level cognitive processing, might be a novel risk marker of underlying cognitive aging and may be uniquely sensitive to decline in memory function, contributing to early identification of individuals more vulnerable to cognitive decline and might be an easy-to-use tool applicable to clinical settings. Future longitudinal studies with audiometric hearing and speech-in-noise performance are needed.

Data availability statement

The data analyzed in this study was obtained from the Baltimore Longitudinal Study of Aging (BLSA), the following licenses/restrictions apply: Researchers can only access BLSA data after approval of an Analysis Plan. Requests to access these datasets should be directed to BLSA, https://blsa.nia.nih.gov/how-apply.

Ethics statement

The studies involving human participants were reviewed and approved by the Institutional Review Board of the Intramural Research Program of the National Institutes of Health. The patients/participants provided their written informed consent to participate in this study.

Author contributions

Study concept or design: NA, YA, AG, JS, FL, LF, SR, JD, and DP. Analysis or interpretation of data: KJ, DP, and JD. Drafting the manuscript: KJ and DP. Critical revision of the manuscript: NA, YA, AG, JS, FL, LF, SR, and JD. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author FL reported being a consultant to Frequency Therapeutics, receiving speaker honoraria from Caption Call, and being the director of a public health research center funded in part by a philanthropic donation from Cochlear Ltd. to the Johns Hopkins Bloomberg School of Public Health.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fneur.2022.1029851/full#supplementary-material

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Evaluation of the non-auditory neurocognitive test MoCA-HI for hearing-impaired

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Background: Since hearing loss and cognitive decline often co-occur among older adults, a cognitive screening test suitable for hearing-impaired people is of high clinical relevance. We report the first evaluation of a German language version of the Montreal Cognitive Assessment—Hearing Impaired version (MoCA-HI).

Objective: The aim of the present study was to compare cognitively healthy participants with and without hearing loss, to examine the impact of age, sex, educational level and degree of hearing impairment on the German MoCA-HI performance, and to develop normative data.

Material and methods: The German MoCA-HI was tested in 94 participants with normal or mild hearing impairment (group 1: 4PTA $\leq$ 40 dB on the better hearing ear) and 81 participants with moderate to profound hearing loss (group 2: 4PTA $>$ 40 dB on the better hearing ear). Additionally, all participants performed the standard MoCA (version 8.2).

Results: No significant group difference between group 1 and 2 was found in the MoCA-HI total score ($p = 0.05$). In contrast, group 1 performed significantly better than group 2 on the standard MoCA ($p < 0.001$). There was no difference between the MoCA and the MoCA-HI performance in group 1 ($p = 0.12$), whereas individuals of group 2 performed significantly better on the MoCA-HI than on the standard MoCA ($p < 0.001$). Test-retest reliability of the MoCA-HI was high ($p < 0.001$). Higher age ($p < 0.001$), male sex ($p = 0.009$) and lower education ($p < 0.001$) were associated with a lower overall MoCA-HI score. Based on the demographic data normative data were developed by a regression-based approach.

Conclusion: The MoCA-HI is a cognitive screening test which is suitable for people with hearing impairment.

KEYWORDS

hearing loss, cognitive screening, MoCA, test battery, dementia

Introduction

Age-related hearing loss and dementia are among the most common chronic diseases in old age. Currently, approximately 430 million people live with disabling hearing loss (1), while 55 million people worldwide have dementia (2). Hearing loss and dementia are commonly co-morbid. Age-related hearing loss is associated with increased risk for cognitive impairment, increasing likelihood of comorbidity of hearing loss with cognitive impairment (3–7). One survey of people with cognitive impairment attending a memory clinic reported that around 85% had a hearing impairment (8).

There is a growing interest in neurocognitive testing in settings outside psychologic or psychiatric ones (9, 10), particularly in hearing rehabilitation settings. Routine hearing assessments depend on cognitive function; tests of speech recognition, for example, are impacted by cognitive factors (11). A patient's cognitive profile is increasingly taken into account in auditory rehabilitation in cochlear implant patients (9, 12–14) and speech recognition outcomes among cochlear implant recipients are better for those with better cognitive ability (15, 16).

Numerous screening tests are available to identify cases of cognitive impairment (17). However, these tests mostly involve spoken stimuli, and persons with hearing loss (or under conditions of simulated hearing loss) perform worse than those with normal hearing (18–20). Hearing impairment may lead to false-positive diagnosis of dementia and/or overestimation of cognitive impairment (19).

Several attempts have been made to adapt cognitive screening tests for people with hearing loss (21, 22). Adaptations included deleting spoken items or presenting spoken items in visual format. Although these adaptations can impact the psychometric properties of the tests [e.g., (23)], the sensitivity and specificity of the adapted versions have mostly not been established.

Dawes et al. developed a visual version of the Montreal Cognitive Assessment (MoCA) (24) for people with hearing impairment (25) and validated it in 461 participants with combinations of hearing and cognitive impairment. It has shown a good sensitivity and specificity for the detection of dementia of 95.74 and 85.71% respectively, at a cut-point of ≤ 24 points with a 2-point adjustment for education, comparable to the standard MoCA (www.mocatest.org). This MoCA-HI is freely available from the MoCA website (www.mocatest.org) to appropriately trained persons after a short fee-based online training offered by the same website. In Dawes et al.'s version, the spoken items of the standard MoCA (version 8.1) were presented visually (e.g., with written instructions) or substituted with alternative visual tasks (e.g., the sentence repetition task was replaced by a sentence formation task). These adaptations were designed to index the same cognitive domain as the standard items and to be of a similar level of difficulty.

Dawes et al.'s validation was carried out using an English version of the MoCA-HI (26). Pooling data across different languages for analysis is planned as differences in performance between different language translations have been reported for the original MoCA and may be due to cultural or linguistic impacts or differences in dementia diagnosis between countries (27). An implication is that performance criteria to identify cognitive impairment derived in English may not be applicable to other languages. Translated versions of the MoCA should be re-validated with local populations. Therefore, we developed a German language translation of the MoCA-HI (28).

The aim of the present study was (1) to compare performance of the German version of the MoCA-HI and the original MoCA in cognitively healthy participants with and without hearing loss, (2) to examine the impact of age, education, sex and level of hearing loss on performance and (3) to derive corresponding performance norms of the German MoCA-HI.

Materials and methods

Inclusion criteria were as follows: (1) age of 60 years or older, (2) native or excellent German speaker, (3) normal or corrected near visual acuity of ≤ 0.3 logMAR, (4) normal performance in the GPCOG (General Practitioner Assessment of Cognition) (29) (a score of 9 points) or a GPCOG score between 5-8 in combination with the additional informant questionnaire of the GPCOG with a score of 4–6 points, (5) GDS-15 (Geriatric Depression Scale - 15) in the normal range (30). Participants with a cognitive impairment as shown by the GPCOG or by medical history, and those with a severe neurological or psychiatric disease or a severe motor disorder that might interfere with testing were excluded. Pure tone audiograms at 500, 1000, 2000 and 4000 Hz for each ear separately were performed with headphones, and visual acuity was examined using a near vision panel. Based on the hearing thresholds, participants were divided into two groups according to the WHO classification (31). Group 1 included normal/mild hearing-impaired participants (4PTA on the better hearing ear ≤ 40 dB), which refers to WHO grade 0 and 1 and group 2 included the moderate to profound hearing loss group (4PTA on the better hearing ear > 40 dB), which refers to WHO grade 2, 3 and 4. MoCA and GPCOG testing were done with hearing devices, MoCA-HI testing without a hearing aid or a cochlear implant. All participants performed the MoCA-HI (Version 1.0 German) and the two spoken tasks of the standard MoCA (Version 8.2), i.e., the list of letters and the sentence repetition. A retest of the MoCA-HI was conducted in 115 participants after at least 4 weeks.

Statistical analysis

To achieve a medium effect size for a group comparison using a *t*-test at an alpha level of 0.05 with a power (1-beta) of 0.90, two groups of at least 70 participants were required. In total, 175 participants were included (group 1: $n = 94$; group 2: $n = 81$). Descriptive statistics including mean (*M*) and standard deviation (*SD*) were used to describe sociodemographic, audiological and cognitive data. *T*-tests were performed to compare group 1 to group 2 with regard to age, education, MoCA-HI total-score and the individual cognitive subdomains and reported by mean difference (*MD*) and *p*-value. To compare the results of the two groups in the adapted tasks of the MoCA-HI and the corresponding tasks of the standard MoCA, the Mann-Whitney-U-test was used. To examine performance differences between the MoCA and the MoCA-HI within each group, the Wilcoxon signed rank test was applied. In order to analyze the impact of hearing impairment on the MoCA-HI-total-score and the cognitive subdomains, multiple regression analysis was carried out including the 4PTA as a continuous measure of hearing ability taking into account age, education and sex. Test-retest-reliability was determined by a Pearson-correlation of the MoCA-HI total-scores at both measurement time points.

Normative scores of the MoCA-HI, taking into account age, education, and sex, were developed for the age group from 60 to 97 years. A regression-based approach which allows to account for multiple variables and analyzes continuous variables such as age and education across the entire range, was chosen (32–35). The uncorrected MoCA-HI total score (without the 2 points for $\leq$ 12 years of education) was used (35). First, 20 different general linear models were examined, as described by (36). For this purpose, 5 basic regression models, the squared covariates and their interaction with sex were tested. The best model was defined as the one that had the minimum predicted residual sum of squares (PRESS) statistic with $\text{PRESS} = \sum \left(y_i - \hat{y}_i^{(-i)} \right)^2$ where $\hat{y}_i^{(-i)}$ estimates the i$^{\text{th}}$ response from a model that was estimated without this observation (36). Further, the Akaike Information Criterion (AIC) of each model was compared with the result of the PRESS statistic.

Based on the final regression model, the formula for the demographically corrected standard values (z-scores) was developed using the z-score formula z = (score–expected score)/residual standard deviation. Cutoff scores were developed based on the z-score-formula for the 10th percentile ($z = -1.28$) for men and women for each age (60–97 years) and all years of education (7–18). Statistics were calculated by the statistical program SPSS (Version 28) and normative data were calculated by Rstudio (2021.09.1). Confidence interval was set at 95% and statistical significance was defined as a $p < 0.05$.

The study was registered on the MoCA homepage (www.mocatest.org). The study met the guidelines of the Declaration of Helsinki, and all participants gave their written consent. All examiners underwent training as required by www.mocatest.org.

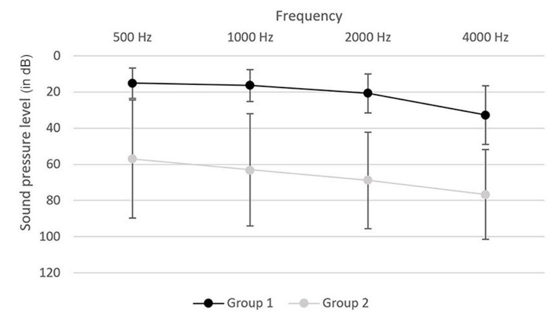

FIGURE 1
Audiogram of group 1 and group 2. Testing was performed in the frequencies of 500, 1000, 2000 and 4000 Hz and graphs are shown for the mean sound pressure level in dB with the standard deviation on the better hearing ear.

TABLE 1 Demographic data.

	Group 1 *M (SD)*	Group 2 *M (SD)*
Total number of participants	94	81
Total number of male participants	56	43
Total number of female participants	38	38
Age (years)	69.43 (7.81)	73.95 (9.22)
Education (years)	14.07 (3.38)	12.43 (2.93)
4PTA (dB)	22.23 (8.78)	66.96 (26.87)

Group 1 includes normal hearing and mild hearing-impaired participants (4PTA on the better hearing ear of ≤ 40 dB), group 2 includes participants with a moderate to profound hearing impairment (4PTA on the better hearing ear > 40 dB).

Results

Demographics

One hundred seventy-five participants aged 60 to 97 years (M = 71.52; SD = 8.77) were included in the present study. 100 subjects were aged between 60 and 71 years (males $n = 59$, females $n = 41$), 60 subjects between 72 and 83 years (males $n = 33$, females $n = 27$) and 15 subjects were aged 84 years or older (males $n = 7$, females $n = 8$). According to the WHO definition, 52 patients did not suffer from hearing loss (WHO 0, 4PTA: 15.45 (SD 5.11) dB), 42 participants were classified as WHO 1 with a mean 4PTA of 30.63 (SD 3.43) dB, 41 were suffering from a hearing loss of 45.70 (SD 5.66) dB in mean (WHO 2). 40 subjects with a mean 4PTA of 88.75 (SD 22.05) belonged to WHO 3 and 4.

Study samples were divided into 2 groups. Group 1 (94 subjects) was normal hearing or only slightly hearing-impaired

(4PTA ≤ 40 dB, WHO 0 and WHO 1) with a mean 4PTA of 22.23 dB (SD 8.78) and group 2 (81 subjects) was moderate or profound hearing-impaired (4PTA > 40 dB, WHO 2, 3 and 4) with a mean 4PTA of 66.96 dB (SD 26.87). Audiometric data are shown in Figure 1. Group 2 [mean age 73.95 (SD 9.22)] was older than group 1 [mean age 69.43 (SD 7.81) ($p < 0.001$)] and had a lower educational level than group 1 ($p < 0.001$) (Table 1).

MoCA-HI score and impact of age, sex, education and hearing level

Mean scores of the MoCA-HI and the subdomains in group 1 and group 2 are shown in Table 2A. There was no significant difference between the MoCA-HI total score of group 1 and group 2 (MD = −1.05; p = 0.05). However, Welch test showed that group 1 performed significantly better than group 2 in the cognitive subdomain of visuospatial and executive functions (MD = −0.39; p = 0.02). None of the other cognitive subdomains, such as naming (MD = −0.03; p = 0.36), attention (MD = −0.18; p = 0.2), language (MD = −0.12; p = 0.33), abstraction (MD = −0.12; p = 0.2), and recall (MD = −0.16; p = 0.54), showed a significant difference between the two groups in the independent sample t-test. For the cognitive subdomain of orientation, Welch's test also showed no significant group difference (MD = −0.04; p = 0.28).

A multiple linear regression analysis revealed that older age (β = −0.28; $p < 0.001$), male sex (β = −0.16; p = 0.009), and lower education (β = 0.48; $p < 0.001$) were associated with a lower MoCA-HI total score and together explained 41.7% (adjusted R^2 = 0.41) of the total variance (F = 40.73; p <

TABLE 2A Mean score in MoCA-HI and the different cognitive subdomains in Group 1 and Group 2.

	Group 1 N = 94 *M (SD)*	Group 2 N = 81 *M (SD)*	Maximum score
MoCA-HI (total score)	24.71 (3.51)	23.67 (3.51)	30
Visuospatial/Executive	3.88 (0.98)	3.49 (1.15)	5
Naming	2.97 (0.18)	2.94 (0.24)	3
Attention	5.20 (0.97)	5.02 (0.84)	6
Language	2.27 (0.79)	2.15 (0.79)	3
Abstraction	1.46 (0.67)	1.33 (0.61)	2
Delayed recall	2.98 (1.78)	2.81 (1.78)	5
Orientation	5.96 (0.20)	5.91 (0.32)	6

Group 1 includes normal hearing and mild hearing-impaired participants (4PTA on the better hearing ear ≤ 40 dB), group 2 includes participants with a moderate to profound hearing impairment (4PTA on the better hearing ear > 40 dB). MoCA-HI, Montreal Cognitive Assessment - Hearing impairment.

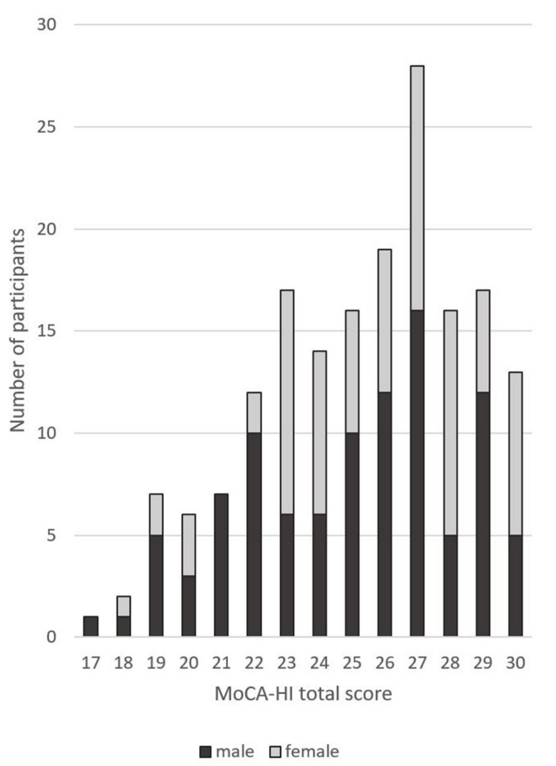

FIGURE 2
Distribution of the adjusted MoCA-HI total score.

TABLE 2B Mean values of the MoCA-HI total score, age, education and 4PTA according to the WHO classification.

	WHO 0 *N* = 52 *M (SD)*	WHO 1 *N* = 42 *M (SD)*	WHO 2 *N* = 41 *M (SD)*	WHO 3 & 4 *N* = 40 *M (SD)*
MoCA-HI total score	25.60 (3.30)	23.62 (3.49)	23.20 (3.27)	24.15 (3.73)
Age (years)	67.50 (6.10)	71.81 (9.04)	76.37 (9.36)	71.48 (8.50)
Education (years)	14.54 (3.44)	13.50 (3.24)	12.20 (2.88)	12.68 (2.99)
4PTA (dB)	15.45 (5.11)	30.63 (3.43)	45.70 (5.66)	88.75 (22.05)

Normal hearing group, 4PTA on the better hearing ear < 26 dB (WHO 0); WHO 1, 4PTA on the better hearing ear 26–40 dB; WHO 2, 4PTA on the better hearing ear 41-60 dB; WHO 3 & 4, 4PTA on the better hearing ear >60 dB; MoCA-HI, Montreal Cognitive Assessment - Hearing impairment.

0.001). Mean total scores in the MoCA-HI in the 4 different WHO groups are shown in Table 2B. There was no difference in MoCA-HI performance using the 4PTA as a continuous variable ($\beta = -0.02$; $p = 0.72$). Further no significant effect of the level of hearing impairment on the different subscores was found ($\beta \leq 0.06$; $p \geq 0.46$).

A retest was performed in 115 participants. The mean retest interval was 60.38 (SD 18.08) days after the first administration with a minimum of 28 and a maximum of 112 days. Test-retest reliability was high with a Pearson correlation of 0.84 ($p < 0.001$). However, the MoCA-HI total score was higher in the retest than at baseline (MD = 0.44; $p = 0.008$), due to a statistically significant improvement in the cognitive subdomain "recall" in the retest ($p < 0.001$). All other subtests remained stable after re-testing.

Comparison of the standard MoCA with the MoCA-HI

There was no difference between group 1 (mean rank = 89.70) and group 2 (mean rank = 86.03) in the adapted items of the MoCA-HI ($p = 0.58$). In contrast, individuals of group 1 (mean rank = 106.27) performed significantly better than subjects of group 2 (mean rank = 66.80) on the sum of the corresponding items of the standard MoCA ($p < 0.001$). Further, group 1 did not differ in the MoCA and MoCA-HI performance ($p = 0.12$), whereas group 2 performed significantly better on the MoCA-HI than on the standard MoCA ($p < 0.001$).

Establishment of normative data

In a first step, MoCA-HI scores were adjusted for education as suggested by Dawes (www.mocatest.org), showing that 35.5% of women and 39.4% of men scored below the original cutoff (see Figure 2). Therefore, in a second step normative data for the German version of the MoCA-HI were calculated taking into account education as well as age and sex using a regression-based approach (Figure 3). A regression model including age, years of education, sex and the interaction of age and sex as covariates had both the lowest PRESS statistic and the lowest AIC and was thus the best predicting model for the MoCA-HI total score, which explained 42.35% of the variance (adjusted $R^2 = 0.41$; F = 31.22; $p < 0.001$). This effect is strongest for education (t = 7.52), followed by sex (t = −2.65), age (t = −1.86), and the interaction of age and sex (t = −1.41), as indicated by the t-values. Based on the present data, the z-Score could be determined as follows: z = (Score–(22.86 + (−0.07 * age) + (0.53 * education) + (−1.11 * sex) + (−0.07 * (age−71.52) * sex)))/2.72. Sex was coded as 0 = female and 1 = male, age and education are inserted in years. The resulting cutoff scores for the 10th percentile are shown in Tables 3A,B.

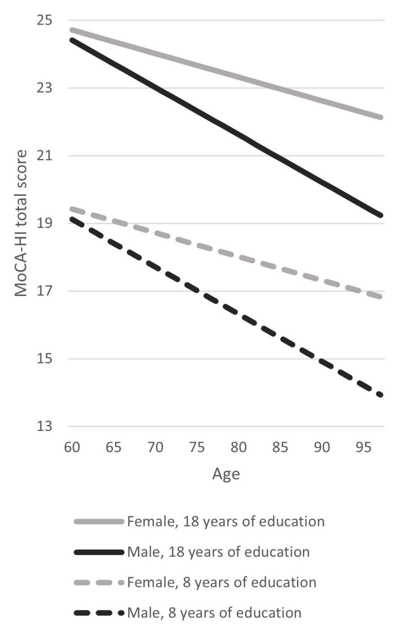

FIGURE 3
Example regression lines for the whole study sample ($n = 175$) representing the relationship of MoCA-HI total score with age, education and sex. Example regression lines are shown for subjects with 8 and 18 years of education. The regression model shows that the MoCA-HI total score was lower in case of less educational years, an increasing age and in male sex. Age had a stronger effect on the MoCA-HI total score in men than in women. 100 of the subjects included were aged between 60 and 71 years (males $n = 59$, females $n = 41$), 60 subjects between 72 and 83 years (males $n = 33$, females $n = 27$) and 15 subjects were aged 84 years or older (males $n = 7$, females $n = 8$).

Discussion

This present study is the first to evaluate the German MoCA-HI in normal-hearing and hearing-impaired subjects and to develop normative data for cognitively healthy individuals adjusted for age, education and sex.

Development of a MoCA version for hearing-impaired

There have been two previous attempts to adapt the MoCA for people with hearing loss. Dupuis et al. adapted the standard MoCA by removing spoken items (sentence repetition, lists of numbers, list of letters, delayed recall) from the assessment and established new cutoff scores proportionally adjusted for the deleted items (18). However, Al-Yawer found in a retrospective analysis that this approach reduced the sensitivity of the test scores of patients with mild cognitive impairment from 90 to 56%, although sensitivity for dementia was not affected (23).

TABLE 3A Highest MoCA-HI total scores just below the 10th percentile for women (z-score ≤ −1.28).

Age (in years)	Education (in years): 7	8	9	10	11	12	13	14	15	16	17	18
60	19	19	20	20	21	21	22	23	23	24	24	25
61	19	19	20	20	21	21	22	22	23	24	24	25
62	19	19	20	20	21	21	22	22	23	23	24	25
63	19	19	20	20	21	21	22	22	23	23	24	24
64	19	19	20	20	21	21	22	22	23	23	24	24
65	18	19	20	20	21	21	22	22	23	23	24	24
66	18	19	19	20	21	21	22	22	23	23	24	24
67	18	19	19	20	20	21	22	22	23	23	24	24
68	18	19	19	20	20	21	21	22	22	23	24	24
69	18	19	19	20	20	21	21	22	22	23	23	24
70	18	19	19	20	20	21	21	22	22	23	23	24
71	18	19	19	20	20	21	21	22	22	23	23	24
72	18	18	19	20	20	21	21	22	22	23	23	24
73	18	18	19	19	20	21	21	22	22	23	23	24
74	18	18	19	19	20	20	21	22	22	23	23	24
75	18	18	19	19	20	20	21	21	22	23	23	24
76	18	18	19	19	20	20	21	21	22	22	23	24
77	18	18	19	19	20	20	21	21	22	22	23	23
78	18	18	19	19	20	20	21	21	22	22	23	23
79	17	18	19	19	20	20	21	21	22	22	23	23
80	17	18	18	19	20	20	21	21	22	22	23	23
81	17	18	18	19	19	20	21	21	22	22	23	23
82	17	18	18	19	19	20	20	21	22	22	23	23
83	17	18	18	19	19	20	20	21	21	22	22	23
84	17	18	18	19	19	20	20	21	21	22	22	23
85	17	18	18	19	19	20	20	21	21	22	22	23
86	17	17	18	19	19	20	20	21	21	22	22	23
87	17	17	18	18	19	20	20	21	21	22	22	23
88	17	17	18	18	19	19	20	21	21	22	22	23
89	17	17	18	18	19	19	20	20	21	22	22	23
90	17	17	18	18	19	19	20	20	21	21	22	23
91	17	17	18	18	19	19	20	20	21	21	22	22
92	17	17	18	18	19	19	20	20	21	21	22	22
93	16	17	18	18	19	19	20	20	21	21	22	22
94	16	17	17	18	19	19	20	20	21	21	22	22
95	16	17	17	18	18	19	20	20	21	21	22	22
96	16	17	17	18	18	19	19	20	21	21	22	22
97	16	17	17	18	18	19	19	20	20	21	21	22

Odd numbers are highlighted in white and even numbers in gray.

Lin et al. developed a timed computerized visual version of the MoCA and reported no difference in performance of the computerized visual MoCA between cognitively normal participants with normal hearing (n = 103) vs. hearing loss (n = 49) (37). Lerch and Benz created a German language version of Lin et al.'s computerized MoCA and tested it in 50 normal hearing and 100 hearing-impaired participants (38). A comparison with the Consortium to Establish a Registry for Alzheimer's Disease (CERAD) and the Mini Mental Status Examination (MMSE) showed that the computerized MoCA-HI

TABLE 3B Highest MoCA-HI total scores just below the 10th percentile for men (z-score ≤-1.28).

Age (in years) \ Education (in years)	7	8	9	10	11	12	13	14	15	16	17	18
60	18	19	20	20	21	21	22	22	23	23	24	24
61	18	19	19	20	20	21	22	22	23	23	24	24
62	18	19	19	20	20	21	21	22	22	23	24	24
63	18	19	19	20	20	21	21	22	22	23	23	24
64	18	18	19	20	20	21	21	22	22	23	23	24
65	18	18	19	19	20	20	21	22	22	23	23	24
66	18	18	19	19	20	20	21	21	22	22	23	23
67	18	18	19	19	20	20	21	21	22	22	23	23
68	17	18	18	19	20	20	21	21	22	22	23	23
69	17	18	18	19	19	20	20	21	21	22	23	23
70	17	18	18	19	19	20	20	21	21	22	22	23
71	17	17	18	19	19	20	20	21	21	22	22	23
72	17	17	18	18	19	19	20	21	21	22	22	23
73	17	17	18	18	19	19	20	20	21	21	22	23
74	17	17	18	18	19	19	20	20	21	21	22	22
75	16	17	17	18	19	19	20	20	21	21	22	22
76	16	17	17	18	18	19	19	20	21	21	22	22
77	16	17	17	18	18	19	19	20	20	21	21	22
78	16	17	17	18	18	19	19	20	20	21	21	22
79	16	16	17	17	18	19	19	20	20	21	21	22
80	16	16	17	17	18	18	19	19	20	20	21	22
81	16	16	17	17	18	18	19	19	20	20	21	21
82	15	16	16	17	18	18	19	19	20	20	21	21
83	15	16	16	17	17	18	18	19	20	20	21	21
84	15	16	16	17	17	18	18	19	19	20	20	21
85	15	16	16	17	17	18	18	19	19	20	20	21
86	15	15	16	16	17	18	18	19	19	20	20	21
87	15	15	16	16	17	17	18	18	19	20	20	21
88	15	15	16	16	17	17	18	18	19	19	20	20
89	14	15	16	16	17	17	18	18	19	19	20	20
90	14	15	15	16	16	17	18	18	19	19	20	20
91	14	15	15	16	16	17	17	18	18	19	19	20
92	14	15	15	16	16	17	17	18	18	19	19	20
93	14	14	15	16	16	17	17	18	18	19	19	20
94	14	14	15	15	16	16	17	17	18	19	19	20
95	14	14	15	15	16	16	17	17	18	18	19	19
96	13	14	15	15	16	16	17	17	18	18	19	19
97	13	14	14	15	15	16	17	17	18	18	19	19

Odd numbers are highlighted in white and even numbers in gray.

correlated with the CERAD plus battery (38). Utoomprurkporn et al. (2021) tested a modified version of Lin et al.'s computerized visual MoCA in 75 hearing aid users (39), 30 cognitive healthy, 30 with MCI and 15 with a clinical diagnosis of dementia reporting good sensitivity and specificity for MCI and dementia in their analysis. However, the small sample size and group differences in age and educational level limit the reliability of sensitivity/specificity estimates.

The visual version of the MoCA reported in the current study has several advantages over previous versions of the MoCA adapted for people with hearing loss. First, rather than deleting spoken items, it replaces the standard spoken items by other items that tap into the same cognitive domain and are of a similar level of difficulty. Secondly, it was validated in a large cohort in a multi-centre study (25, 26). Thirdly, it may be administered in either paper-and-pencil format or computerized presentation.

Performance of the German version of the MoCA-HI and the MoCA in participants with vs. without hearing loss

Group 2 (hearing loss of ≥ 41 dB) performed worse than group 1, which had no hearing loss or only a mild hearing loss, on the standard MoCA, but not on the three adapted tasks of the MoCA-HI. In line with that, there was no significant difference in the performance in the MoCA and MoCA-HI of group 1, while group 2 performed significantly worse in the standard MoCA than in the MoCA-HI. Thus, at least people with a severe hearing impairment may benefit from a visual version of the MoCA and the MoCA-HI may prevent false-positive diagnosis of dementia especially in case of a severe or profound hearing loss (19). However, the impact of a mild hearing loss cannot be answered right now and should be studied in larger samples in the future.

Impact of age, education, sex and level of hearing loss on performance

The MoCA-HI total score was best predicted by a regression model including age, education, sex, and the interaction of age and sex; age had a stronger effect on the total score in men than in women. This is in line with previous studies on the original MoCA, where regression models including age, education and sex had the best predictive power (33, 35, 40, 41). Given these differences, age-, education- and sex-specific normative values were developed to adjust for these demographic variables and to optimize the detection of cognitive impairment for the German MoCA-HI version. Hearing status based on 4PTA of the better ear did not impact on the total MoCA-HI performance as shown by regression analysis taking into account age, sex and educational level. Therefore, even if the WHO classification of the 4PTA of the better hearing ear used in the present study does not fully reflect the hearing abilities in daily life, this cognitive test battery seems to be suitable for anyone regardless of the hearing level.

Re-test reliability

To use the MoCA-HI in clinical practice, a re-test is necessary. In the present study participants performed slightly better in the re-test with less than 1 point more. Although this improvement was statistically significant, it did not make a difference to the clinical classification on the MoCA-HI. Practice effects cannot fully be ruled out in re-testing (42), although Faletti et al., have demonstrated that an interval of 4 weeks between testing and re-testing might be sufficient (43). In the present study the better performance in the re-test was only due to the large improvement in the recall subtest. Therefore, a further version of the MoCA-HI should be developed, including new terms in the MoCA subtest recall, before introducing the MoCA-HI assessment into clinical routine.

Limitations

One limitation of our study is that we relied on the GPCOG to establish normal cognition criteria. The GPCOG is somewhat like the standard MoCA in including spoken items, so hearing status may have impacted categorization as normal cognition based on GPCOG performance. Some people with hearing loss might have been incorrectly excluded. However, we do not consider this to be a serious issue, since it was our aim to include only cognitive healthy individuals in this analysis.

Previous research indicated that performance criteria to identify cognitive impairment developed in English may not be applicable to translations of the MoCA in other languages (27). Cut-points for the English MoCA-HI may not be applicable to the German MoCA-HI. In a follow-up project, we are currently collecting data to establish optimal performance criteria for identification of cognitive impairment for the German MoCA-HI. The analysis of demographic correlates of performance reported in the current paper suggests that adjustments for age, sex and educational level may facilitate optimal discriminative power.

Conclusion

The German translation of the MoCA-HI is suitable in subjects with and without hearing loss and has high retest reliability. Performance criterion for identification of cognitive impairment should be developed, considering the impact of age, sex and educational level. A language-specific validation is required due to linguistic and cultural differences.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The present study was approved by the Ethic Institution of the Ruhr-University Bochum (No. 20-7076). The patients/participants provided their written informed consent to participate in this study.

Author contributions

CV, LG, and PD designed the study. HF collected the data and did the statistical analysis with critical feedback from FL and MT. CV and HF wrote the manuscript with contributions from PD and critical feedback from LG, ZN, and RW. All authors contributed to the article and approved the submitted version.

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Conflict of interest

CV has received reimbursement of scientific meeting participation fees and accommodation expenses, as well as honoraria for preparing continuing medical education events and funding for research projects that they initiated, from MED-EL.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Hearing loss, hearing aid use, and subjective memory complaints: Results of the HUNT study in Norway

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Objective: This study aimed to explore the association between hearing loss severity, hearing aid use, and subjective memory complaints in a large cross-sectional study in Norway.

Methods: Data were drawn from the fourth wave of the Trøndelag Health Study (HUNT4 Hearing, 2017–2019). The hearing threshold was defined as the pure-tone average of 0.5, 1, 2, and 4 kHz in the better ear. The participants were divided into five groups: normal hearing or slight/mild/moderate/severe hearing loss. Subjective self-reported short-term and long-term memory complaints were measured by the nine-item Meta-Memory Questionnaire (MMQ). The sample included 20,092 individuals (11,675 women, mean age 58.3 years) who completed both hearing and MMQ tasks. A multivariate analysis of variance (adjusted for covariates of age, sex, education, and health cofounders) was used to evaluate the association between hearing status and hearing aid use (in the hearing-impaired groups) and long-term and short-term subjective memory complaints.

Results: A multivariate analysis of variance, followed by univariate ANOVA and pairwise comparisons, showed that hearing loss was associated only with more long-term subjective memory complaints and not with short-term subjective memory complaints. In the hearing-impaired groups, the univariate main effect of hearing aid use was only observed for subjective long-term memory complaints and not for subjective short-term memory complaints. Similarly, the univariate interaction of hearing aid use and hearing status was significant for subjective long-term memory complaints and not for subjective short-term memory complaints. Pairwise comparisons, however, revealed no significant differences between hearing loss groups with respect to subjective long-term complaints.

Conclusion: This cross-sectional study indicates an association between hearing loss and subjective long-term memory complaints but not with subjective short-term memory complaints. In addition, an interaction between hearing status and hearing aid use for subjective long-term memory complaints was observed in hearing-impaired groups, which calls for future research to examine the effects of hearing aid use on different memory systems.

KEYWORDS

hearing loss, subjective memory complaints, hearing aid use, short-term (working) memory, long-term memory

1. Introduction

Hearing loss is one of the most common sensory disabilities in older adults. It adversely affects language understanding. Hearing loss is also a risk factor for cognitive decline [e.g., (1)] and dementia (2, 3). Furthermore, hearing loss impacts neural systems involved in the processing of speech signals [e.g., (4)], which leads to structural and functional changes in the brain (5, 6).

The extent to which hearing loss affects the human memory system has been less extensively investigated. The human memory system consists of multiple theoretical systems, including short-term memory (the capacity for retention of a small amount of information for a short period of time) and long-term memory. Long-term memory is typically categorized into declarative memory (conscious, explicit recollection or recognition of events and facts) and non-declarative memory (unconscious, implicit knowledge of habits, skills, routines, and procedures) (7, 8).

There are objective and subjective methods to measure memory in humans. Objective memory refers to the recall of items, personal experiences, and general knowledge. On the other hand, subjective memory complaints refer to people's self-evaluation of memory dysfunction and individuals' awareness of memory failure in the absence of objective memory impairment (9). One advantage of using subjective self-reported memory scales is their independence from participants' sensory functioning which is likely to affect performance in objective memory tasks. It should be noted that objective tests of memory function can be independent of sensory function when the method of testing is not dependent on the sensory function of interest. For example, the outcomes of visual tests of memory function are probably unaffected by hearing loss status when participants meet the criteria of normal or corrected to normal vision. With regard to objective memory assessment, prior research showed mixed results regarding the effects of hearing loss on objective memory tasks. For example, Rönnberg et al. (10) by using memory tests that were independent of the hearing functioning of participants found that hearing loss adversely affected semantic and episodic long-term memory but not short-term memory. Using data from the United Kingdom Biobank cohort study, Rönnberg et al. (11) reported that hearing loss negatively affected both long-term and short-term visuospatial memory tasks. Loughrey et al. (12), using data from the Irish Longitudinal Study of Aging, found no direct effect of subjective self-reported hearing difficulties on episodic long-term memory performance. Regarding subjective memory complaints, Curhan et al. (13, 14), using data from longitudinal cohort studies, investigated the extent to which self-reported hearing loss affected subjective memory concerns in men and women. The results showed that hearing loss was linked to increased complaints regarding subjective memory function in both men and women. In addition, more self-reported hearing loss was associated with greater subjective memory complaints. Jayakody et al. (15) studied the association between subjective memory complaints and peripheral hearing and central auditory processing in a sample of individuals aged 45–85 years old with average hearing thresholds (for the better hearing ear), at frequencies of 0.5, 1, 2, and 4 kHz (4PTA), of <40 dBHL. The results showed that, compared with people with no subjective memory complaints ($n = 34$), those with subjective memory complaints ($n = 61$) performed poorly only on a sentence-identification-in-noise test. No significant differences were observed between groups in terms of 4PTA and quick speech-in-noise test results. The association between speech-in-noise testing and memory complaints in Jayakody et al. (15) is not surprising as perceiving speech in noise demands a greater cognitive load. Individuals with memory complaints could have reduced cognitive capacities for processing speech signals in noisy conditions. In addition, the lack of association between subjective memory complaints and PTA4 is not surprising given the hearing was better than 40 dBHL (normal to mild hearing loss).

Currently, sound amplification with a hearing aid is the most common rehabilitative treatment to enhance speech perception ability in people with hearing loss. Modern digital hearing aids greatly enhance speech perception in people with hearing loss; however, hearing aid users still lag behind people with normal hearing when perceiving speech signals in the absence of a supportive semantic context [see (16, 17)]. Literature regarding hearing aids and cognitive function in people with hearing loss is not conclusive. Some studies have shown no difference between hearing-aid users and non-hearing-aid users in terms of cognitive function [e.g., (18–21)]. However, Maharani et al. (22) reported that hearing aid use slowed down episodic memory decline. In addition, Rönnberg et al. (11) reported that hearing aid use had a small positive effect on short-term visuospatial memory but not on long-term visuospatial memory. Karawani et al. (23) showed that using a hearing aid for longer than 6 months was associated with neuroplastic changes in the brain and increased working memory capacity. No effect of hearing aid use was observed on processing speed and attentional capacity.

Using a larger sample than prior studies, the present study aimed to investigate the association between hearing loss, hearing aid use, and subjective memory complaints, after controlling for confounders including age, sex, education, and health variables, using data from the HUNT4 Hearing in Norway. No study has yet examined the extent to which hearing aid use affects subjective memory complaints in people with hearing loss.

2. Materials and methods

2.1. Participants

The HUNT4 Hearing, which was a part of HUNT4, was conducted in Nord-Trøndelag County in Norway [see (24) for more information about HUNT4 Hearing]. All residents aged 20 years and over were invited to take part. The participation rate for HUNT4 Hearing was approximately 43%, and 28,302 completed the audiometric tasks. The baseline sample in this study consisted of 20,092 individuals (11,675 women, mean age 58.3 years) who completed the meta-memory questionnaire (MMQ). The participants signed an informed consent form for their participation in HUNT4 Hearing. The study was approved by the regional committee for medical and health research ethics and the Norwegian Data Protection Authority (23178 HUNT Hørsel).

2.2. Hearing status

Engdahl et al. (25) provided detailed information about the hearing screening of participants and measuring audiometric thresholds in the HUNT4 Hearing. In short, several teams were involved in collecting data for this project. Each team had a trained audiologist and two trained assistants. A questionnaire was used to evaluate subjective hearing loss, tinnitus, hearing aid use, and other risk factors for causing hearing loss. Then, the participants underwent otoscopy and pure-tone audiometry. The pure-tone audiometric thresholds were measured using Interacoustics audiometers (type AD629) in semiportable, dismountable sound booths (IAC Moduline System, 102 mm thick, 1,450 × 1,450 × 2,100 mm^3).

We defined the hearing status of participants based on hearing thresholds for the pure-tone average of four frequencies (500, 1,000, 2,000, and 4,000 Hz, or 4PTA) in the better hearing ear: normal hearing (4PTA hearing threshold, ≤15 dB), slight hearing loss (4PTA, 16–25 dB), mild hearing loss (4PTA, 26–40 dB), moderate hearing loss (4PTA, 41–55 dB), and severe hearing loss (4PTA, ≥ 56 dB).

2.3. Meta-Memory Questionnaire

In the HUNT study, the nine-item MMQ was used to examine participants' subjective memory complaints. The MMQ was initially developed for a Nordic study on aging and health, to assess memory function in a single score (26). The MMQ comprises nine items about memory complaints. The first two items ask about memory function in general: "(1) Do you have problems with your memory?" and "(2) Has your memory changed since you were younger?" The response categories are "no," "yes, sometimes," and "yes, a lot." The next seven items ask about specific memory functions, starting with the question "do you have problems remembering": "(3) that happened few minutes ago," "(4) names of other people," "(5) dates," "(6) to carry out planned activities," "(7) that happened a few days ago," "(8) that happened years ago," and "(9) keeping track of a conversation." The possible responses for these seven items are "never," "sometimes," and "often."

Almkvist et al. (27), after conducting a principle component factor analysis on the MMQ in the third wave of the HUNT cohort study (2006–2008, HUNT3), revealed that items 1, 2, 4, 5, and 8 were related to declarative long-term memory complaints and items 3, 6, 7, and 9 were related to short-term memory complaints. The scoring for questions 1 and 2 was as follows: 0 = no, 1 = yes, sometimes, and 2 = yes, a lot. For questions 3–9, the scoring was as follows: 1 = never, 2 = sometimes, and 3 = often. The total score was calculated by summing the scores for each subjective memory component (the range was from 3 to 13 for long-term subjective memory complaints and 4–12 for short-term memory subjective memory complaints). We conducted a preliminary factor analysis using data from HUNT4. The results corroborated the findings by Almkvist et al. (27), as factor analysis revealed two main factors: short-term memory complaints (items 3, 6, 7, and 9) and long-term memory complaints (items 1, 2, 4, 5, and 8).

TABLE 1 Sample characteristics stratified by the hearing status of participants 463 ($n = 16,141$).

Hearing status	Average Age (standard deviation)	Sex (%)	Average PTA4 (standard deviation)	Average subjective long-term memory complaints (standard deviation)	Average subjective short-term memory complaints (standard deviation)	Using hearing aid? (%)	Stroke? (%)	Hospital admission for head injury (%)	Diabetes? (%)	Smoking habits (%)	Educational level (%)
Normal hearing	47.20 (14.99)	Females: 62 Males: 38	7.06 (6.18)	6.92 (2.04)	5.52 (1.78)		Yes (2) No (98)	Yes (7) No (92) I do not know (1)	Yes (4) No (96)	Never smoked (44) Former occasional smoker (10) Former daily smoker (36) Smoking occasionally (1) Daily smoker (8)	Primary (19) Secondary (31) Tertiary (49)
Slight hearing loss	65.15 (10.53)	Females: 51 Males: 49	23.06 (4.68)	7.29 (1.92)	5.67 (1.94)	Yes (8) No (92)	Yes (5) No (95)	Yes (7) No (92) I do not know (1)	Yes (10) No (90)	Never smoked (35) Former occasional smoker (6) Former daily smoker (48) Smoking occasionally (0.5) Daily smoker (10)	Primary (35) Secondary (31) Tertiary (35)
Mild hearing loss	71.13 (9.96)	Females: 48 Males: 52	35.12 (5.76)	7.45 (1.99)	5.75 (1.95)	Yes (32) No (68)	Yes (7) No (93)	Yes (6) No (93) I do not know (1)	Yes (11) No (89)	Never smoked (34) Former occasional smoker (5) Former daily smoker (53) Smoking occasionally (0.4) Daily smoker (8)	Primary (43) Secondary (26) Tertiary (31)
Moderate hearing loss	76.58 (9.21)	Females: 60 Males: 40	49.68 (5.94)	7.70 (2.00)	6.13 (2.06)	Yes (73) No (27)	Yes (9) No (91)	Yes (8) No (91) I do not know (1)	Yes (12) No (88)	Never smoked (35) Former occasional smoker (3) Former daily smoker (56) Smoking occasionally (0.3) Daily smoker (6)	Primary (47) Secondary (28) Tertiary (25)
Severe hearing loss	77.07 (12.75)	Females: 40 Males: 60	69.05 (11.09)	7.61 (2.22)	5.98 (2.16)	Yes (92) No (8)	Yes (10) No (90)	Yes (8) No (90) I do not know (2)	Yes (18) No (82)	Never smoked (39) Former occasional smoker (3) Former daily smoker (47) Smoking occasionally (0.6) Daily smoker (11)	Primary (44) Secondary (27) Tertiary (29)

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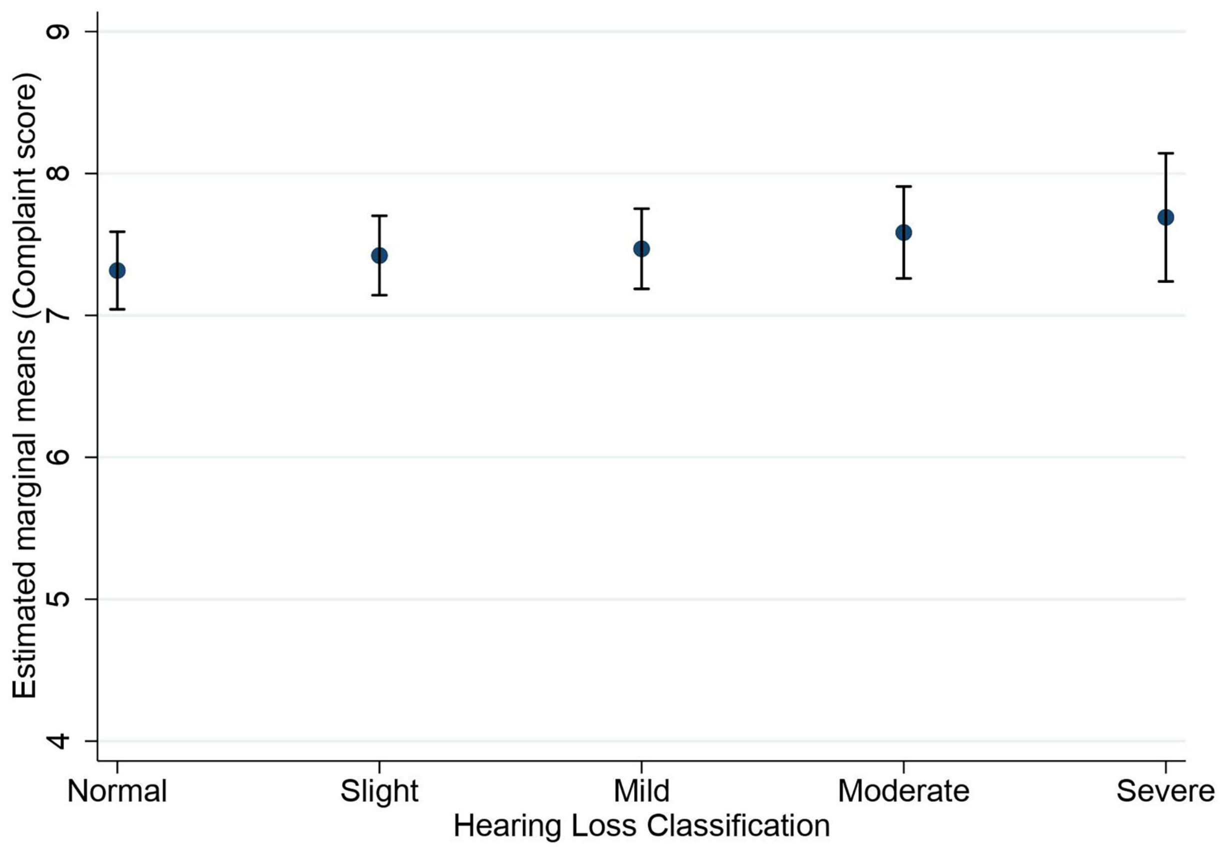

FIGURE 1
Estimated marginal means of subjective long-term memory complaints as a function of hearing status. Estimates are averaged over the levels of age at the means of the covariates sex, education, stroke, diabetes, smoking, and hospital admission for a head injury. The error bars indicate 95% confidence intervals.

2.4. Statistical analysis

SPSS version 28 statistical software was used to analyze the data. A multivariate analysis of variance (MANOVA) with follow-up univariate analyses was performed to assess the effect of hearing status (normal hearing and various types of hearing loss) on long-term memory and short-term memory complaints. Pairwise comparisons were performed using the Bonferroni method. Wilks' lambda statistic was used to assess multivariate significance. The same MANOVA was also used to determine the effects of hearing loss severity and hearing aid use on subjective long-term memory and short-term memory complaints. Analyses were adjusted for the covariates of sex, age, education, stroke, diabetes, smoking, and hospital admission for a head injury. As the relationships between age and hearing and age and cognition are nonlinear, we categorized participants' age into different groups with 10-year intervals and treated age as a fixed factor in the analysis. All the other covariates were also categorical but treated as linear in the analyses. Missing data were listwise deleted in this study. The number of participants with missing data for each covariate was as follows: sex: $n = 0$; age: $n = 13$; education: $n = 151$; stroke: $n = 1,312$; diabetes: $n = 463$; smoking: $n = 146$; and hospital admission for a head injury: $n = 2,670$.

3. Results

Table 1 shows baseline sample characteristics stratified by hearing status. Because of missing data, the final sample was reduced to 16,141 participants (mean age at entry 57.7 years, 9,175 women). As Table 1 shows, individuals with moderate/severe degrees of hearing loss use hearing aids more than individuals with slight/mild degrees of hearing loss. In addition, participants with moderate/severe degrees of hearing loss were slightly older than participants with moderate/mild degrees of hearing loss and participants with normal hearing.

Figures 1, 2 show the estimated marginal means for subjective long-term and short-term memory complaints

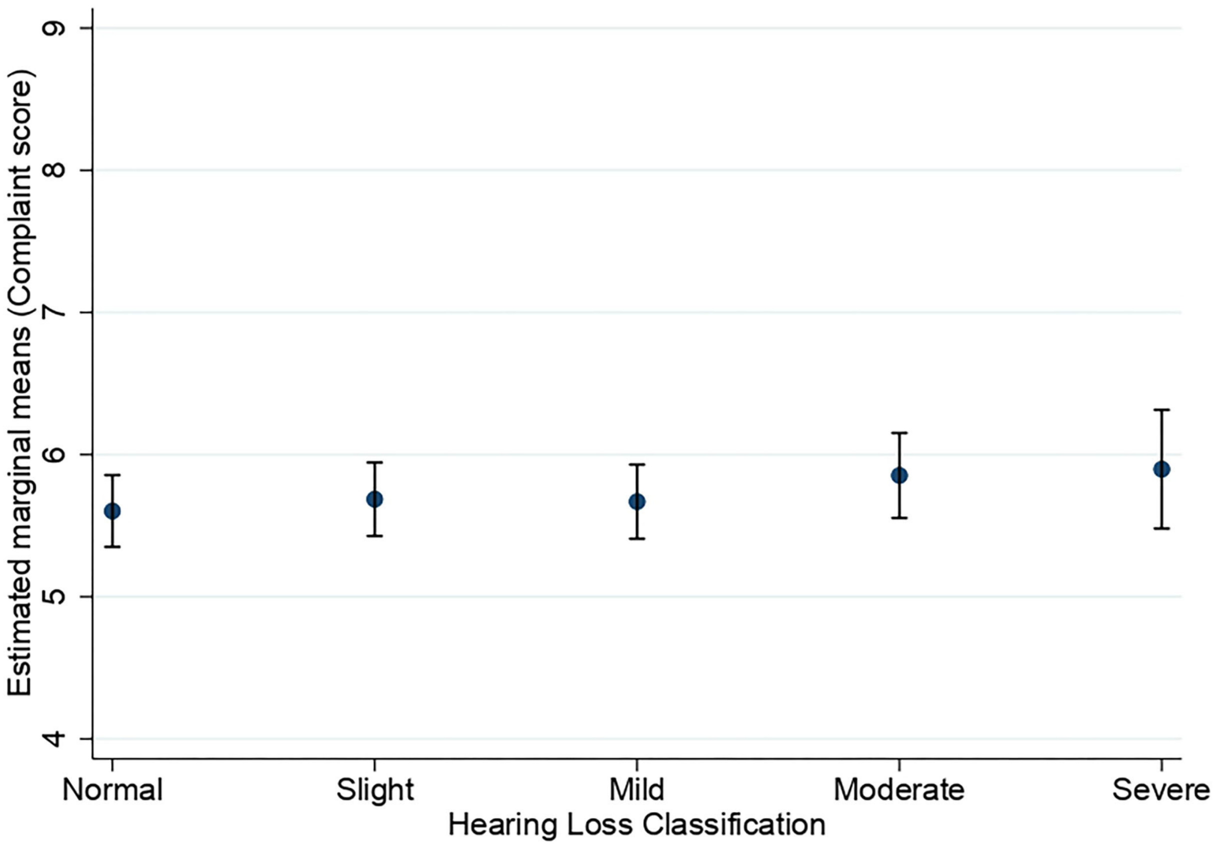

FIGURE 2
Estimated marginal means of subjective short-term memory complaints as a function of hearing status. Estimates are averaged over the levels of age at the means of the covariates sex, education, stroke, diabetes, smoking, and hospital admission for a head injury. The error bars indicate 95% confidence intervals.

as a function of hearing status. A two-way MANOVA analysis showed the multivariate main effect for hearing status was marginally insignificant (Wilk's λ = 0.999, $F_{(8,32,214)}$ = 1.88, p = 0.058]. However, subsequent univariate ANOVAs revealed a main effect of hearing status for the subjective long-term memory complaints [$F_{(4,16,108)}$ = 2.93, p = 0.020, η^2 = 0.001] and not for subjective short-term memory complaints [$F_{(4,16,108)}$ = 1.97, p = 0.10]. Bonferroni-adjusted pairwise comparisons in subjective long-term memory showed that the normal hearing group (M = 6.96) reported significantly fewer complaints than the slight hearing loss group only (M = 7.24, p = 0.011).

Figures 3, 4 show the estimated marginal means for subjective long-term and short-term memory complaints as a function of hearing status and hearing aid use in the hearing-impaired groups. A three-way MANOVA was conducted to examine the effects of hearing status and hearing aid use on subjective long-term and short-term memory complaints in groups of people with hearing loss. The multivariate main effect for hearing status was not significant [Wilk's λ = 0.998, $F_{(6,7,714)}$ = 1.46, p = 0.19]. However, the main effect for hearing aid use was marginally significant [Wilk's λ = 0.998, $F_{(2,3,857)}$ = 3.06, p = 0.047, η^2 = 0.002]. The interaction between hearing status and hearing aid use was not significant [Wilk's λ = 0.997, $F_{(6,7,714)}$ = 1.63, p = 0.134]. A subsequent univariate ANOVA analysis showed that the main effect of hearing status was not significant for neither subjective long-term memory complaints [$F_{(3,3,858)}$ = 1.42, p = 0.234] nor subjective short-term memory complaints [$F_{(3,3,858)}$ = 1.73, p = 0.159]. The main effect of hearing aid use was significant for subjective long-term memory [$F_{(1,3,858)}$ = 5.70, p = 0.017, η^2 = 0.001] but not for subjective short-term memory [$F_{(1,3,858)}$ = 3.31, p = 0.07]. The interaction between hearing status and hearing aid use was only significant for subjective long-term memory complaints [$F_{(3,3,858)}$ = 2.76, p = 0.041, η^2 = 0.002] and not for subjective short-term memory complaints [$F_{(3,3,858)}$ =0.26, p = 0.852]. All pairwise comparisons showed

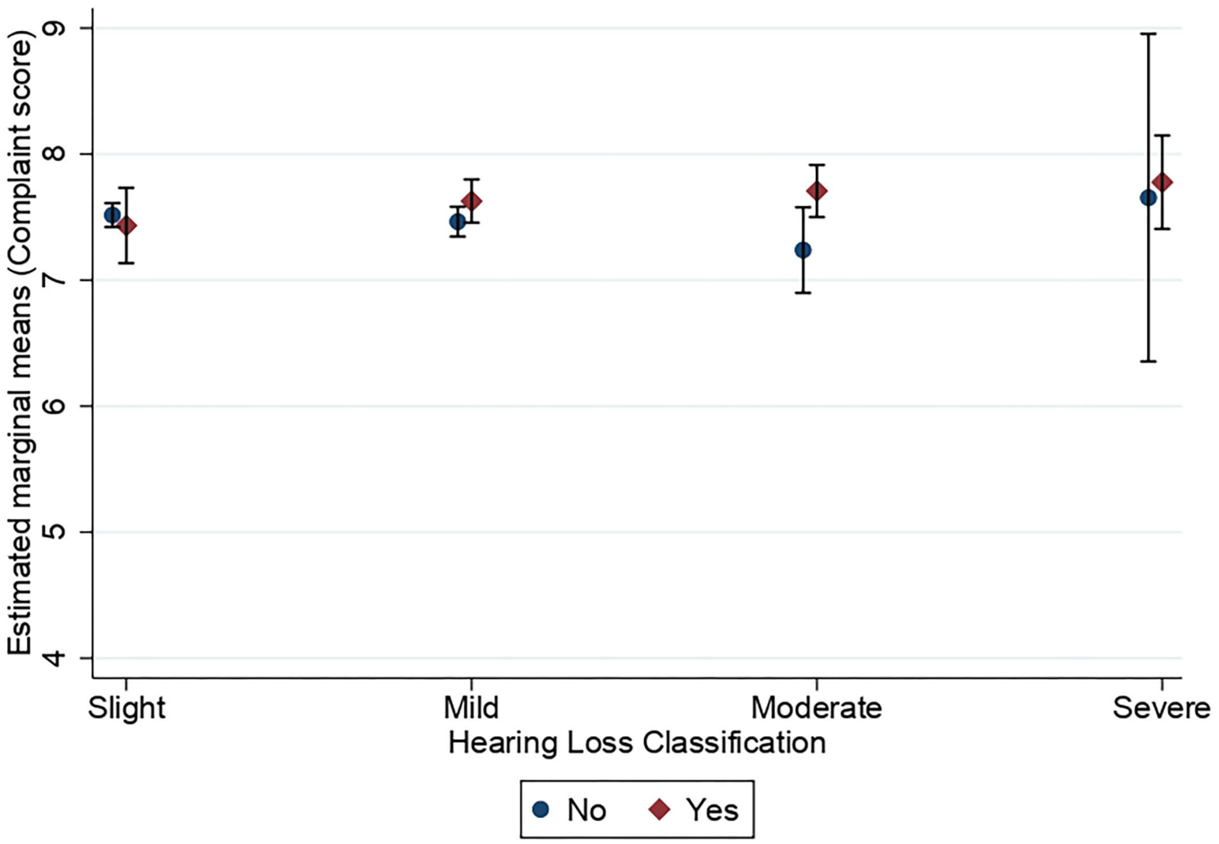

FIGURE 3
Estimated marginal means of subjective long-term memory complaints as a function of hearing status and the use of hearing aids. Estimates are averaged over the levels of age at the means of the covariates sex, education, stroke, diabetes, smoking, and hospital admission for a head injury. The error bars indicate 95% confidence intervals.

no significant differences between hearing loss groups with respect to subjective long-term memory.

4. Discussion

Using data from a large cross-sectional study, we found that hearing loss is associated with increased subjective long-term memory complaints and not with subjective short-term memory complaints. Our findings add to the literature by showing that the negative effect of hearing loss on subjective memory complaints depends, to some extent, on the type of memory system. These findings are in line with the findings of Rönnberg et al. (10) who reported an adverse effect of hearing loss for objective long-term memory and not for objective short-term memory. The interaction between hearing aid use and hearing status on long-term memory in the hearing-impaired group is an interesting finding. One interpretation of this finding might be that as the long-term memory system is susceptible to hearing loss, this memory system can benefit from hearing rehabilitation by hearing aid. This interpretation calls for future research to further assess the effects of hearing aid use on different memory systems in people with hearing loss.

Curhan et al. (13, 14) showed a negative effect of self-reported hearing loss on subjective memory complaints. Our study, by using objective hearing measures, extends the literature by showing that the association between hearing loss and subjective memory complaints depends greatly on the type of subjective memory system. Jayakody et al. (15) reported no association between 4PTA hearing thresholds and subjective memory complaints. We reason that one explanation for this inconsistency between our findings and Jayakody et al. (15) might be that the sample size in this study was larger than Jayakody et al., which enabled us to detect small associations between different types of hearing ability and types of subjective memory complaints.

Several possible mechanisms have been hypothesized to explain the link between hearing loss and memory function. Short-term memory has a limited capacity to carry out

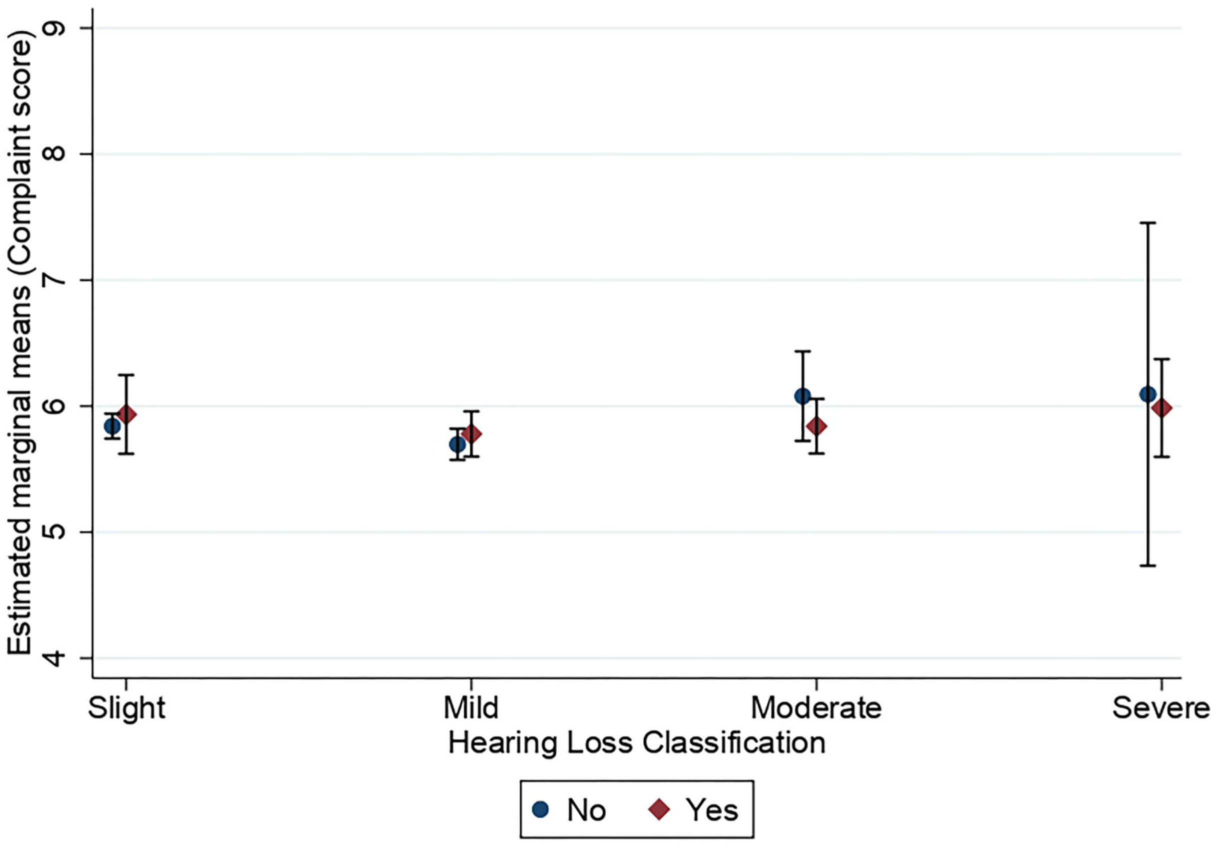

FIGURE 4
Estimated marginal means of subjective short-term memory complaints as a function of hearing status and use of hearing aids. Estimates are averaged over the levels of age at the means of the covariates sex, education, stroke, diabetes, smoking, and hospital admission for a head injury. The error bars indicate 95% confidence intervals.

operations for encoding, storage, rehearsal, and subsequent recall of information. Rönnberg et al. (28), in their ease of language understanding model (ELU model), proposed that working memory is employed continuously to reconstruct meaningful speech signals from less clearly heard speech signals, to map them onto corresponding phonological and lexical representations in long-term memory. In the ELU model, working memory has a dual function *to combine* speech cues that are distributed across time and frequency to finally infer meaning from the incoming speech signal. Thus, working memory is an active memory system in language understanding in people with hearing loss which subsequently results in less or no deterioration of working memory due to hearing loss.

Regarding long-term memory, the ELU model (28) assumes that the reconstruction of input signals by working memory is not always successful. Failed reconstructions of speech signals by working memory minimize the successful encoding of communicated words, meanings for lexical items, and events into episodic long-term memory. Consequently, this reduces the use of episodic long-term memory by people with hearing loss, resulting in the deterioration of episodic long-term memory in those individuals, associated with less practice and usage. In addition, the ELU model hypothesized that the mismatch between the impoverished speech signal and corresponding phonological/lexical representations, due to failed reconstructions, results in relatively less use or even disuse of semantic long-term memory in people with hearing loss. This decreased use or disuse of semantic long-term memory in people with hearing loss adversely affects the integrity of phonological and lexical representations and processing in the mental lexicon in people with hearing loss.

The strength of the present study lies in the large sample of participants in a population-based study that provides sufficient power to detect small associations between various types of hearing status and types of subjective memory complaints. In addition, the present study was the only one that used objective hearing measures to assess the hearing status of participants to evaluate the association between hearing status and subjective memory complaints. Controlling cofounders that likely biased the results was the other strength. One important limitation of the present study is that the duration of hearing aid use was not collected in HUNT4. We assume that the duration of hearing aid use plays a critical role in the association between hearing loss severity and subjective memory complaints in people with hearing loss. We encourage future studies to include the duration of hearing aid use on the association between hearing loss and subjective or objective memory functioning in people with hearing loss. The duration of hearing loss is another possible factor in the association between hearing loss and subjective memory complaints. Unfortunately, the data regarding the duration of hearing loss were not available in the HUNT 4. The present study, however, is a cross-sectional study that limits the inference of causality. Future longitudinal studies are needed to determine the direction of causality between hearing loss and subjective memory complaints and also the extent to which hearing aid use affects subjective memory complaints in people with hearing loss. Furthermore, as noted in the Method section, the participation rate was quite low at 43% which may limit the generalizability of the results. In addition, there may be potential confounders (like genetic factors) that were not included in our study. Another limitation of the current study is the small effect sizes found for the main effects of hearing loss on subjective long-term memory complaints. This may suggest that other factors associated with aging are contributing to a decrease in subjective memory complaints in people with hearing loss.

5. Conclusion

This study indicates an association between hearing loss and subjective long-term memory complaints and not for subjective short-term memory complaints. An interaction between hearing status and hearing aid use on subjective long-term memory was observed in hearing-impaired groups, which demands future research attention.

Data availability statement

The data analyzed in this study was obtained from the Trøndelag Health Study (the HUNT Study), the following licenses/restrictions apply: Access to the datasets is subject to approval by the Principal Investigators of the HUNT Study. Requests to access these datasets should be directed to the HUNT Study, kontakt@hunt.ntnu.no.

Ethics statement

The studies involving human participants were reviewed and the study was approved by the regional committee for medical and health research ethics and The Norwegian Data Protection Authority. The patients/participants provided their written informed consent to participate in this study.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Exploring neurocognitive factors and brain activation in adult cochlear implant recipients associated with speech perception outcomes—A scoping review

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Background: Cochlear implants (CIs) are considered an effective treatment for severe-to-profound sensorineural hearing loss. However, speech perception outcomes are highly variable among adult CI recipients. Top-down neurocognitive factors have been hypothesized to contribute to this variation that is currently only partly explained by biological and audiological factors. Studies investigating this, use varying methods and observe varying outcomes, and their relevance has yet to be evaluated in a review. Gathering and structuring this evidence in this scoping review provides a clear overview of where this research line currently stands, with the aim of guiding future research.

Objective: To understand to which extent different neurocognitive factors influence speech perception in adult CI users with a postlingual onset of hearing loss, by systematically reviewing the literature.

Methods: A systematic scoping review was performed according to the PRISMA guidelines. Studies investigating the influence of one or more neurocognitive factors on speech perception post-implantation were included. Word and sentence perception in quiet and noise were included as speech perception outcome metrics and six key neurocognitive domains, as defined by the DSM-5, were covered during the literature search (Protocol in open science registries: 10.17605/OSF.IO/Z3G7W of searches in June 2020, April 2022).

Results: From 5,668 retrieved articles, 54 articles were included and grouped into three categories using different measures to relate to speech perception outcomes: (1) Nineteen studies investigating brain activation, (2) Thirty-one investigating performance on cognitive tests, and (3) Eighteen investigating linguistic skills.

Conclusion: The use of cognitive functions, recruiting the frontal cortex, the use of visual cues, recruiting the occipital cortex, and the temporal cortex still available for language processing, are beneficial for adult CI users. Cognitive assessments indicate that performance on non-verbal intelligence tasks positively correlated with speech perception outcomes. Performance on auditory or visual working memory, learning, memory and vocabulary tasks were unrelated to speech perception outcomes and performance on the Stroop task not to word perception in quiet. However, there are still many uncertainties regarding the explanation of inconsistent results between papers and more comprehensive studies are needed e.g., including different assessment times, or combining neuroimaging and behavioral measures.

Systematic review registration: https://osf.io/z3g7w.

KEYWORDS

cochlear implants, neurocognition, scoping review, sensorineural hearing loss, postlingual, speech perception

1. Introduction

Cochlear implants (CIs) are considered an effective treatment for severe-to-profound sensorineural hearing loss, when hearing aids provide insufficient benefits. However, speech perception performance outcomes of this treatment are highly variable among adult CI listeners (Holden et al., 2013). Different biological and audiological factors, such as residual hearing before implantation and duration of hearing loss, only contribute to a small extent when explaining this variation (Zhao et al., 2020). A multicentre study using data from 2,735 adult CI users investigated how much variance in word perception outcomes in quiet could be explained by previously identified factors. When including 17 predictive factors (e.g., duration of hearing loss, etiology, being a native speaker, age at implantation, and preoperative hearing performance) in a linear regression model, the variance explained was only 0.12–0.21 (Goudey et al., 2021).

To decrease uncertainty, other factors, such as (neuro)cognition need to be considered. Neurocognitive factors are skills used to acquire knowledge and manipulate information and reasoning. In addition to bottom-up factors, top-down neurocognitive factors have been proposed to contribute to variation in postoperative speech perception (Baskent et al., 2016; Moberly et al., 2016a). In this context, top-down processing means that higher-order cognitive processes drive lower-order systems. For example, prior knowledge is used for processing incoming information from the senses such as speech (bottom-up information). Bottom-up processes are lower-order mechanisms that, in turn, can trigger additional higher-order processing (Breedlove and Watson, 2013). Interactions of top-down processes and neurocognitive functions with the incoming speech signal, have been shown to be highly important for distorted speech recognition (Davis and Johnsrude, 2007; Stenfelt and Rönnberg, 2009; Mattys et al., 2012). Given that speech signal output from a CI is distorted, neurocognitive mechanisms are needed for active and effortful decoding of this speech. This is thought to enable CI listeners to compensate for the loss of spectro-temporal resolution (Baskent et al., 2016; Moberly et al., 2016a). Several studies have investigated the association of neurocognitive factors and brain activation patterns with CI performance. These studies did not only use varying designs and methods, but also observed varying results. A literature review may help interpret and summarize these outcomes. After a preliminary search for existing reviews in PROSPERO and PubMed (June 2020) showed that these studies were not collected and evaluated in a review before, this scoping review was initiated.

The objective of this scoping review is to gain understanding of which brain activation patterns and top-down neurocognitive factors are associated with speech perception outcomes in hearing-impaired adults after cochlear implantation. This is also done by exploring differences between poorer and better performers. When referring to top-down neurocognitive factors or mechanisms, we refer to the ones that can be classified under one of six neurocognitive domains, defined in the Diagnostic Statistical Manual of Mental Disorders, Fifth Edition (DSM-5); (1) complex attention, (2) executive function, (3) social cognition, (4) learning and memory, (5) perceptual-motor function, and (6) language (**Figure 1**; Sachdev et al., 2014).

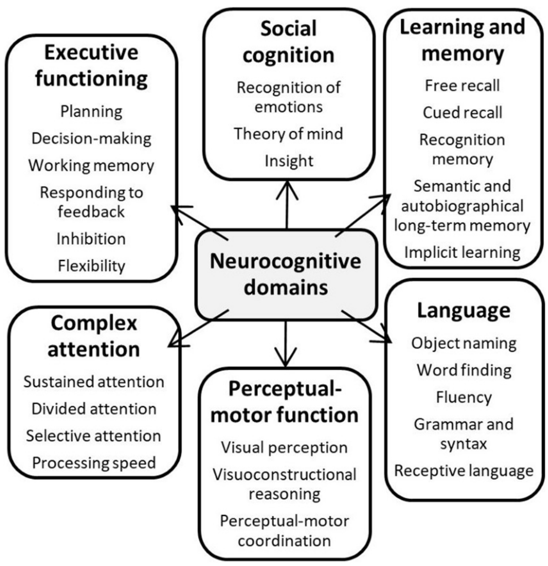

FIGURE 1
Key cognitive domains defined by the Diagnostic Statistical Manual of Mental Disorders, Fifth Edition (DSM-5). [Source: Sachdev et al. (2014)].

Abbreviations: CI, Cochlear Implant; CVLT, California Verbal Learning Test; DSM-5, Diagnostic Statistical Manual of Mental Disorders, Fifth Edition; EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy; (f)MRI, (functional) magnetic resonance imaging; MoCA, Montreal Cognitive Assessment; OSPAN, Operation Span; PET, positron emission tomography; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analysis; RAN, Rapid Automatic Naming; SAGE, Self-Administered Gerocognitive Examination; SicSpan, Size comparison Span; TMT (–A/B), Trail Making Task (version A or B); TOWRE, Test of Word Reading Efficiency; TRT, Text Reception Threshold; VEP, visual evoked potential; WAIS-III, Wechsler Adult Intelligence Scale III; WJ-IV, Woodcock-Johnson IV (test battery); WRAT, Wide Range Achievement Test.

1. **Complex attention** involves sustained attention, divided attention, selective attention, and processing speed. Attention is a state or condition of selective awareness or perceptual receptivity by which a single stimulus or task (sustained), or several (divided) are selected for enhanced processing, while possibly other irrelevant stimuli, thoughts, and actions are ignored (selective). Cortical regions that play an important role in attentional processes are the posterior parietal lobe and cingulate cortex (Breedlove and Watson, 2013).
2. **Executive function** includes planning, decision-making, working memory, responding to feedback, inhibition, flexibility, and non-verbal intelligence – all high-level control processes that manage other cognitive functions important for generating meaningful goal-oriented behavior. The frontal lobe is mainly involved in these processes (Breedlove and Watson, 2013).
3. **Social cognition** refers to cognitive processes involved in social behavior (Hogg and Vaughan, 2018). In other words, how people think about themselves and others and how these processes affect judgment and behavior in a social context, leading to socially appropriate or less appropriate behavior. These behaviors include the recognition of emotions, having theory of mind and insight (Sachdev et al., 2014).
4. **Learning and memory** include short-term memory, measured by free and cued recall, recognition memory, semantic and autobiographical long-term memory, and implicit learning. Learning is acquiring new and relatively enduring information, behavior patterns or abilities, because of practice or experience. Memory is the ability to store learned information and retrieve or reactivate it over time. Structures of the limbic system, the temporal and frontal cortex are mainly involved in memory formation, but plasticity within the brain also indicates learning (Breedlove and Watson, 2013).
5. **Perceptual-motor function** includes visual perception, visuoconstructional reasoning and perceptual-motor coordination (Sachdev et al., 2014). These are processes involved in movement and being able to interact with the environment.
6. **Language**, the most sophisticated structured system for communicating (Breedlove and Watson, 2013), encompasses skills needed for both language production (object naming, word finding, fluency, grammar and syntax) and language comprehension (receptive language and grammar and syntax). Areas involved in language processing are Broca's area in the frontal lobe, along with the primary motor cortex, the supramarginal gyrus in the parietal cortex, and Wernicke's area, primary auditory cortex and angular gyrus in the temporal cortex (Breedlove and Watson, 2013).

These domains are not mutually exclusive, meaning that some cognitive functions might be part of processes underlying other cognitive functions. For example, social cognitive skills involve executive functions, such as decision-making. In the same way, this review will explore which cognitive factors are involved in or part of speech perception processing in adult CI users, which can be classified as a neurocognitive factor under the language domain. Furthermore, CI users might recruit several alternative brain regions during auditory and speech perception. Identifying these activation patterns could pinpoint neurocognitive mechanisms that facilitate or constrain speech perception outcomes (Lazard et al., 2010). Therefore, in addition to studies including behavioral cognitive measures, studies using neuroimaging metrics will be explored.

In this review, speech perception outcomes encompass word or sentence perception in quiet and noise. Besides assessing CI performance, some studies use these speech perception outcome metrics to classify patients as good or poor performers (e.g., Suh et al., 2015; Kessler et al., 2020; Völter et al., 2021). However, there are no general guidelines for classifying good and poor performers, resulting in varying performance classification between studies. See for example, Kessler et al. (2020), divided good and poor performers based on sentence perception in noise. Other examples with respect to word perception in quiet are Völter et al. (2017), who used as cut-off scores > 30 and < 70% for, respectively poor and good performers, while Mortensen et al. (2006), opted for > 60 and < 96% limits. Suh et al. (2015) used 80% speech perception score to split between poor and good performers. Therefore, when discussing studies having implemented performance classification, their participants will be referred to as "better" and "poorer" performers in this review.

Discussing and summarizing the wide variety of studies investigating the association between neurocognitive factors and CI performance in a systematic scoping review might provide new insights and guide new research on this topic. Research in this field helps understand CI outcome variation and could be particularly valuable to improve care for poorer performing adult CI listeners. Being able to more accurately predict performance outcomes will facilitate managing their expectations. Furthermore, identification of the root causes of poorer performance could lead to the development of individualized aftercare.

2. Methods

2.1. Protocol and registration

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) was used for this systematic scoping review (Moher et al., 2009). A systematic scoping review was performed instead of a systematic literature review because of the variability in methods between the included studies. Therefore, this review does not include any meta-analysis or risk of bias assessment. Furthermore, Population, Concept, and Context (PCC) was used as the research question framework (Peters et al., 2015). The population being postlingually deaf adult CI users, the concept being speech perception outcomes, in the context of neurocognition. The protocol of this review was registered in the open science registries 10.17605/OSF.IO/Z3G7W.

2.2. Eligibility criteria

This review encompasses studies investigating the influence of one or more neurocognitive factors on speech perception after cochlear implantation. Word and sentence perception in quiet and noise were included as speech perception outcome metrics.

Studies including participants listening in both unimodal (CI-only), bimodal (CI and hearing aid) and bilateral (CI both ears) conditions were eligible. To provide a complete overview, the six key neurocognitive domains as defined by the DSM-5 were covered during the literature search. No limitations on cognitive measures were implemented. Included study designs were cross-sectional studies, non-randomized control trials, quasi-experimental studies, longitudinal studies, prospective and retrospective cohort studies and meta-analysis performed in a clinical setting. Studies from publication year 2000 and onward were included. Furthermore, all studies involving children and adults with a prelingual onset of deafness were excluded. There were no restrictions on publication status or language of publication (**Figure 2B**).

2.3. Data sources and search strategy

Four scientific databases: PubMed, Embase, PsychInfo and Web of Science were searched. BioRxiv and medRxiv were used to search for any preprints. Terms and their synonyms related to the outcomes, predictive factors based on the DSM-5 neurocognitive domains and patient population were included in the search strategy. Thesauruses like MeSH and Emtree were used besides free-text terms in titles and abstracts. The search strategies for each database can be found in **Supplementary Material Part A**. Reference lists of articles were scanned for additional suitable studies. Systematic searches were conducted up to July 2020 and assisted by a trained librarian. In April 2022 a second search was performed using the same protocol.

2.4. Study selection

Literature screening was performed in two steps. First, the results of all databases were merged. Duplicates were removed using Rayyan QCRI systematics review app (Ouzzani et al., 2016) and Endnote (EndNote X9, 2013, Clarivate, Philadelphia, PA, USA). Second, two authors (LB and NT) blindly selected relevant studies by screening titles and abstracts based on the eligibility criteria in the same app. In case it was unclear from the title and abstract if an article should be included, the decision was made based on full-text. Any study selection conflict was resolved by discussion between two authors (LB and NT).

2.5. Data extraction and management

After screening all included publications, a custom data extraction form was used for data capturing, which was piloted before data collection commencement. The final form included details relating to study design, participants, eligibility criteria, hearing device, speech perception measurement, cognitive measurement, relation between cognitive measurement and outcome, analysis method, limitations, possible biases and the conclusion of the author.

3. Results

A total of 5,652 unique articles were retrieved. After screening titles, abstracts of 150 articles remained for full-text screening. Of these 150 articles, 96 were excluded based on reading the full-text. In 26 studies, there was no speech perception outcome reported or used in the relevant analysis (Giraud et al., 2000, 2001a,b; Gfeller et al., 2003; Oba et al., 2013; Berding et al., 2015; Finke et al., 2015; Jorgensen and Messersmith, 2015; Song et al., 2015b; Wang et al., 2015; McKay et al., 2016; Shafiro et al., 2016; Perreau et al., 2017; Amichetti et al., 2018; Butera et al., 2018; Bönitz et al., 2018; Cartocci et al., 2018; Lawrence et al., 2018; Moberly et al., 2018b; Patro and Mendel, 2018, 2020; Dimitrijevic et al., 2019; Chari et al., 2020; Zaltz et al., 2020; Schierholz et al., 2021; Abdel-Latif and Meister, 2022). Twenty-two studies were excluded based on population criteria, studies testing children and adults with prelingual onset of hearing loss (El-Kashlan et al., 2001; Most and Adi-Bensaid, 2001; Lyxell et al., 2003; Rönnberg, 2003; Middlebrooks et al., 2005; Doucet et al., 2006; Heydebrand et al., 2007; Rouger et al., 2007; Hafter, 2010; Li et al., 2013; Lazard et al., 2014; Bisconti et al., 2016; Anderson et al., 2017; Finke et al., 2017; Miller et al., 2017; Moradi et al., 2017; Purdy et al., 2017; McKee et al., 2018; Verhulst et al., 2018; Winn and Moore, 2018; Lee et al., 2019; Smith et al., 2019). In 22 studies, no neurocognitive measure was present (Meyer et al., 2000; Vitevitch et al., 2000; Wable et al., 2000; Giraud and Truy, 2002; Lachs et al., 2002; Lonka et al., 2004; Kelly et al., 2005; Debener et al., 2008; Tremblay et al., 2010; Winn et al., 2013; Moberly et al., 2014; Turgeon et al., 2014; Ramos-Miguel et al., 2015; Collett et al., 2016; Purdy and Kelly, 2016; Sterling Wilkinson Sheffield et al., 2016; Harris et al., 2017; Alemi and Lehmann, 2019; Balkenhol et al., 2020; Crowson et al., 2020; Naples and Berryhill McCarty, 2020; Lee et al., 2021). Fifteen reviews were excluded as they did not include an original study (Wilson et al., 2003, 2011; Mitchell and Maslin, 2007; Peterson et al., 2010; Aggarwal and Green, 2012; Anderson and Kraus, 2013; Lazard et al., 2013; Anderson and Jenkins, 2015; Baskent et al., 2016; Pisoni et al., 2016, 2017; Wallace, 2017; Oxenham, 2018; Bortfeld, 2019; Glennon et al., 2020). Two articles were excluded because they focused on a reversed hypothesis (the influence of CI on cognition) (Anderson and Jenkins, 2015; Nagels et al., 2019) and nine articles were excluded because no abstract and/or full-text paper was available. Fifty-four articles remained after full-text screening. From scanning the references lists of these papers, 28 abstracts were considered. After reading four full-text papers (Lee et al., 2001; Suh et al., 2009; Tao et al., 2014; Wagner et al., 2017), none of the articles were included, leading to 54 included articles (**Figure 2A**).

The selected articles were grouped into three categories: (1) Studies investigating brain activation patterns in CI users in relation to speech perception performance (N = 18), this includes articles assessing cross-modal activation, (2) Studies investigating performance on cognitive tests in relation to performance on speech perception tests (N = 17), and (3) Studies investigating the use of linguistic skills and information and the relationship with speech perception performance (N = 5). Note that some studies investigated both brain activation and cognitive and linguistic functions (N = 1), or cognitive and linguistic skills (N = 13). Each category of studies will be discussed below. An overview of these studies is shown in **Supplementary Tables 1–4**.

3.1. Brain activation

Three of the 15 studies observed activation patterns during auditory or speech perception, whereas nine focused on cross-modal activation. Three papers used speech imagery tasks preoperatively

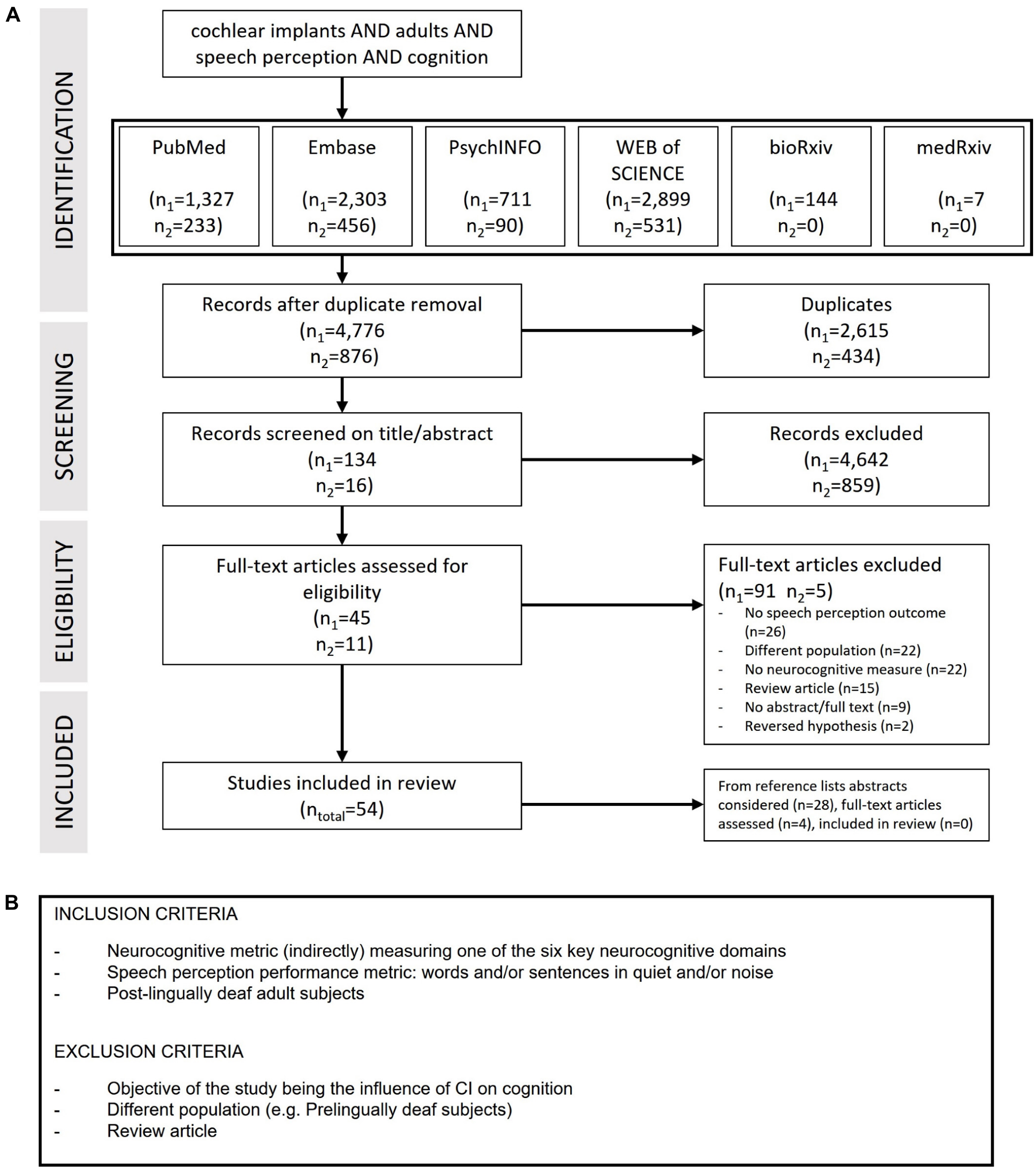

FIGURE 2
(A) Preferred reporting items for systematic reviews and meta-analysis (PRISMA) flowchart of the literature search and study selection. Last date of first search June 2020, numbers are indicated with n_1. Last date of second search April 2022, numbers are indicated with n_2. **(B)** Inclusion and exclusion criteria of the articles.

instead of speech perception tasks. These studies are discussed below. To better understand the brain areas involved, data are visualized in Figure 3.

3.1.1. Brain responses to auditory stimuli

Three studies divided their participants into better and poorer performers based on speech perception performance and explored the differences in brain activation while listening. These are Mortensen et al. (2006), Suh et al. (2015), Kessler et al. (2020) (see Table 1 for an overview) and are summarized below:

First, Mortensen and colleagues showed alternative patterns of activation between better performers (96–100% word score in quiet) and poorer performers (<60% word score in quiet), while listening passively to a range of speech and non-speech stimuli. Better performers showed increased activity in the left inferior prefrontal, left and right anterior and posterior temporal cortex (auditory cortex), and the right cerebellum. Poorer performers only showed increased activity in the left temporal areas ($p < 0.05$) (Mortensen et al., 2006).

Second, Suh et al. (2015) measured preoperative brain activation during listening to noise and compared the results of a group of postoperative poorer and better (cutoff: 80%-word score) performers. Participants with higher activity in the inferior temporal gyrus and premotor areas (part of frontal cortex) became better performers ($p = 0.005$), and participants with higher activation in the occipital lobe (visual cortex) became poorer performers ($p = 0.01$) (Suh et al., 2015).

In the third study, Kessler et al. (2020), examined brain activation during a speech discrimination task consisting of correct and incorrect sentences. When dividing the group of participants into

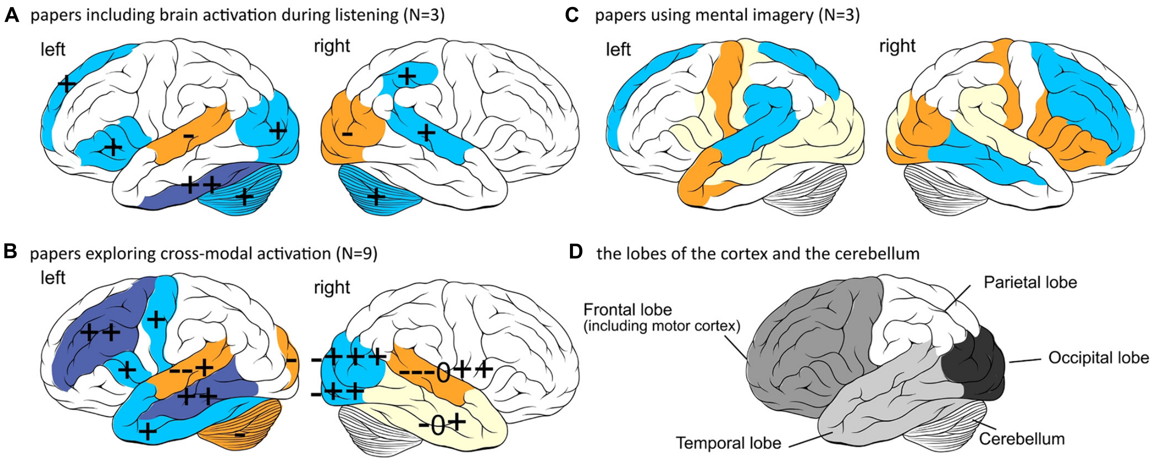

FIGURE 3
Regions of the cortex found to be activated in the papers related to speech perception outcomes. +, −, and 0 indicates a positive correlation, negative correlation, or null results, respectively found in an included paper. Accuracy of the depiction depends on accuracy of the reports, neuroimaging and analysis technique used in the papers. Top: left hemisphere, Bottom: right hemisphere. **(A)** The parts of the cortex found to be activated during auditory perception related to speech perception outcomes. Blue areas are found to be positively correlated and orange areas negative. **(B)** The parts of the cortex found to be activated during auditory perception, and visual perception. Blue areas are found to be mostly positively correlated and orange areas mostly negative. Yellow areas show conflicting results. The right amygdala (+), cingulate sulcus (+) and bilateral thalami (−) are not depicted because they are not located on the outside cortex. **(C)** The parts of the cortex found to be activated during speech imagery tasks preoperatively. Blue areas are found to be positively correlated and orange areas negative. Yellow areas show conflicting results. Since most of this data is from the same participant group, no signs are used to indicate findings per paper. Left and right medial temporal lobes including hippocampal gyrus are not depicted because they are not located on the outside cortex. **(D)** The lobes of the cortex (frontal, parietal, temporal, and occipital lobe) and the cerebellum. This image can be used as a guidance to read the text and interpret part **(A–C)** of the figure. The outline of the brain was drawn by Patrick J. Lynch, medical illustrator and C. Carl Jaffe, MD, cardiologist, https://creativecommons.org/licenses/by/2.5/.

TABLE 1 **Overview of included papers studying brain responses to auditory stimuli.**

References, sample size	Method	Speech perception measure	Statistical test (y/n) indicating a power analysis	Key findings
Mortensen et al., 2006, Nbetter = 7 Npoorer = 5	PET during several speech and non-speech stimuli	SQ	*T*-test of high performing vs low performing group (n)	(+) The better performers showed more activation in the left inferior prefrontal and right anterior and posterior temporal cortex and the right cerebellum. (−) The poorer performers showed more activation in the left temporal areas $p < 0.05$.
Suh et al., 2015, *N* = 15	PET during noise–preoperatively	WQ + SQ	Mann-Whitney U test for difference in means (n)	(+) ITG and premotor area in better performers $p = 0.0005$. (−) Occipital area in poorer performers $p = 0.01$.
Kessler et al., 2020, *N* = 21 (see also Tables 4, 8, 10)	SPECT scan and EEG during semantic correct vs. incorrect sentences	WQ SQ + N	Independent *T*-test and difference images (n)	Sentence test groups: (+) Better performers show higher activation in the left occipital area and right temporal area ($p < 0.001$) during task. (−) Poorer performers show higher activation in the left and right frontal BA9 and left ITG ($p < 0.001$) during task.

For each paper sample size (N), neuroimaging method, speech perception outcome measure (WQ, words in quiet; SQ, sentences in quiet; SQ+N, sentences in quiet and noise); statistical test [including a report of a power analysis (y), yes; (n), no], and key findings are reported [(+), positive significant result; (−) negative significant result; *(ns) non-significant result*]. EEG, electroencephalography, ITG, inferior temporal gyrus, PET, positron emission tomography, SPECT, single-photon emission computed tomography. A more detailed version can be found in Supplementary Table 2.

better and poorer performers [median split with cutoff +7.6 dB Signal to Noise Ratio (SNR) on a sentence test in noise], better performers showed significantly higher activity in the right parietal and temporal area and left occipital area ($p < 0.001$, uncorrected for multiple comparisons), and poorer performers significantly higher activation in the superior frontal areas ($p < 0.001$, uncorrected for multiple comparisons). Activity during resting state revealed that poorer performers had a higher activity in the right motor and premotor cortex and right parietal cortex, whereas better performers had higher activity in the left hippocampal area, left inferior frontal areas and left inferior temporal cortex ($p < 0.001$, uncorrected for multiple comparisons). The differences in activity between better and poorer performers in the bilateral temporal, frontal, parietal, and bilateral motor cortex were significantly positively correlated with performance on a monosyllabic word test and the MWT-B verbal intelligence test ($p > 0.001$, uncorrected and $p < 0.05$ FWE). There were also small positive correlations between this activity in the left temporal, parietal and occipital regions with working memory span scores, and activity in the left temporal lobe with a verbal learning task (only in testing without correction for multiple comparisons and not in tests including FWE) (Kessler et al., 2020).

3.1.2. Responses to audio, visual and audio-visual stimuli indicating cross-modal activation

In individuals with hearing loss cross-modal activation occurs when two things are at play. (1) The visual cortex is involved in auditory perception. (2) The auditory cortex is also recruited and used to process visual stimuli instead of or in addition to auditory stimuli to understand speech (Bavelier and Neville, 2002). Several studies have investigated whether such reorganization occurs in postlingually deaf participants and whether it is related to postoperative speech perception performance, as this reorganization might limit these areas to return to their original functioning (see **Table 2** for an overview). These studies are summarized below (* indicates whether the study reported sufficient power):

Six of the ten studies observed activation in the temporal lobe (auditory cortex) in response to visual stimuli and activation in the occipital lobe (visual cortex) in response to auditory stimuli [they used ROI (Regions Of Interest)] (Buckley and Tobey, 2010; Sandmann et al., 2012; Chen et al., 2016, 2017; Kim et al., 2016; Zhou et al., 2018). Buckley and Tobey (2010) did not find any significant correlation between activation in the temporal lobe in response to visual stimuli and word and sentence perception in noise ($r = 0.1618$, $p = 0.6155$*). On the contrary, Sandmann et al. (2012) did find activation in the right temporal cortex evoked by visual stimuli to significantly negatively correlate with word perception in quiet ($r = -0.75$, $p < 0.05$) and positively correlate with sentence perception in noise ($r = 0.72$, $p < 0.05$). Kim et al. (2016), also found that better performers (>60% word score in quiet) showed a significantly smaller P1 amplitude in response to visual stimuli compared to poorer performers (<40% word score) ($p = 0.002$*). Additionally, better performers showed larger P1 amplitudes in the occipital cortex ($p = 0.013$*). Both effects showed a correlation with a word intelligibility test (occipital: $r = 0.755$, $p = 0.001$; temporal: $r = -0.736$, $p = 0.003$*) (Kim et al., 2016). Zhou et al. (2018) confirmed these results and found a significant negative correlation between temporal cortex activation and word perception in quiet and sentences in quiet and noise ($r = -0.668$, $p = 0.009$). Along the same lines, correlations to sentence perception in quiet and noise revealed a higher activation in the visual cortex to be positively correlated, as opposed to higher activation in the auditory cortex induced by visual stimuli ($r = 0.518$, $p = 0.027$). It was found that if the beneficial activation in the visual cortex was higher than the activation in the auditory cortex induced by visual stimuli, speech perception was better (Chen et al., 2016). A follow-up analysis calculated the correlations of the continuous input streams of the different areas. It was found that CI users with significantly higher connectivity for auditory than visual stimuli performed better on a word perception test in quiet ($r = 0.525$, $p = 0.021$), but no correlation was found for a sentence perception test in quiet or noise. This might have facilitated auditory speech perception learning processes by supporting visual cues, such as lip reading (Chen et al., 2017).

Three out of ten studies analyzed whole brain activation in response to auditory, visual and audiovisual stimuli (Strelnikov et al., 2013; Song et al., 2015a; Layer et al., 2022). Strelnikov et al. (2013) also found significant negative correlations of temporal lobe activity with word perception in quiet (rest: $r = 0.9$, visual: $r = 0.77$, audiovisual: $r = 0.7$, $p < 0.05$) and positive correlations with posterior temporal cortex and occipital lobe activation (rest: $r = 0.9$, visual: $r = 0.8$, audiovisual: $r = 0.5$, $p < 0.05$). However, Song et al. (2015a) found a negative correlation between occipital lobe activation and word perception in quiet (left: rho = −0.826, $p = 0.013$, right: rho = −0.777, $p = 0.019$). Similarly, Layer et al. (2022) did not find a correlation between activation in the left temporal cortex in response to audiovisual stimuli with word perception in quiet ($r = 0.27$, $p = 0.29$). While the whole brain was observed in these studies, Strelnikov et al. (2013) found activation in the inferior frontal area to be positively correlated with word perception in quiet (rest: $r = 0.809$, visual: $r = 0.77$, audiovisual: $r = 0.90$, $p < 0.05$). This is in line with results from the previous section "3.1.1 Brain responses to auditory stimuli". Song et al. (2015a) also observed activation in the right amygdala to be positively correlated with word perception in quiet (rho = −0.888, $p = 0.008$).

Lastly, one paper by Han et al. (2019) measured activity pre-implantation and found a significant negative correlation between activity in the superior occipital gyrus and postoperative word score in quiet ($r = -0.538$, $p < 0.001$), as well as a positive correlation with the dorsolateral and dorsomedial frontal cortex ($r = 0.595$, $p > 0.001$). No significant correlation was found with activity in the auditory pathway areas, the inferior colliculus, and the bilateral superior temporal gyrus.

Another way to consider cortical reorganization, focusing more on altered cortical structure than brain activity, is analyzing gray matter probabilities using Magnetic Resonance Imaging (MRI) pre-implantation. Researchers found that gray matter probability in the left superior middle temporal cortex ($r = 0.42$) and bilateral thalamus ($r = -0.049$, $p < 0.05$) significantly predicted postoperative word recognition in quiet (Sun et al., 2021). Similarly, Knopke et al. (2021) demonstrated that white matter lesions (captured using the Fazekas Score) predicted word perception scores in quiet after implantation in 50–70 year-old CI users, but not in older users. The white matter score explained 27.4% of the speech perception variance in quiet ($p < 0.05$, df = 24 and 21), but was not replicated for a sentence test in noise.

3.1.3. Imaging during "mental auditory tasks" other than auditory/speech perception

A group of studies by Lazard et al. (2010, 2011) and Lazard and Giraud (2017) used "mental auditory tasks" to overcome the negative impact of hearing impairment pre-implantation. The tasks involved imagining words or sounds without auditory input. It was hypothesized that performance on these tasks would involve brain areas similar to the ones involved in auditory processing and therefore show good correlations with speech perception outcomes postoperatively. These studies are summarised below (see **Table 3** for an overview):

Lazard et al. (2010) found preoperative imaging data can be used to distinguish future better (>70% word score in quiet) and poorer (<50% word score in quiet) performers based on a rhyming task recruiting phonological strategies during reading. Better performers relied on a dorsal phonological route (dynamic stimulus combination) during a written rhyming task, while poorer performers involved a ventral temporo-frontal route (global) and additionally recruited the right supramarginal gyrus. More specifically, they found a significant positive correlation between brain activation during the phonological task and post-CI word recognition in quiet in the left frontal, parietal, posterior temporal and bilateral occipital cortices. A negative correlation was found in the bilateral anterior temporal, inferior frontal cortex and

TABLE 2 Overview of included papers studying cross-modal activation.

References, sample size	Method	Speech perception measure	Statistical test, (y/n) indicating a power analysis reported	Key findings
Buckley and Tobey, 2010, $N = 12$	EEG (N1, Visual evoked potential) during presentation of visual gradients	WQ SN	Linear regression analysis of word and sentence scores against the amplitude of the N1 response. ROI: temporal lobe (y).	*(ns)* $r = 0.1618$, $p = 0.6155$
Sandmann et al., 2012, $N = 11$	EEG (P100, N150, P270) during presentation of visual checkerboard patters	WQ SN	Spearmans rank correlations between ERPs and speech perception (n).	WQ: (–) Right auditory cortex level 3 $r = -0.78$, $p < 0.05$, level 4: $r = -0.75$, $p < 0.05$ for right implanted participants SN: (+) Right auditory cortex level 3: *(ns)* $r = 0.63$, $p = 0.07$, level 4: $r = 0.72$, $p < 0.05$
Strelnikov et al., 2013, $N = 10$	PET during auditory and visual words vs. non-word presentation	WQ	Regression analysis and correlation analysis with family-wise error correction $p < 0.05$ (n).	(+) The right occipital cortex during rest: $r = 0.9$, during visual stimuli: $r = 0.8$ and audiovisual stimuli: $r = 0.5$, $p < 0.05$, In the left inferior frontal pole during rest $r = 0.809$, visual stimuli: $r = 0.77$ and audiovisual stimuli: $r = 0.90$ $p < 0.05$ (–) In the middle STG/STS and occipital cortex during rest: $r = -0.9$, visual stimuli: $r = -0.8$ and audiovisual stimuli: $r = -0.7$, $p < 0.05$
Song et al., 2015a, $N = 10$	PET during video with a speaker saying digits in auditory, visual and audiovisual condition congruent and incongruent – preoperatively	WQ	Correlation analysis between contrast images of each condition and word perception scores. Controlled for sex and age. P = 0.001 threshold (n).	(+) During congruent audiovisual stimuli the amygdala rho = 0.888, $p = 0.008$ (–) During congruent audiovisual stimuli the left rho = –0.826, $p = 0.013$ and right rho = –0.777, $p = 0.019$ occipital gyrus
Kim et al., 2016, $N = 14$	EEG (VEP) while patterned visual stimuli are presented	WQ	Spearman correlation analysis between words scores and amplitude and latency of P1 in ROIs: occipital and temporal electrodes, (y, but sample size insufficient).	(+) Larger P1 amplitude in occipital cortex $r = 0.755$, $p = 0.001$ Central visual field size $r = 0.699$, $p = 0.009$ (–) Larger P1 in right temporal cortex $r = -0.736$, $p = 0.003$
			Mann-whitney test to compare means per group.	(+) P1 in occipital cortex larger $p = 0.013$ in better performers (–) P1 in right temporal cortex smaller in better performers $p = 0.002$
Chen et al., 2016, $N = 19$	fNIRS during visual checkerboard stimuli and auditory stimuli	SQ + N	Pearsons correlation analysis between activation differences condition and SQ + N. ROI: right occipital cortex and left, right temporal cortex (n).	(+) $r = 0.518$, $p = 0.027$
Chen et al., 2017, $N = 19$	fNIRS during visual checkerboard stimuli and auditory word and reversed words	WQ SQ + N	Spearman correlation analysis between cross modal activation and speech recognition. ROI: temporal and occipital cortex (n).	WQ: (+) More cross modal plasticity for auditory than for visual stimuli $r = 0.525$, $p = 0.021$ SQ + N: *(ns)*
Zhou et al., 2018, $N = 15$	fNIRS during audio, visual and audiovisual speechreading	WQ, SQ + N	Pearson correlation between activation levels and speech test scores. ROI: STG/STS (n).	(–) Left STS and STG $r = -0.668$, $p = 0.009$
Han et al., 2019, $N = 27$	PET during noise, no instruction – preoperatively	WQ	Pearson correlation between change in brain metabolism ($p = 0.001$) and speech test scores (n).	(+) Dorsolateral and dorsomedial frontal areas $r = 0.595$, $p > 0.001$ (–) Superior occipital gyrus $r = -0.538$, $p < 0.001$
Sun et al., 2021, $N = 94$	MRI scan looking at gray matter—cortical reorganization	WQ	Clusters with random forest regression. Vector machine regression as a linear method (n).	(+) Left medial temporal cortex $r = 0.42$, $p < 0.05$ (–) Left superior temporal cortex $r = -0.32$, bilateral thalami $r = -0.049$, $p < 0.05$
Knopke et al., 2021, $N_{young50-70} = 25$, $N_{old<70} = 23$	White matter lesions with Fauzekas score	WQ SQ + N	Multiple linear regression analysis with backward elimination (n), df = 24 and 21.	(+) Lesions are a significant predictor of speech perception in quiet in younger group. 27.4%, $p < 0.05$ *(ns)* Older group
Layer et al., 2022, $N = 17$	EEG during visual, auditory and audiovisual "ki" and "ka"	WQ	Pearson correlation with Benjamin Hochberg procedure for multiple comparisons (n).	*(ns)* Left auditory cortex activation and speech perception. $r = 0.27$, $p = 0.29$

For each paper sample size (N), neuroimaging method, speech perception outcome measure (WQ, words in quiet; SN, sentences in noise; SQ+N, sentences in quiet and noise); statistical test [including a report of a power analysis (y), yes; (n), no], and key findings are reported [(+), positive significant result; (–) negative significant result; *(ns), non-significant result*]. EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy; MRI, magnetic resonance imaging; PET, positron emission tomography; ROI, region of interest; STG/STS, superior temporal gyrus/sulcus. A more detailed version can be found in **Supplementary Table 2**.

TABLE 3 Overview of included papers studying brain activation during mental auditory tasks.

References, sample size	Method	Speech perception measure	Statistical test, (y/n) indicating a power analysis reported	Key findings
Lazard et al., 2010, $N = 7$	fMRI during a phonological rhyming task and word categorization task–preoperatively	WQ	Multiple regression analysis between fMRI data and phonological performance on a reading task, duration of deafness and hearing loss and word recognition scores (n).	(+) During the phonological task the left frontal, parietal, posterior temporal and occipital cortex (–) During the phonological task the anterior temporal, inferior frontal and right supramarginal gyrus. $p < 0.001$ uncorrected.
			Poorer vs. better performers based on Lafon test t-test.	(+) Dorsal regions and bilateral occipital regions more activated in better performers. (–) Bilateral ventral network (anterior temporal lobe, inferior frontal cortex and left temporal occipital junction) and right supramarginal gyrus more activated in poorer performers.
Lazard et al., 2011, $N = 10$	fMRI during a visual imaging task of colors and sounds–preoperatively	WQ	Regression analysis (n).	(+) During sound imagery activity in the left inferior frontal gyrus was positively correlated with speech perception $r = 0.94$, $p = 0.0001$.
			Poorer vs. better performers based on word perception t-test.	(+) The dorsal fronto-parietal and occipital regions more activated in better performers. (–) The ventral network (bilateral medial temporal lobes incl hippocampal gyrus) more activated in poorer performers.
Lazard and Giraud, 2017, $N = 11$	fMRI during visual rhyming decision task–preoperatively	WQ	Correlation between occipital-temporal coupling and speech perception (n).	(+) Better performers: left posterior STG/STS (–) Poorer performers: left and right fronto-parietal regions, left visual cortex, right posterior STS, right visual cortex. $p < 0.001$ uncorrected.

For each paper sample size (N), neuroimaging method, speech perception outcome measure (WQ, words in quiet), statistical test [including a report of a power analysis (y), yes; (n), no], and key findings are reported [(+), positive significant result, (–), negative significant result; *(ns), non-significant result*]. fMRI, functional magnetic resonance imaging; STG/STS, superior temporal gyrus/sulcus. A more detailed version can be found in **Supplementary Table 2**.

right supramarginal gyrus. This indicates that poorer performers rely more on semantic information, bypassing the phoneme identification and better performers rely more on visual input ($P < 0.001$ uncorrected).

The same research group correlated preoperative imaging data measured during an auditory imagery task with post-CI word scores in quiet. This showed a decline in activity in the dorsal and frontoparietal cortex and an increase in the ventral cortical regions, right anterior temporal pole and hippocampal gyrus. Activation levels of the right posterior temporal cortex and the left insula were not significantly correlated, but activation levels of the inferior frontal gyrus were positively correlated with word scores in quiet ($r = 0.94$, $p = 0.0001$) (**Figure 3C**; Lazard et al., 2011).

Lastly, Lazard and Giraud (2017) used a visual phonological rhyming task, including non-words that are pronounced as words, and measured brain activity preoperatively. They correlated this with postoperative word scores in quiet and found that response time on the task ($r = 0.60$, $p = 0.008$) and reorganized connectivity across the bilateral visual, right superior temporal sulcus and the left superior parietal cortex/postcentral gyrus correlated significantly with poorer CI performance ($p < 0.001$). Slower response times were associated with increased activity in the frontoparietal regions and better CI performance. Based on these papers, the group of Lazard concluded that poorer performers use more semantic concepts of sounds instead of phoneme identification, even when not confronted with auditory input. Better performers seemed to be able to utilize additional visual input to support speech perception, as also seen in the studies investigating cross-modal plasticity.

3.2. Cognitive tasks

In this review, 31 studies used cognitive tests to assess one or more neurocognitive function(s) and related these outcomes to speech perception outcomes. The studies are described below. **Table 4** summarizes time, type of speech perception measurements and related cognitive domain of the papers. Additionally, the sample size and whether a power analysis is reported are noted down. Note that most studies performed cognitive testing postoperatively. If a study performed cognitive assessment preoperatively this will be explicitly mentioned. All speech perception measures were performed postoperatively.

3.2.1. General cognitive measures

Three of the included papers used general (diagnostic) cognitive measures, not specifying which of the cognitive domains were measured by the task. These four more clinical tests, mostly used to detect early signs of Dementia (see **Table 5a** for an overview), are: (1) The Mini-Mental State Examination (MMSE) which did not significantly correlate with word perception in quiet ($r^2 = 0.061$, $p = 0.280$, $N = 15$) (Zucca et al., 2022). (2) The Self-Administered Gerocognitive Examination (SAGE), where preoperative screening of cognitive functions significantly positively correlated with word recognition in quiet [$r^2(32) = 0.1955$, $p = 0.0025$] and sentence perception in quiet [$r^2(32) = 0.1564$, $p = 0.0067$] and noise [$r^2(32) = 0.1543$, $p = 0.007$] (Wazen et al., 2020). (3) The Montreal Cognitive Assessment (MoCA), which was included in a multivariate model explaining variance in sentence perception performance in

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TABLE 4 Overview of included papers involving cognitive and language assessments.

References	Time of cognitive assessment		Speech perception measure				Cognitive domain (positive or negative outcome 0/−1/+1)							Sample size	Power reported (y/n)
	Preoperative	Postoperative	Words	Sentences	Quiet	Noise	Complex attention	Executive function	Social cognition	Learning and memory	Perceptual-motor function	Language	General		
Collison et al., 2004	–	x	x	–	x	–	–	0	–	–	–	0	–	15	–
Hay-McCutcheon et al., 2005	x	–	x	x	x	x	–	–	–	–	–	–1	–	34	–
Haumann et al., 2012	x	–	x	–	x	–	–	–	–	–	–	0	–	97	–
			–	x	–	x	–	–	–	–	–	1	–		–
Holden et al., 2013	x	–	x	–	–	–	–	0	–	0	–	0	–	92	–
Kaandorp et al., 2015	–	x	x	x	x	x	–	–	–	–	–	0	–	24	–
Finke et al., 2016	–	x	x	x	x	–	–	0	–	–	–	0/1	–	13	–
Moberly et al., 2016b	–	x	–	x	–	x	0	0/−1	–	–	–	–	–	30	–
Hua et al., 2017	–	x	x	–	x	–	0/−1	0/1	–	–	–	–	–	17	*n*
			–	x	–	x	0/1	0	–	–	–	–	–		–
Moberly et al., 2017a	–	x	x	x	x	x	–	0	–	–	–	0	–	30	–
Moberly et al., 2017b	–	x	–	x	x	x	–	0/−1/1	–	–	–	–	–	30	–
Moberly et al., 2017c	–	x	–	x	x	–	–	0/1	–	–	–	–	–	30	–
Kaandorp et al., 2017	–	x	x	x	x	x	–	–1	–	–	–	0/1	–	20	–
Mattingly et al., 2018	–	x	–	x	x	–	–	1	–	–	–	–	–	39	–
Moberly et al., 2018a	–	x	x	x	x	–	–	0/1	–	–	–	1	–	42	–
Moberly et al., 2018c	–	x	x	–	x	–	–	0/1	–	–	–	1	–	34	–
			–	x	x	–	–	0/1	–	–	–	0/1	–		–
Pisoni et al., 2018	–	x	x	–	x	–	–	0	–	0	–	0	–	25	–
			–	x	x	–	–	0/1	–	0/1	–	0	–		–
O'Neill et al., 2019	–	x	–	x	x	–	–	0/1	–	–	–	–	–	30	–
Hillyer et al., 2019	–	x	–	x	x	–	0	0/1	–	–	0	–	–	21	–

(Continued)

TABLE 4 (Continued)

References	Time of cognitive assessment		Speech perception measure				Cognitive domain (positive or negative outcome 0/−1/+1)							Sample size	Power reported (y/n)
	Preoperative	Postoperative	Words	Sentences	Quiet	Noise	Complex attention	Executive function	Social cognition	Learning and memory	Perceptual-motor function	Language	General		
Moberly and Reed, 2019	–	x	–	x	x	–	–	0/1	–	–	–	1	–	41	–
Mussoi and Brown, 2019	–	x	–	x	–	x	0	1	–	–	–	–	–	20	–
Dingemanse and Goedegebure, 2019	–	x	–	x	x	–	–	0	–	–	–	–	–	50	–
			–	x	–	x	–	1	–	–	–	–	–		–
Tamati et al., 2020	–	x	–	x	x	–	–	1	–	1	–	–	–	21	–
Kessler et al., 2020	–	x	x	x	x	x	–	0	–	0	–	0	–	21	–
Skidmore et al., 2020	–	x	x	x	x	–	–	0	–	0	0	–	–	40	–
Tinnemore et al., 2020	–	x	–	x	x	–	0	0	–	–	–	–	–	10	–
Wazen et al., 2020	x	–	x	x	x	x	–	–	–	–	–	–	1	40	–
Zhan et al., 2020	x	–	x	x	x	x	–	0/−1/1	–	–	–	–	–	19	–
Bosen et al., 2021	–	x	–	x	x	–	–	1/0	–	–	–	0	–	20	–
Moberly et al., 2021	–	x	x	–	x	–	–	0/−1/1	–	–	–	1	–	18, 17, 16	–
			–	x	x	–	–	0/−1/1	–	–	–	0/1	–		–
Tamati et al., 2021	–	x	–	x	x	–	–	–	–	–	–	1	–	21	–
Tamati and Moberly, 2021	–	x	x	–	x	–	–	0/1	–	–	–	–	–	15	–
Völter et al., 2021	–	x	x	–	x	–	0/1	0/1	–	1	–	1/−1	–	19 + 15	–
Zucca et al., 2022	x	–	x	–	x	–	0/1	0	–	0	0	0	0	15	–
Ray et al., 2022	–	x	–	x	x	x	–	–	–	–	–	1	–	32	*
Walia et al., 2022	–	x	–	x	–	x	–	–	–	–	–	–	1	39	*n*
Luo et al., 2022	–	x	x	x	–	x	–	0/−1/1	–	–	–	–	–	14	–

Overview of the included papers that assess cognitive or language skills before or after implantation in adults and relate this with speech perception outcomes. For each paper it is indicated whether the cognitive or language assessment was performed preoperatively or postoperatively. Additionally it is indicated what speech perception outcome was considered, either words in quiet or noise or sentences in quiet or noise or both. Furthermore, it is shown whether a non-significant result for tests assessing a cognitive domain (0), a positive or relevant relationship (1) or a negative relationship (−1) was found. And lastly for each paper the sample size and if a power analysis is reported (y, yes and sufficient; *n*, yes and not sufficient for this test) are noted down. *Stated this is a robust approach regarding sample size.

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TABLE 5 Overview of included papers (a) using general cognitive measures and (b) studying complex attention.

Cognitive measure	Speech measure	Statistical analysis	Results	References	*N*
(a) General cognitive measures					
MSSE	WQ	Mann-Whitney U test, regression analysis	*(ns)* $p = 0.545$; $r^2 = 0.061$, $\beta = 0.247$, $p = 0.280$	Zucca et al., 2022*	15
SAGE	WQ	Linear correlation	(+) $r^2(32) = 0.1955$, $p = 0.0025$ language $p = 0.01$, visuospatial $p = 0.007$, executive control $p = 0.03$, memory $p = 0.02$, reasoning $p = 0.02$	Wazen et al., 2020*	40
	SQ + N	Linear correlation	(+) SQ: $r^2(32) = 0.1564$, $p = 0.0067$, SN: $r^2(32) = 0.1543$, $p = 0.007$	Wazen et al., 2020*	40
MoCA	SN	Simple and multiple linear regression	In a model with a measure of neuronal health (Ecochg-TR) MoCA scores explained 64.5% of the variance $\beta = 2.06$ $p < 0.05$, or in interaction with Ecochg-TR $\beta = 0.12$ $p < 0.05$.df = 29	Walia et al., 2022	39
Clock drawing test	WQ	Mann-Whitney U test, regression analysis	*(ns)* $p = 0.117$; $r^2 = 0.177$, $\beta = 0.421$, $p = 0.058$	Zucca et al., 2022*	15
(b) Complex attention					
Attention					
Leiter-3 attention sustained	SQ	Pearson correlation	*(ns)* $r = 0.14$, non-word $r = 0.29$	Moberly et al., 2016b	30
			(ns) Normal: $r = 0.14$, non-word: $r = 019$	Moberly et al., 2017b	30
	SN	Pearson correlation	*(ns)* Dyslexia test: $r = 0.14$, HINT-C: $r = 0.19$	Moberly et al., 2016b	30
			(ns) $r = 0.19$	Moberly et al., 2017b	30
WJ-IV letter and number pattern matching, pair cancelation task	SQ	Pearson correlations, controlling for age	*(ns)*	Hillyer et al., 2019	21
ALAcog M3 attentional task	WQ	Rank ANOVA, DFA	(+) Cohen's d = 1.12, $p = 0.003$ discriminant $r = 0.50$	Völter et al., 2021	34
TMT-B	WQ	Pearson correlations	(–) CI only: $r = -0.52$, $p < 0.05$, corrected for age: $r = -0.53$, $p < 0.05$ Bimodal: $r = 0.75$, $p > 0.01$, corrected for age: $r = -0.67$, $p < 0.01$	Hua et al., 2017	17
		Rank ANOVA	(+) Cohen's d = 0.96, $p = 0.018$	Völter et al., 2021	
		Mann-Whitney U test, regression analysis	*(ns)* $p = 0.087$, $r^2 = 0.086$, $\beta = -0.370$, $p = 0.119$	Zucca et al., 2022*	15
	SN	Pearson correlations	(+) $r = 0.55$, $p > 0.05$ *(ns)* corrected for age $r = 0.46$	Hua et al., 2017	17
Processing speed					
WJ-IV letter and number pattern matching, pair cancelation task → see attention					
WAIS-III symbol search test	SN	Zero-order correlations	*(ns)*	Mussoi and Brown, 2019	20
NIH toolbox pattern comparison processing speed test	SQ	Generalized linear mixed-effects regression analysis	(+) $p = 0.006$ (for normal hearing, but no interaction, so same results for CI)	Tinnemore et al., 2020	10
WAIS-III coding test	SN	Zero-order correlations	*(ns)*	Mussoi and Brown, 2019	20
WJ-IV numbers reversed and pictures test	SQ	Pearson correlations, controlling for age	*(ns)*	Hillyer et al., 2019	21

(Continued)

TABLE 5 (Continued)

Cognitive measure	Speech measure	Statistical analysis	Results	References	N
TMT-A	WQ	Pearson correlations	*(ns)* CI only: $r = -0.27$, corrected for age: $r = -0.53$ (-) Bimodal $r = -0.60$, $p > 0.05$ *(ns)* corrected for age: $r = -0.48$	Hua et al., 2017	17
		Rank ANOVA	*(ns) Cohen's d = 0.8, p = 0.053*	Völter et al., 2021	34
		Mann-Whitney U test, regression analysis	(+) $r^2 = 0.236$, $\beta = -0.486$, $p = 0.035$, *(ns)* $p = 0.115$	Zucca et al., 2022*	15
	SN	Pearson correlations	*(ns)* $r = 0.19$, corrected for age: $r = 0.16$	Hua et al., 2017	17

Overview of included papers using general cognitive measures and assessing complex attention. The task, speech perception outcome measure (W, words; S, sentence; Q, quiet; N, noise), statistical analysis, key finding [(+), positive significant result; (–) negative significant result; *(ns), non-significant result*], reference and sample size (N) are reported. DFA, discriminant factor analysis; HINT, Hearing in Noise Test; MoCA, Montreal Cognitive Assessment; NIH, National Institutes of Health; SAGE, Self-administered Gerocognitive Examination, TMT-A/B, Trail Making Task version A or B; WAIS-III, Wechsler Adult intelligence scale III, WJ-IV, Woodcock-Johnson IV, *Cognitive measure preoperatively. A more detailed version can be found in **Supplementary Table 4**.

noise. Together with neuronal health measures, MoCA explained 64.5% of this variance ($\beta = 2.06$, $p < 0.05$, df = 29) (Walia et al., 2022). (4) The clock drawing test, a short subtest of SAGE, which did not show a significant relationship with word perception in quiet ($r^2 = 0.177$, $p = 0.058$, $N = 15$) (Zucca et al., 2022).

3.2.2. Complex attention

3.2.2.1. Attention

Attention is a state of selective awareness by which a single stimulus is selected for enhanced processing. Tasks assessing attention mainly involve target selection. For the papers included in this review, the "Leiter-3 sustained attention task," "Woodcock-Johnson IV (WJ-IV) letter and number pattern matching task and the pair cancelation task", and the "ALAcog M3 attentional task" are used (see **Table 5b** for an overview). These tests involve targets like figures, letters, numbers or repeated patterns on paper among a set of distractors (Moberly et al., 2016b, 2017b; Hillyer et al., 2019; Völter et al., 2021). Of these tasks, only performance on the ALAcog attentional task was significantly different between better and poorer performers on a word test in quiet (Cohen's d = 1.12, $p = 0.003$) (Völter et al., 2021). The other tests showed no significant relationship with sentences in quiet or noise (Moberly et al., 2016b, 2017b; Hillyer et al., 2019).

Another task used in several studies to investigate attention is the Trail Making Task B (TMT-B). For this task the participant has to draw a "trail" of consecutive numbers and letters: 1-A-2-B-3-C etc. Across the studies that this task was used in, the results were inconsistent showing both significant negative and positive correlations with words in quiet (WQ: CI only: $r = -0.52$, $p < 0.05$, corrected for age: $r = -0.53$, $p < 0.05$, bimodal $r = 0.75$, $p > 0.01$ corrected for age: $r = -0.67$, $p < 0.01$; Cohen's d = 0.96, $p = 0.018$) and positive ($r = 0.55$, $p > 0.05$) or non-significant correlations (when measured preoperatively: $p = 0.087$) with sentences in noise (Hua et al., 2017; Völter et al., 2021; Zucca et al., 2022).

3.2.2.2. Processing speed

Processing speed is the time required to complete a mental task (Kail and Salthouse, 1994). To test this, one task is used that also assesses attention: the "WJ-IV letter and number pattern matching task and the pair cancelation task." Furthermore, the "Wechsler Adult Intelligence Scale III (WAIS-III) symbol search." the "NIH toolbox pattern comparison processing speed test", the "WAIS-III coding test" and the "WJ-IV numbers reversed test" are used (see **Table 5b** for an overview) (Hillyer et al., 2019; Mussoi and Brown, 2019; Tinnemore et al., 2020). Of all of these tests only the pattern comparison test showed a significant relationship with sentences in quiet ($p = 0.006$) (Tinnemore et al., 2020).

Another task used to measure processing speed is the TMT-A. For this task the participant has to draw a trail from 1 to 25. When measured preoperatively, performance on TMT-A was a significant factor in regression analysis for words in quiet postoperatively ($r^2 = 0.236$, $p = 0.035$) (Zucca et al., 2022). However, when TMT-A was measured postoperatively, performance was in general not significantly related to perception of words in quiet or sentences in noise (WQ: CI only non-significant $r = -0.27$, Bimodal $r = -0.60$, $p > 0.05$, corrected for age non-significant $r = -0.48$, SN $r = 0.19$; Cohen's d = 0.8, $p = 0.053$) (Hua et al., 2017; Völter et al., 2021).

3.2.3. Executive function

3.2.3.1. Non-verbal intelligence

Non-verbal intelligence is an executive function that relates to thinking skills and problem-solving abilities that do not require language. "Ravens progressive matrices task," the "WAIS-III matrix reasoning test," "Leiter-3 visual pattern task," "Test of Non-verbal Intelligence–3 (TONI-3) pointing to pictures" and the "Leiter-3 figure ground and form completion" were used to measure this (see **Table 6** for an overview).

In this review, the Ravens task is used most frequently to measure non-verbal intelligence (Moberly et al., 2017c, 2018a,c, 2021; Mattingly et al., 2018; Pisoni et al., 2018; Moberly and Reed, 2019; O'Neill et al., 2019; Skidmore et al., 2020; Zhan et al., 2020; Tamati and Moberly, 2021; Tamati et al., 2021). The task is to pick the piece that fits within the pattern of a visual geometric matrix. A significant relationship between performance on the Ravens task and word perception in quiet was found in five out of six included papers ($r = 0.35$, $p < 0.05$; $r^2 = 0.325$, $p < 0.001$; $r^2 = 0.64$, $p < 0.05$; $r = 0.196$, $p = 0.421$) (Moberly et al., 2018a,c, 2021; Pisoni et al., 2018; Zhan et al., 2020; Tamati et al., 2021). However, it should be noted, that in a study by Tamati and Moberly (2021) this positive correlation was found after 10 trials of word perception, when the listener was adapted to the talker ($r = 0.68$, $p = 0.009$, df = 10). In a study by Moberly et al. (2021) this positive correlation was found for participants with low auditory sensitivity ($r = 0.52$, $p = 0.02$) (where auditory sensitivity was determined by Spectral-Temporally Modulated Ripple Test performance). Eight out of ten studies (some using the same group of participants) using this task reported a significant relationship between performance and sentence perception in quiet [$r(26) = 0.53$, $p < 0.01$; PRESTO words: $r = 0.45$,

TABLE 6 Overview of included papers studying non-verbal intelligence.

Cognitive measure	Speech measure	Statistical analysis	Results	References	*N*
Non-verbal intelligence					
Ravens Progressive Matrices (RPM)	WQ	Pearson correlations	*(ns)* $r = 0.196$, $p = 0.421$	Zhan et al., 2020*	19
			(+) Later in time for hard words: $r = 0.68$, $p = 0.009$ *(ns)* Q1 easy: $r = -0.09$, $p = 0.372$ hard: $r = 0.32$, $p = 0.180$ Q4 easy: $r = 0.14$, $p = 0.371$ hard: $r = 0.47$, $p = 0.048$ TA easy: $r = 0.26$, $p = 0.371$ hard: $r = -0.42$, $p = 0.116$	Tamati and Moberly, 2021	15
		Partial correlation analysis, controlled for age	(+) $r = 0.35$, $p < 0.05$	Moberly et al., 2018a	42
		Correlational and regression analysis	(+) $r = 0.64$, $p < 0.05$, and additional value in model	Pisoni et al., 2018	25
		Linear regression analysis	(+) $r^2 = 0.325$, $p < 0.001$, $\beta = 0.570$ (also mediated by age)	Moberly et al., 2018c	34
		ANOVA, spearmans rank-order correlations Divided in 3 groups	(+) Low-smrt group: rho = 0.52, $p = 0.02$ *(ns)* intermediate-smrt: *rho = 0.33, p = 0.10*, high-smrt: *rho = 0.42, p = 0.05*	Moberly et al., 2021	51
	SQ	Pearson correlations	*(ns)* $r = 0.319$, $p = 0.086$	O'Neill et al., 2019	30
			(+) PRESTO words: $r = 0.41$, $p < 0.01$, PRESTO sentence $r = 0.47$, $p < 0.01$, Harvard words $r = 0.35$, $p < 0.05$, Harvard sentence $r = 0.46$, $p < 0.01$	Mattingly et al., 2018	39
			(ns) PRESTO: $r = 0.295$, $p = 0.221$, Harvard standard: $r = 0.208$, $p = 0.392$, anomalous: $r = 0.212$, $p = 0.383$	Zhan et al., 2020*	19
		Pearson correlations, DFA	Matrix coefficient = 0.35, rank 2, df = 10	Tamati et al., 2020	21
		Partial correlation analysis	(+) Harvard: $r(26) = 0.53$, $p < 0.01$, *(ns)* PRESTO	Moberly et al., 2017c	30
		Partial correlation analysis, controlled for age	(+) PRESTO words: $r = 0.45$, $p < 0.01$, PRESTO sentences: $r = 0.47$, $p < 0.01$, Harvard sentences $r = 0.39$, $p < 0.05$	Moberly et al., 2018a	42
		ANOVA, spearmans rank-order correlations Divided in 3 groups	(+) PRESTO High-smrt group: $r = 0.52$, $p = 0.01$ *(ns)* Harvard, low-smrt: *rho = 0.30, p = 0.13*, intermediate-smrt: *rho = 0.44, p = 0.05*, high-smrt: *rho = 0.22, p = 0.19* PRESTO: low-smrt: *rho = 0.26, p = 0.17*, intermediate-smrt: *rho = 0.35, p = 0.09.*	Moberly et al., 2021	51
		Correlational and regression analysis	(+) Harvard words: $r = 0.71$, $p < 0.05$, sentences: $r = 0.60$, $p < 0.05$ PRESTO words: $r = 0.62$, $p < 0.05$, PRESTO sentences: $r = 0.68$, $p < 0.05$, and additional value in model	Pisoni et al., 2018	25
		Linear regression analysis	(+) Harvard words: $r^2 = 0.291$, $\beta = 0.540$, $p = 0.001$ PRESTO words: $r^2 = 0.357$, $\beta = 0.598$, $p < 0.001$	Moberly et al., 2018c	34
		Blockwise multiple linear regression analysis	(+) Adding ravens to predict anomalous sentences $\beta = 0.421$, p = 0.08 *(ns)* meaningful: $\beta = -0.141$, $p = 0.173$, df = 32	Moberly and Reed, 2019	41
	SQ WQ	Partial least squares regression	*(ns)*	Skidmore et al., 2020	40
	SQ + N	Pearson correlations	*(ns)* SQ: $r = 0.253$, $p = 0.295$ SN: $r = 0.167$ $p = 0.493$	Zhan et al., 2020*	19
WAIS-III matrix reasoning test	WQ	Non-parametric correlation and principal component measures.	*(ns)* when corrected for age	Holden et al., 2013*	92
Leiter-3 visual pattern test	SQ + N	Pearson correlation	*(ns)* Dyslexia test: $r = 0.33$, HINT-C: $r = 0.26$, non-word: $r = 0.33$	Moberly et al., 2016b	30
TONI-3 pointing pictures	WQ	Pearson correlations	*(ns)* $r = 0.155$	Collison et al., 2004	15
Leiter-3 figure ground	SQ + N	Pearson correlation	*(ns)* Dyslexia test: $r = 0.15$, HINT-C: $r = 0.13$, non-word: $r = 0.15$	Moberly et al., 2016b	30
Leiter-3 form completion	SQ + N	Pearson correlation	*(ns)* Dyslexia test: $r = -0.09$, HINT-C: $r = -0.16$, non-word: $r = -0.09$	Moberly et al., 2016b	30

Overview of included papers using general cognitive measures and assessing complex attention. The task, speech perception outcome measure (W, words; S, sentence; Q, quiet, N, noise), statistical, key finding [(+), positive significant result; (–) negative significant result; *(ns), non-significant result*], reference and sample size (N) are reported. DFA, discriminant factor analysis, HINT, Hearing in Noise Test; TONI, Test of Non-verbal Intelligence; WAIS-III, Wechsler Adult intelligence scale III; *Cognitive measure preoperatively. A more detailed version can be found in **Supplementary Table 4**.

TABLE 7 Overview of included papers studying visual working memory.

Cognitive measure	Speech measure	Statistical analysis	Results	References	N
Visual working memory					
Visual digit span	WQ	Pearson correlations	*(ns)* $r = 0.269, p = 0.265$	Zhan et al., 2020*	19
			(ns) Q1 easy: $r = -0.15, p = 0.350$ hard: $r = 0.19, p = 0.246$ Q4 easy: $r = -0.14, p = 0.371$ hard $r = 0.17, p = 0.269$ TA easy: $r = -0.04$ $p = 0.444$ hard $r = 0.04, p = 0.448$	Tamati and Moberly, 2021	15
		Partial correlation analysis, controlled for age	*(ns)* $r = 0.09$	Moberly et al., 2018a	42
		Linear regression analysis	*(ns)* $r^2 = 0.005$, $\beta = 0.068$, $p = 0.704$	Moberly et al., 2018c	34
		ANOVA, spearmans rank-order correlations divided in three groups	*(ns)* Low-smrt: $rho = -0.18, p = 0.25$, intermediate-smrt: $rho = 0.19, p = 0.23$, high-smrt: $rho = -0.01, p = 0.49$	Moberly et al., 2021	51
	SQ	Pearson correlations	*(ns)* Harvard standard: $r = 0.333, p = 0.163$, anomalous $r = 0.232, p = 0.339$, PRESTO: $r = 0.418$ $p = 0.075$	Zhan et al., 2020*	19
			(+) Controlling for age: CI only $r = 0.539, p = 0.016$	Hillyer et al., 2019	21
		Partial correlation analysis	(+) Harvard $r(26) = 0.40, p = 0.035$, *(ns)* PRESTO	Moberly et al., 2017c	30
			(ns) Controlled for age: Harvard words $r = 0.12$, sentences: $r = 0.26$ PRESTO words: 0.08 sentences: $r = 0.17$	Moberly et al., 2018a	42
		Pearson correlations, DFA	Matrix coefficient = 0.00, rank 10, df = 10	Tamati et al., 2020	21
		Linear regression analysis	*(ns)* Harvard: $r^2 = 0.010$, $\beta = 0.101$, $p = 0.576$, PRESTO: $r^2 = 0.003$, $\beta = 0.057$, $p = 0.751$,	Moberly et al., 2018c	34
		Blockwise multiple linear regression analysis	*(ns)* Meaningful: $\beta = -0.010, p = 0.910$, anomalous: $\beta = 0.335, p = 0.740$, df = 32	Moberly and Reed, 2019	41
		ANOVA, spearmans rank-order correlations divided in 3 groups	(+) PRESTO, Intermediate-smrt: rho = 0.49, p = 0.03, *(ns)* Harvard: low-smrt: $rho = 0.11, p = 0.34$, intermediate-smrt: $rho = 0.44, p = 0.05$, high-smrt: $rho = -0.05, p = 0.42$ PRESTO: low-smrt: $rho = -0.07, p = 0.40$, high-smrt: $rho = -0.03, p = 0.46$	Moberly et al., 2021	51
	WQ SQ	Partial least squares regression	*(ns)*	Skidmore et al., 2020	40
	SQ + N	Pearson correlations	*(ns)* SQ: $r = 0.309, p = 0.198$ SN: $r = 0.44, p = 0.057$	Zhan et al., 2020*	19
WJ-IV numbers reversed test and pictures→see processing speed Table 5					
Leiter-3 forward and reverse memory	SQ	Pearson correlation	*(ns)* $r = 0.23$, non-word: $r = 0.14$	Moberly et al., 2017b	30
			(ns) Non-words: $r = 0.23, r = 0.20$	Moberly et al., 2016b	30
	SN	Pearson correlation	*(ns)* HINT-C: $r = 0.23, r = 0.20$, Dyslexia: $r = 0.23, r = -0.28$	Moberly et al., 2016b	30
			(ns) $r = 0.13$	Moberly et al., 2017b	30
WAIS-III visual object span	WQ	Pearson correlations	*(ns)* $r = 0.196, p = 0.421$	Zhan et al., 2020*	19
	SQ	Partial correlation analysis	*(ns)*, df = 26	Moberly et al., 2017c	30
		Pearson correlations	*(ns)* Harvard standard: $r = 0.253, p = 0.296$, anomalous $r = 0.125, p = 0.609$, PRESTO: $r = 0.241, p = 0.321$	Zhan et al., 2020*	19
	WQ SQ	Partial least squares regression	*(ns)*	Skidmore et al., 2020	40
	SQ + N	Pearson correlations	*(ns)* SQ: $r = 0.355, p = 0.136$ SN: $r = 0.426, p = 0.069$	Zhan et al., 2020*	19
Visual letter span task	WN + SN	Pearson correlations	*(ns)* WN: $r = -0.27, p = 0.35$, SN: $r = -0.11, p = 0.71$	Luo et al., 2022	14
WAIS-III visual symbol span	WQ	Pearson correlations	(+) $r = 0.599$ $p = 0.007$	Zhan et al., 2020*	19
	SQ	Partial correlation analysis	*(ns)*	Moberly et al., 2017c	30
		Pearson correlations	(+) Harvard standard: $r = 0.541, p = 0.017$, *(ns)* Harvard anomalous $r = 0.345, p = 0.148$, PRESTO: $r = 0.443, p = 0.057$	Zhan et al., 2020*	19
	WQ SQ	Patial least squares regression	*(ns)*	Skidmore et al., 2020	40

(Continued)

TABLE 7 (Continued)

Cognitive measure	Speech measure	Statistical analysis	Results	References	*N*
	SQ + N	Pearson correlations	(+) SQ: $r = 0.504$, $p = 0.028$, SN: $r = 0.486$, $p = 0.035$	Zhan et al., 2020*	19
Alacog 2-back test	WQ	Rank ANOVA, DFA	*(ns) Cohen's d = 0.5, p = 0.22*	Völter et al., 2021	34
Alacog OSPAN	WQ	Rank ANOVA, DFA	(+) Cohen's $d = 1.01$, $p = 0.0068$	Völter et al., 2021	34

Overview of included papers assessing visual working memory. The task, speech perception outcome measure (W, words; S, sentence; Q, quiet; N, noise), statistical analysis, key finding [(+), positive significant result; (–), negative significant result; *(ns), non-significant result*], reference and sample size (N) are reported. DFA, discriminant factor analysis, OSPAN, Operation Span, WAIS-III, Wechsler Adult intelligence scale III; WJ-IV, Woodcock-Johnson IV; *Cognitive measure preoperatively. A more detailed version can be found in **Supplementary Table 4**.

$p < 0.01$; $r = 0.62$, $p < 0.05$; $r = 0.41$, $p < 0.01$, and sentences: $r = 0.47$, $p < 0.01$; $r = 0.68$, $p < 0.05$; $r = 0.47$, $p < 0.01$; Harvard words: $r = 0.71$, $p < 0.05$; $r = 0.35$, $p < 0.05$ and sentences $r = 0.39$, $p < 0.05$; $r = 0.60$, $p < 0.05$; $r = 0.46$, $p < 0.01$; Adding Ravens score to a blockwise multiple linear regression analysis to predict anomalous sentences $p = 0.08$, df = 32] (Moberly et al., 2017c, 2018a,b, 2021; Mattingly et al., 2018; Pisoni et al., 2018; Moberly and Reed, 2019; O'Neill et al., 2019; Skidmore et al., 2020; Zhan et al., 2020). For one of these studies, Ravens task performance discriminated highly between two groups of better and poorer performers on sentences in quiet (Matrix coefficient = 0.35, rank 2, df = 10) (Tamati et al., 2020). In another study, Moberly et al. (2021) found that there was only a significant positive correlation between Ravens score and sentence perception in participants with high auditory sensitivity ($r = 0.52$, $p = 0.01$). Lastly, in another paper they found that there was only a predictive value of Ravens score with anomalous sentences and not meaningful sentences ($p = 0.008$, df = 32) (Moberly and Reed, 2019). The other tasks used to assess non-verbal intelligence did not show any significant results when related to speech perception performance ($r = -0.16$ to 0.33) (Collison et al., 2004; Holden et al., 2013; Moberly et al., 2016b).

3.2.3.2. Working memory

Working memory is a buffer that holds memories accessible while a task is performed (Breedlove and Watson, 2013). It has been suggested that a linear relationship exists between the ambiguity of the speech stimulus and the working memory capacity needed, to decide what words were perceived (Rönnberg, 2003). Working memory can be assessed in different ways and using different modalities; visual (see **Table 7** for an overview), auditory, audio-visual and verbal (see **Table 8** for an overview).

3.2.3.2.1. Visual working memory

The "visual digit span task," "Leiter-3 forward and reversed memory test, letters, and symbols," "ALAcog 2-back test" and "Operation Span" (OSPAN) are used to assess visual working memory (Moberly et al., 2016b, 2017c, 2018c, 2021; Mattingly et al., 2018; Hillyer et al., 2019; Moberly and Reed, 2019; Skidmore et al., 2020; Tamati et al., 2020; Zhan et al., 2020; Tamati and Moberly, 2021; Völter et al., 2021; Luo et al., 2022).

The most used in the included literature is the visual digit span. Scores on this task showed no significant correlations with word perception in quiet ($r = -0.14$ to 0.448, $p = 0.32$–0.704) (Moberly et al., 2018a,c, 2021; Pisoni et al., 2018; Skidmore et al., 2020; Zhan et al., 2020; Tamati and Moberly, 2021). For sentence perception in quiet and noise, three out of nine papers found a significant correlation (Moberly et al., 2017c, 2018a,c, 2021; Hillyer et al., 2019; Moberly and Reed, 2019; Skidmore et al., 2020; Tamati et al., 2020; Zhan et al., 2020). More specifically, Moberly et al. (2017c) found a positive correlation with one of two sentence perception tasks in quiet [$r(26) = 0.40$, $p = 0.035$] and Hillyer et al. (2019) a positive correlation when corrected for age ($r = 0.539$, $p = 0.016$). Furthermore, digit span did not significantly discriminate between better and poorer performers on sentence perception in quiet (Matrix coefficient = 0.00, rank 10, df = 10) (Tamati et al., 2020). Lastly, Moberly et al. (2021), found a positive correlation with one of two sentence perception tasks in quiet for participants with an intermediate degree of auditory sensitivity (rho = 0.49, $p = 0.03$).

For similar span tests using pictures or objects, like in the forward and reversed memory test, letters, and symbols, performance showed a significant relationship with word and sentence perception in quiet and noise in one of seven papers (Moberly et al., 2016b, 2017c; Hillyer et al., 2019; Skidmore et al., 2020; Zhan et al., 2020; Luo et al., 2022). This paper showed a positive relationship between symbol and object span measured preoperatively and word perception in quiet and sentence perception in quiet and noise postoperatively (words: $r = 0.599$, $p = 0.007$, sentences in quiet $r = 0.504$, $p = 0.028$ and noise: $r = 0.486$, $p = 0.035$) (Zhan et al., 2020).

Lastly, the OPSAN and 2-back task were applied in one paper each. Performance on the 2-back did not differ significantly between better and poorer performers on a word task in quiet (Cohen's d = 0.5, $p = 0.22$), but the OSPAN score was significantly worse for poorer performers (Cohen's d = 1.01, $p = 0.0068$) (Völter et al., 2021).

3.2.3.2.2. Auditory working memory

Similar tasks are used to measure working memory capacity with auditory stimuli instead of visual stimuli (**Table 8**). The digit span task is used in four of the included studies (r = –0.27, p = 0.35) (Holden et al., 2013; Moberly et al., 2017a; Bosen et al., 2021; Luo et al., 2022). Scores on these tasks were not significantly correlated to words nor sentences in quiet and noise when administered preimplantation (measured once) or postimplantation (Holden et al., 2013; Moberly et al., 2017b). Only one paper reported a significant correlation with sentence perception in quiet, but this effect disappeared when corrected for auditory sensitivity based on spectral or temporal resolution thresholds (r = 0.51, p = 0.03, after correcting for auditory resolution: r = 0.39, p = 0.08) (Bosen et al., 2021).

3.2.3.2.3. Audio-visual working memory

Lastly, stimuli can be presented in the auditory and visual modality at the same time (Hillyer et al., 2019; Mussoi and Brown, 2019; Zucca et al., 2022; **Table 8**). The audiovisual digit span test was applied in three included studies, with no significant results when related to words in quiet (e.g., when measured preoperatively forward: $r^2 = 0.003$, p = 0.826, backward: $r^2 = 0.036$, p = 0.410), but a significant positive correlation with sentences in quiet (r = 0.539 p = 0.016) and noise (r = 0.573, p = 0.018) (Hillyer et al., 2019; Mussoi and Brown, 2019; Zucca et al., 2022).

Interestingly, Luo et al. (2022) used a cued modality working memory task, where participants needed to remember auditory digits

TABLE 8 Overview of included papers studying auditory, audio-visual and verbal working memory.

Cognitive measure	Speech measure	Statistical analysis	Results	References	N
Auditory working memory					
Auditory digit span	WQ	Non-parametric correlation and principal component measures. Divided in six groups	*(ns)* when corrected for age	Holden et al., 2013*	92
	WN	Pearson correlations	*(ns) r = −0.27, p = 0.35*	Luo et al., 2022	14
	SQ	Pearson correlation	(+) $r = 0.51$, $p = 0.03$, after correcting for auditory resolution *(ns) r = 0.39, p = 0.08*	Bosen et al., 2021	20
	WQ SQ + N	Correlation analysis	*(ns)*, df = 28	Moberly et al., 2017a	30
	SN	Pearson correlations	*(ns) r = −0.21, p = 0.48*	Luo et al., 2022	14
Audio-visual working memory					
Audio-visual digit span	WQ	Mann-Whitney U test, regression analysis	*(ns)* forward: $p = 0.199$; $r^2 = 0.003$, $\beta = 0.051$, $p = 0.826$, backward: $p = 0.382$; $r^2 = 0.036$, $\beta = 0.190$, $p = 0.410$	Zucca et al., 2022*	15
	SN	Zero-order correlations	(+) $r = 0.573$, $p = 0.018$	Mussoi and Brown, 2019	20
Cued modality working memory task	WN	Pearson correlations	(−) Auditory cued working memory: $r = -0.54$, $p = 0.0047$ Auditory uncued working memory: $r = -0.60$, $p = 0.02$ → after correcting for auditory resolution: $r = -0.65$, $p = 0.03$	Luo et al., 2022	14
	SN	Pearson correlations	(−) Auditory cued working memory: $r = -0.66$, $p = 0.01$ Auditory uncued working memory: $r = -0.54$, $p = 0.0045$	Luo et al., 2022	14
Verbal working memory					
Listening span	SQ + N	Pearson correlation	(+) SQ: $r = 0.64$, $p < 0.01$ non-word $r = 0.68$, $p < 0.01$, SN: $r = 0.57$, $p < 0.01$	Moberly et al., 2017b	30
Reading span	WQ	Pearson correlation also corrected for age	(−) Bimodal $r = -0.71$, $p > 0.01$, corrected for age $r = 0.70$, $p < 0.01$, *(ns)* CI only: $r = 0.44$, corrected for age: $r = 0.42$	Hua et al., 2017	17
		Spearman correlation coefficients	*(ns) rho = 0.09, p = 0.58*	Dingemanse and Goedegebure, 2019	50
	WN	Pearson correlations	*(ns) r = −0.05, p = 0.86*	Luo et al., 2022	14
	SQ	Pearson correlation	*(ns)* Short: $r = -0.3$ non-word: $r = -0.02$	Moberly et al., 2017b	30
			(+) $r = 0.430$, $p = 0.018$	O'Neill et al., 2019	30
	SN	Pearson correlation also corrected for age	*(ns)*: $r = -0.48$, corrected for age: $r = -0.44$	Hua et al., 2017	17
		Pearson correlation	*(ns) r = 0.1*	Moberly et al., 2017b	30
	WQ + N SN	Correlation analysis, regression analysis	(−) SN: $r = -0.59$, $p = 0.006$, SRTdiff: $r = -0.57$, $p = 0.009$, explained additional 46% *(ns)* WQ: $r = 0.03$, WN: $r = -0.26$	Kaandorp et al., 2017	20
	SQ + N	Spearman correlation coefficients	(+) Words: $r = 0.37$, $p = 0.011$, Sentence: $r = 0.38$, $p = 0.009$	Dingemanse and Goedegebure, 2019	50
	SN	Pearson correlations	*(ns) r = −0.03, p = 0.91*	Luo et al., 2022	14
SicSpan	WQ	Correlation analysis	*(ns)*, df = 11	Finke et al., 2016	13
	SQ	Correlation analysis	*(ns)*, df = 11	Finke et al., 2016	13
	SN	Independent *T*-test	*(ns)*	Kessler et al., 2020	21

Overview of included papers using assessing auditory, audio-visual, and verbal working memory. The task, speech perception outcome measure (W, words; S, sentence; Q, quiet; N, noise), statistical analysis, key finding [(+), positive significant result; (−), negative significant result; *(ns), non-significant result*), reference and sample size (N) are reported. SicSpan, Size comparison Span; SRT, sound reception threshold, WAIS-III, Wechsler Adult intelligence scale III; *Cognitive measure preoperatively. A more detailed version can be found in **Supplementary Table 4**.

and visual letters and recall one of them or both. In the cued conditions they were instructed beforehand what they needed to recall after the stimuli were presented, but no instruction was given in the uncued condition. They found that for both the cued and uncued auditory condition, the score on the task was significantly negatively correlated with sentence (cued: $r = -0.66$, $p = 0.01$, uncued: $r = -0.54$, $p = 0.045$) and word perception in noise (cued: $r = -0.54$, $p = 0.047$, uncued: $r = -0.60$, $p = 0.02$). However, after correcting for spectral and temporal resolution, only the significant negative correlation between auditory uncued performance on the working memory task and word perception in noise remained ($r = -0.65$, $p = 0.03$). The authors suggest this might be because the same underlying strategies are used, and because top-down correction using semantic information is not possible, unlike for sentence perception and cued working memory. However, this paper had small sample sizes and results should be interpreted with caution (Luo et al., 2022).

TABLE 9 Overview of included papers studying cognitive inhibition and flexibility.

Cognitive measure	Speech measure	Statistical analysis	Results	References	*N*
Cognitive inhibition					
Stroop task	WQ	Pearson correlations	*(ns)* $r = -0.455$, $p = 0.058$	Zhan et al., 2020*	19
			(–) Later in time for hard words: $r = -0.50$, $p = 0.044$ *(ns)* Q1: easy $r = -0.22$, $p = 0.317$ hard $r = -0.27$, $p = 0.197$ Q4: *easy* $r = -0.05$, $p = 0.430$ TA: easy $r = 0.14$ $p = 0.371$ hard $r = -0.58$ $p = 0.072$	Tamati and Moberly, 2021	15
		Partial correlation analysis, controlled for age	*(ns)* $r = 0.12$	Moberly et al., 2018a	42
		Linear regression analysis	*(ns)* $r^2 = 0.056$, $p = 0.108$	Moberly et al., 2018c	34
		ANOVA, spearmans rank-order correlations divided in 3 groups	(–) High-smrt: rho = –0.49, $p = 0.02$, *(ns)* low-smrt: *rho = 0.31*, $p = 0.12$, intermediate-smrt: *rho = 0.09*, $p = 0.36$	Moberly et al., 2021	51
	SQ	Pearson correlations	*(ns)* Incongruent: harvard: standard $r = -0.321$, $p = 0.193$, anomalous: $r = -0.319$, $p = 0.197$, PRESTO $r = -0.301$, $p = 0.224$	Zhan et al., 2020*	19
			(–) Incongruent: non-word $r = -0.43$, $p < 0.05$ *(ns)* congruent: $r = -0.28$	Moberly et al., 2016b	30
			(–) Real words: $r = -0.41$, $p < 0.05$, non-words: $r = -0.43$, $p < 0.05$	Moberly et al., 2017b	30
		Partial correlation analysis, controlled for age	*(ns)* Harvard: words $r = -0.13$, sentences $r = -0.23$, PRESTO: words $r = -0.05$, sentences $r = -0.12$	Moberly et al., 2018a	42
		Pearson correlations, DFA	Control: matrix coefficient = –0.08, rank 7 Interference: matrix coefficient = 0.06, rank 8, df = 10	Tamati et al., 2020	10
		Linear regression analysis	*(ns)* Harvard: $r^2 = -0.085$, $p = 0.099$, PRESTO: $r^2 = 0.017$, $p = 0.468$	Moberly et al., 2018c	34
		Blockwise multiple linear regression analysis	(–) Adding Stroop to the model to predict meaningful SQ: $\beta = -0.259$, $p = 0.008$, *(ns)* anomalous: $\beta = 0.163$, $p = 0.273$, df = 32	Moberly and Reed, 2019	41
		ANOVA, spearmans rank-order correlations divided in 3 groups	(–) Harvard sentences high-smrt: rho = –0.047, $p = 0.03$, *(ns)* Harvard: low-smrt: *rho = 0.27*, $p = 0.16$, intermediate-smrt: *rho* = –0.35, $p = 0.09$, PRESTO: low-smrt: *rho = 0.40*, $p = 0.06$, intermediate-smrt: *rho* = –0.40, $p = 0.07$, high-smrt: *rho* = –0.35, $p = 0.08$	Moberly et al., 2021	51
	SN	Pearson correlations	(–) Incongruent: dyslexia: $r = -0.41$, $p < 0.05$, HINT-C: $r = -0.43$, $p < 0.05$ *(ns)* congruent: dyslexia: $r = -0.28$, HINT-C: $r = -0.36$	Moberly et al., 2016b	30
			(–) $r = -0.43$, $p < 0.05$	Moberly et al., 2017b	30
	WQ SQ	Patial least squares regression	*(ns)*	Skidmore et al., 2020	40
	SQ + N	Pearson correlations	(+) Incongruent: SQ: $r = -0.484$, $p = 0.042$ *(ns)* incongruent: SN: $r = -0.412$, $p = 0.09$	Zhan et al., 2020*	19
Flanker task	WQ	Rank ANOVA, DFA	(+) Cohen's $d = 0.58$, $p = 0.037$, discriminant $r = 0.21$	Völter et al., 2021	34
	SN	Generalised linear mixed-effects regression analysis	*(ns)*	Tinnemore et al., 2020	10
Flexibility					
TMT-B → see attention Table 5					
NIH DCCS test	SQ	Generalized linear mixed-effects regression analysis	(+) Higher than average scores associated with speech recognition $p = 0.006$, estimate = 0.35	Tinnemore et al., 2020	10

Overview of included papers using general cognitive measures and assessing cognitive inhibition and flexibility. The task, speech perception outcome measure (W, words; S, sentence; Q, quiet; N, noise), statistical analysis, key finding [(+), positive significant result; (–), negative significant result; *(ns), non-significant result*), reference and sample size (N) are reported. DCCS, dimensional change card sort; DFA, discriminant factor analysis, MoCA, Montreal Cognitive Assessment; NIH, National Institutes of Health, TMT-B, Trail Making Task version B; *Cognitive measure preoperatively. A more detailed version can be found in Supplementary Table 4.

3.2.3.2.4. Verbal working memory

Other working memory tasks involve more language perception skills. These measures are thought to assess verbal working memory more specifically, using both auditory and visual stimuli. Examples of such tasks are the "Reading Span task," the "Size Comparison Span" (SicSpan) task and the "Listening span task" (**Table 8**; Finke et al., 2016; Hua et al., 2017; Kaandorp et al., 2017; Moberly et al., 2017b; Dingemanse and Goedegebure, 2019; O'Neill et al., 2019; Kessler et al., 2020). For the Reading or Listening span, participants must decide for each sentence they see or hear whether the sentence is semantically true or false, while retaining items that are presented in memory and recalling them after the true/false task.

Reading span was used most frequently in the included papers. For these studies, performance did not significantly correlate with word perception scores in quiet and noise in three papers

(Kaandorp et al., 2017; Dingemanse and Goedegebure, 2019; Luo et al., 2022). A significant positive correlation was, however, found for bimodal listening to words in quiet (r = 0.71, $p > 0.01$) (Hua et al., 2017). In two out of six included papers there was a significant positive correlation between Reading span and sentence perception in quiet or noise (r = 0.430, p = 0.018; r = 0.38, p = 0.009) (Hua et al., 2017; Moberly et al., 2017b; Dingemanse and Goedegebure, 2019; O'Neill et al., 2019; Luo et al., 2022) and one paper showed a significant negative correlation (r = –0.57, p = 0.009) (Kaandorp et al., 2017).

Furthermore, only one paper implemented the Listening span and found performance to be significantly positively correlated with sentence perception in quiet and noise (quiet: r = 0.64, non-word quiet: r = 0.68, noise: r = 0.57, $p < 0.01$) (Moberly et al., 2017b). For SicSpan the two included studies found no significant relationship with sentence or word perception in quiet and noise (Finke et al., 2016; Kessler et al., 2020).

3.2.3.3. Cognitive inhibition

Cognitive inhibition is the ability to suppress goal-irrelevant information. For example, being able to ignore background noise or lexical competitors. In the included papers two tasks were used to assess inhibitory control: the "Flanker task" and the "Stroop task" (see **Table 9** for an overview). Both tasks contain congruent, incongruent, and neutral conditions. In the congruent condition, the participant must respond to a target where the rest of the properties of the trial are aligned with the required response. In the incongruent condition, the participant must respond to a target where the rest of the properties of the trial are opposite to the required response and in the neutral condition the rest of properties of the trial do not have the ability to evoke a response conflict (Zelazo et al., 2014; Knight and Heinrich, 2017).

Eleven included studies used the Stroop task, where response time was measured, and a lower value represented better performance on the task. Four of four studies show that performance on this task, both preoperatively and postoperatively, did not significantly correlate with or predict word perception in quiet (Moberly et al., 2018c; Skidmore et al., 2020; Zhan et al., 2020). Two exceptions exist which showed a significant negative correlation with word perception in quiet: (1) in a group having high auditory sensitivity (rho = –0.49, p = 0.02) (Moberly et al., 2021) (2) with word perception after ten trials of a task, when the listener has adapted to the speech (r = –0.50, p = 0.044) (Tamati and Moberly, 2021). Three of seven studies showed a significant negative relation with sentence perception tests in quiet (adding Stroop to the model to predict meaningful SQ p = 0.008, β = –0.259; r = –0.43, $p < 0.05$; r = –0.41, $p < 0.05$) (Moberly et al., 2016b, 2017b, 2018a,c; Moberly and Reed, 2019; Tamati et al., 2020; Zhan et al., 2020). Additionally, a significant negative correlation was found between Stroop task performance and sentence perception in quiet, for a group having high auditory sensitivity (rho = –0.047, p = 0.03) (Moberly et al., 2021). Furthermore, preoperative Stroop was significantly negatively correlated with postoperative sentence perception in quiet and noise (AzBio: Q r = –0.484, p = 0.042, N r = –0.412, p = 0.09, Harvard: standard r = –0.321, p = 0.193, anomalous r = –0.319, p = 0.197, PRESTO r = –0.301, p = 0.224) (Zhan et al., 2020) (Note that many of these studies including the Stroop task were performed in the same lab, some using the same participants, which might hamper generalizability).

Additionally, two included studies used the Flanker task. They showed that performance on this task significantly differed between better and poorer performers on a word task in quiet (Cohen's d = 0.58, p = 0.037) (Völter et al., 2021). However, the performance did not significantly predict performance for sentence perception in quiet (Tinnemore et al., 2020).

3.2.3.4. Flexibility

Flexibility, often referred to as executive control, encompasses functions related to planning and task switching. It is mostly found to be supported by the frontal lobe (Gilbert and Burgess, 2007), which seems to be more activated in better performers. The TMT-B is not only used to measure attention, but also executive control or flexibility. Additionally, the "NIH Toolbox Dimensional Change Card Sort Test" (DCCS) is used (see **Table 9** for an overview). As discussed before, the TMT-B score showed inconsistent correlations with word or sentence perception in quiet (Hua et al., 2017; Völter et al., 2021; Zucca et al., 2022). The other task was only applied in one paper. Performance on the DCCS, which asks participants to match cards with a target card based on different properties, was found to be significant in a general linear model with sentences in quiet (p = 0.006) (Tinnemore et al., 2020).

3.2.4. Social cognition

None of the included studies contained measures of social cognition related to speech perception outcomes.

3.2.5. Learning and memory

Memory is the ability to store learned information and retrieve it over time. In the brain activation section, it was observed that the temporal and frontal cortex are recruited in better performers. Those areas are mainly involved in memory formation, and together with brain plasticity indicate learning (Breedlove and Watson, 2013). These skills can be measured in different ways. In the included papers this is done using recall tasks (Moberly et al., 2017a; Hillyer et al., 2019; Völter et al., 2021), learning tasks (Zucca et al., 2022), or both (Holden et al., 2013; Pisoni et al., 2018; Kessler et al., 2020; Skidmore et al., 2020; Tamati et al., 2020; Ray et al., 2022), mostly in the verbal domain (see **Table 10a** for an overview).

In five papers recall tasks were used (Moberly et al., 2017a; Hillyer et al., 2019; Kessler et al., 2020; Völter et al., 2021; Zucca et al., 2022). Performance scores did not significantly correlate with, predict or dissociate better and poorer performers on sentence perception in quiet or noise. However, there was a significant difference in the "ALAcog delay recall score" between CI users that had higher and lower performance on a word perception task (Cohen's d = 0.88, p = 0.04) (Völter et al., 2021) as opposed to Zucca et al. (2022) who did not find a significant result when it was measured preoperatively (p = 0.343, p = 0.445).

Furthermore, the CVLT test battery was used in five included papers to assess verbal learning and recall (Holden et al., 2013; Pisoni et al., 2018; Skidmore et al., 2020; Tamati et al., 2020; Ray et al., 2022). The CVLT includes various short- and long-term recall tasks, and calculates several scores reflecting word recall strategies. In two out of five papers, scores on this task did not significantly correlate with word and sentence perception in quiet or noise when administered pre- or post-implantation (Holden et al., 2013; Pisoni et al., 2018; Skidmore et al., 2020). If a relationship was found, it was always a subtest of the battery. In these studies, (1) recall on list B, was positively correlated with words and sentence perception in quiet (WQ: r = 0.47 SQ: r = 0.56, r = 0.52, $P < 0.05$) (Pisoni et al., 2018), (2) sub-scores short delay cued recall, semantic clustering, subjective clustering, primacy recall and recall consistency were important predictors of sentence perception in quiet and noise (Ray et al., 2022) and (3) list B and Y/N discriminability could discriminate very little between better and poorer performers on a sentences in quiet task, and T1/T4 not at all (Tamati et al., 2020).

3.2.6. Perceptual-motor function

Perceptual motor skills allow individuals to interact with the environment by combining the use of senses and motor skills. These skills are involved in many of the tasks discussed above. Only two papers used tasks that explicitly measure these skills (see **Table 10b** for an overview) (Hillyer et al., 2019; Zucca et al., 2022). Tasks used to measure this skill are the "WJ-IV visualization parts A and B," the "corsi block tapping test" and the "block rotation task." These tasks were only applied in one paper each and did not show any significant relation with speech perception performance (e.g., r = 0.081–0.103, p = 0.156–0.588) (Hillyer et al., 2019; Zucca et al., 2022).

3.3. Language

Many of the cognitive tasks mentioned above already include verbal ability assessments, for example verbal working memory, learning and recall. Although these different cognitive functions do not seem to correlate consistently with speech perception outcomes, it is valuable to explore what the included literature says about language skills in CI users and the relationship with speech perception outcomes. An overview of the studies including language assessments can be found in **Table 4**.

3.3.1. Object naming and word finding (vocabulary)

Vocabulary is the language user's knowledge of words. In the included papers vocabulary is assessed by picture naming tasks (Collison et al., 2004; Holden et al., 2013; Kaandorp et al., 2015; Völter et al., 2021), choosing synonym tasks (Collison et al., 2004; Kaandorp et al., 2015, 2017), discriminating real words from pseudowords

TABLE 10 Overview of included papers studying learning and memory and perceptual motor function.

Cognitive measure	Speech measure	Statistical analysis	Results	References	*N*
(a) Learning and memory					
Recognition memory					
WJ-IV picture recognition test	SQ	Pearson correlations, controlling for age	*(ns)*	Hillyer et al., 2019	21
Verbal learning and recall					
Auditory word recall (and delayed recall) task	WQ	Mann-Whitney U test, regression analysis	*(ns)* immediate: $p = 0.343$; $r^2 = 0.049$, $\beta = 0.222$, $p = 0.346$ differite: $p = 0.455$: $r^2 = 0.110$, $\beta = 0.331$, $p = 0.154$	Zucca et al., 2022*	15
		Rank ANOVA, DFA	(+) Delayed recall, Cohen's d = 0.88, p = 0.04 discriminant r = 0.29 *(ns)* recall: *Cohen's d = 0.6, p = 0.12*	Völter et al., 2021	34
	WQ + N SQ + N	Correlation analysis	*(ns)*	Moberly et al., 2017a	30
CERAD-plus test battery	WQ SQ + N	Independent *T*-test	*(ns)*	Kessler et al., 2020	21
CVLT –II	WQ	Non-parametric correlation and principal component measures. Divided in six groups	*(ns)* when corrected for age	Holden et al., 2013*	92
		Correlational and regression analysis	(+) List B: r = 0.47, $p < 0.05$, added value to model	Pisoni et al., 2018	25
	SQ	Correlational and regression analysis	(+) List B: Harvard words r = 0.48, $p < 0.05$, sentences: r = 0.56, $p < 0.05$, PRESTO words: r = 0.52, $p < 0.05$, sentences r = 0.52, $p < 0.05$, List A trial five Harvard words: r = 0.46, $p < 0.05$ *(ns)* rest	Pisoni et al., 2018	25
		Pearson correlations, DFA	List B: matrix coefficient = 0.16, rank 5, discriminability: matrix coefficient = 0.12, rank 6, T1/T5: matrix coefficient = –0.04, rank 9, df = 10	Tamati et al., 2020	21
	WQ SQ	Patial least squares regression	*(ns)*	Skidmore et al., 2020	40
	SQ + N	Partial least squares regression with VIP (robust approach)	(+) Most important variables: short-delay cued recall, semantic clustering, subjective clustering, primacy recall and recall consistency (VIP more than one), refittet model 35.8% explained, Each variable explained more than 50% of the variance	Ray et al., 2022	32
(b) Perceptual-motor function					
WJ-IV visualization parts A and B	SQ	Pearson correlations, controlling for age	*(ns)*	Hillyer et al., 2019	21
Corsi block tapping test	WQ	Mann-Whitney U test, regression analysis	*(ns)* backward: $p = 0.220$; $r^2 = 0.103$, $\beta = 0.284$, $p = 0.156$, forward: $p = 0.588$;, $r^2 = 0.081$, $\beta = 0.321$, $p = 0.212$	Zucca et al., 2022*	15
Block rotation task	SQ	Pearson correlations, controlling for age	*(ns)*	Hillyer et al., 2019	21

Overview of included papers assessing cognitive a) learning and memory and b) perceptual motor function. The task, speech perception outcome measure (W, words; S, sentence; Q, quiet; N, noise), statistical analysis; key finding [(+), positive significant result; (–), negative significant result; *(ns), non-significant result*], reference and sample size (N) are reported. CVLT, California Verbal learning test; DFA, discriminant factor analysis, MoCA, Montreal Cognitive Assessment; WJ-IV, Woodcock-Johnson IV; *Cognitive measure preoperatively. A more detailed version can be found in **Supplementary Table 4**.

TABLE 11 Overview of included papers studying vocabulary and verbal fluency.

Cognitive measure	Speech measure	Statistical analysis	Results	References	*N*
Object naming and word finding (vocabulary)					
Picture naming task	WQ	Pearson correlations	*(ns) r = 0.501*	Collison et al., 2004	15
		Non-parametric correlation and PCA.	*(ns)* when corrected for age	Holden et al., 2013*	92
		Rank ANOVA, DFA	(–) objects Cohen's $d = -1.28$, $p = 0.0026$, Colors: Cohen's $d = -0.82$, $p = 0.031$, letters: Cohen's $d = -1.25$, $p = 0.0026$, numbers: Cohen's $d = -1.34$, $p = 0.0038$, discriminant: $r = 0.56$	Völter et al., 2021	34
	WQ + N SQ	Regression modeling	*(ns)*	Kaandorp et al., 2015	24
Choosing a synonym task	WQ	Pearson correlations	*(ns)* Part of VCS see below	Collison et al., 2004	15
	WQ SQ + N	Regression modeling	*(ns)*	Kaandorp et al., 2015	24
		Correlation analysis	*(ns)* WQ: $r = -0.19$, WN: $r = -0.19$, SN: $r = -0.33$, SRTdiff: $r = -0.27$	Kaandorp et al., 2017	20
Word naming test	WQ SQ + N	Correlation analysis	*(ns)* WQ: $r = -0.02$, WN: $r = -0.03$, SN: $r = 0.12$, SRTdiff: $r = 0.18$	Kaandorp et al., 2017	20
Word vs non-word discrimination task	WQ	Correlation analysis	*(ns)*, df = 11	Finke et al., 2016	13
		Rank ANOVA, DFA	(–/+) Sensitivity Cohen's $d = -1.27$, $p = 0.0021$ Discriminant $r = 0.54$, Response time existing words Cohen's d = 0.85, $p = 0.017$,	Völter et al., 2021	34
	SQ	Correlation analysis	*(ns)*, df = 11	Finke et al., 2016	13
	WQ SQ + N	Correlation analysis, regression analysis	(+) SRTdiff: $r = 0.45$, $p = 0.047$, explained additional 36% in model *(ns)* WQ: $r = -0.25$, WN: $r = 0.07$, SN: $r = 038$	Kaandorp et al., 2017	20
	WQ SQ + N	Correlation analysis	*(ns)*, df = 28	Moberly et al., 2017a	30
WordFam-150 test	WQ	Correlation analysis	*(ns)*	Pisoni et al., 2018	25
	SQ	Correlation analysis	(+) PRESTO sentences $r = 0.45$, $p < 0.05$ *(ns)* Harvard words and sentences and PRESTO words	Pisoni et al., 2018	25
		Pearson correlation	*(ns)* $r = 0.21$, $p = 0.39$, corrected for age $r = 0.16$, $p = 0.50$	Bosen et al., 2021	20
	WQ SQ	Partial least squares regression	*(ns)*	Skidmore et al., 2020	40
WJ-III verbal comprehension section (VCS)	WQ	Pearson correlations	*(ns)* $r = 0.286$	Collison et al., 2004	15
WAIS-III similarities test	WQ	Non-parametric correlation and PCA	*(ns)* when corrected for age	Holden et al., 2013*	92
Verbal fluency					
Verbal Fluency Task	WQ	Correlation analysis	*(ns)* $r(11) = 0.536$, $p = 0.059$	Finke et al., 2016	13
		Rank ANOVA	(+) Cohen's $d = 0.80$, $p = 0.025$	Völter et al., 2021	34
		Mann-Whitney U test, regression analysis	*(ns)* Phonemic: $p = 0.218$; $r^2 = 0.002$, $\beta = 0.049$, $p = 0.834$ semantic: $p = 0.052$; $r^2 = 0.165$, $\beta = 0.407$, $p = 0.067$	Zucca et al., 2022*	15
	SQ	Independent *T*-test	*(ns)*	Kessler et al., 2020	21
		Correlation analysis	*(ns)* $r(11) = 0.518$, $p = 0.061$	Finke et al., 2016	13

Overview of included papers assessing vocabulary and verbal fluency. The task, speech perception outcome measure (W, words, S, sentence; Q, quiet; N, noise), statistical analysis, key finding [(+), positive significant result; (–), negative significant result; *(ns), non-significant result*), reference and sample size (N) are reported. DFA, discriminant factor analysis; PCA, principal component analysis; *Cognitive measure preoperatively. A more detailed version can be found in **Supplementary Table 4**.

(Kaandorp et al., 2017; Moberly et al., 2017a; Kessler et al., 2020; Tamati et al., 2020; Völter et al., 2021), by reporting the degree of familiarity with words (Pisoni et al., 2018; Skidmore et al., 2020; Bosen et al., 2021; Tamati et al., 2021), or describing the similarity or difference between two words (Holden et al., 2013) (see **Table 11** for an overview). In three out of ten papers there was an indication of

TABLE 12 Overview of included papers studying speed of lexical and phonological access and degraded receptive language.

Cognitive measure	Speech measure	Statistical analysis	Results	References	N
Speed of lexical and phonological access					
TOWRE	WQ	Partial correlation analysis, controlled for age	(+) Words: $r = 0.47$, $p < 0.01$	Moberly et al., 2018a	42
		Correlational and regression analysis	(+) TOWRE words: $r = 0.55$, $p < 0.05$, TOWRE non-words: $r = 0.41$, $p < 0.05$.	Pisoni et al., 2018	25
		Linear regression analysis	(+) Words: $r^2 = 0.312$, $\beta = 0.558$, $p = 0.001$, non-words: $r^2 = 0.173$, $\beta = 0.416$, $p = 0.014$	Moberly et al., 2018c	34
		ANOVA, spearmans rank-order correlations divided in 3 groups	(+) Intermediate-smrt: rho = 0.48, $p = 0.03$, high-smrt: rho = 0.42, $p = 0.05$ *(ns)* low-smrt: *rho = −0.08, p = 0.39*	Moberly et al., 2021	51
	SQ	Pearson correlations	(+) Real words and Harvard standard: $r = 0.36$, $p = 0.015$, real words and Harvard anomalous: $r = 0.42$, $p = 0.004$, total and Harvard standard: $r = 0.35$, $p = 0.018$, total and Harvard anomalous: $r = 0.36$, $p = 0.016$, real words and PRESTO words: $r = 0.40$, $p = 0.006$, total and PRESTO words: $r = 0.47$, $p = 0.014$	Tamati et al., 2021	48
		Partial correlation analysis, controlled for age	(+) Words and PRESTO words: $r = 0.47$, $p < 0.01$, words and PRESTO: $r = 0.54$, $p < 0.01$, non-words: $r = 0.40$, $p < 0.05$, words and Harvard words: words $r = 0.37$, $p < 0.05$, words and Harvard sentences: words $r = 0.57$, $p < 0.05$, non-words $r = 0.45$, $p < 0.01$	Moberly et al., 2018a	42
		Pearson correlations, DFA	Words: Matrix coefficient = 0.25, rank 3, Non-words: Matrix coefficient = 0.22, rank 4, df = 10	Tamati et al., 2020	21
		Correlational and regression analysis	(+) TOWRE words: Harvard sentences $r = 0.47$, $p < 0.05$, PRESTO words $r = 0.41$, $p < 0.05$, sentences $r = 0.41$, $p < 0.05$, TOWRE non-words: Harvard words r = 0.49, $p < 0.05$, sentences $r = 0.48$, $p < 0.05$, PRESTO sentences $r = 0.48$, $p < 0.05$ *(ns)* rest	Pisoni et al., 2018	25
		Linear regression analysis	(+) Words and Harvard words $r^2 = 0.175$, $\beta = 0.418$, $p = 0.015$ words and PRESTO words $r^2 = 0.187$, $\beta = 0.435$, $p = 0.011$	Moberly et al., 2018c	34
		Blockwise multiple linear regression analysis	(+) Adding TOWRE words to predict anomalous sentences $\beta = 0.391$, $p = 0.010$ *(ns)* meaningful: $\beta = -0.81$, *p = 0.414*, df = 32	Moberly and Reed, 2019	41
		ANOVA, Spearmans rank-order correlations Divided in 3 groups	(ns) Harvard: low-smrt: rho = –0.23, $p = 0.20$, intermediate-smrt: rho = 0.35, $p = 0.09$, High-smrt: rho = –0.23, $p = 0.20$ PRESTO: low-smrt: rho = –0.31, p = 0.12, intermediate-smrt: rho = 0.30, $p = 0.13$, high-smrt: rho = 0.37, $p = 0.07$	Moberly et al., 2021	51
	WQ SQ	Partial least squares regression	*(ns)*	Skidmore et al., 2020	40
WRAT word reading	WQ SQ	Partial least squares regression	*(ns)*	Skidmore et al., 2020	40
Speechreading sentences	WQ SQ + N	Pearson correlations	(–) Young group: $r = -0.872$, $p = 0.002$ *(ns)* Older group: *r = 0.0562, p = 0.189*	Hay-McCutcheon et al., 2005*	34
LEMO subtest of internal homophonic word reading	WQ	Rank ANOVA	(+) Cohen's $d = -1.23$, $p = 0.0039$	Völter et al., 2021	34
Audiovisual non-word repetition task	WQ + N SQ + N	Correlation analysis	*(ns)*, df = 28	Moberly et al., 2017a	30
Degraded receptive language					
TRT	WQ	Rank ANOVA	(–) Periodic bars: Cohen's $d = -1.57$, $p = 0.00002$, Floating bars: Cohen's $d = -1.25$, $p = 0.00021$, Random dots: Cohen's $d = -0.94$, $p = 0.0021$	Völter et al., 2021	34
	SN	Correlation analysis	SN unmmodulated: (–) TRT random dots $r = -0.23$ $P = 0.036$ $r^2 = 0.05$, TRT random bars $r = -0.27$, $P = 0.012$, $r^2 = 0.07$, SN modulated: TRT random dots $r = -0.29$, $P = 0.007$, $r^2 = 0.09$, TRT random bars $r = -0.28$, $P = 0.009$, $r^2 = 0.08$ SN fixed: (+) TRT random noise $r = 0.26$, $P = 0.026$, $r^2 = 0.07$	Haumann et al., 2012*	97
	WQ SQ	Correlation analysis	*(ns) WQ: r = −0.22, WN: r = −0.19, SN: r = −0.33, SRTdiff: r = −0.27*	Kaandorp et al., 2017	20
Fragmented sentences test	WQ	Linear regression analysis	(+) $r^2 = 0.157$, $\beta = 0.396$, $p < 0.001$	Moberly et al., 2018c	34
	SQ	Linear regression analysis	*(ns)* Harvard: *$r^2 = 0.055$, $\beta = 0.234$, p = 0.109* PRESTO: *$r^2 = 0.11$, $\beta = 0.334$, p = 0.058*	Moberly et al., 2018c	34

Overview of included papers assessing speed of lexical and phonological access and degraded receptive language . The task, speech perception outcome measure (W, words; S, sentence; Q, quiet; N, noise), statistical analysis (including a report of a power analysis (y), yes; (n), no; df, degrees of freedom), key finding [(+), positive significant result, (–), negative significant result; *(ns), non-significant result*), reference and sample size (N) are reported. DFA, discriminant factor analysis, TOWRE, Test of word reading efficiency; TRT, text reception threshold; *Cognitive measure preoperatively. A more detailed version can be found in **Supplementary Table 4**.

a relationship between vocabulary and speech perception outcomes. First, there was a difference in score on the Rapid Automatic Naming (RAN) task and a lexical decision task between a group of poorer and better performing CI users on a word perception task in quiet, where better performers had significantly higher RAN task scores (Cohen's d = −0.82 to −1.34, p = 0.0021–0.031) and non-word discrimination task scores (Cohen's d = −1.27, p = 0.0021) (Völter et al., 2021). Secondly, performance on a lexical decision task was found to be a significant predictor of the average score of both word and sentence perception in noise (r = 0.45, p = 0.047) (Kaandorp et al., 2017). Third, there was a significant correlation between performance on a word recognition test and sentences in quiet (r = 0.45, $p < 0.05$) (Pisoni et al., 2018).

3.3.2. Verbal fluency

Verbal fluency is the readiness in which words are accessed and produced from one's own long-term lexical knowledge. Four of the papers address verbal fluency (Finke et al., 2016; Kessler et al., 2020; Völter et al., 2021; Zucca et al., 2022) (see **Table 11** for an overview). Performance on the verbal fluency tasks was assessed in four papers. In three out of four no significant relationship with word and sentence perception in quiet was found (Finke et al., 2016; Kessler et al., 2020; Zucca et al., 2022). Performance did significantly differ between better and poorer performers on a word perception task in quiet (Cohen's d = 0.8, p = 0.025) (Völter et al., 2021).

3.3.3. Speed of lexical and phonological access

Speed of lexical and phonological access represents how fast written text is generated into phonemes or meaningful speech. Speed of lexical and phonological access is assessed in ten of the included papers. Speed reading tasks of real and non-words and sentences, such as the "Test Of Word Reading Efficiency" (TOWRE) and the "Wide Range Achievement Test" (WRAT), are mostly used for this (Hay-McCutcheon et al., 2005; Moberly et al., 2018a,c, 2021; Pisoni et al., 2018; Moberly and Reed, 2019; Skidmore et al., 2020; Tamati et al., 2020, 2021) (see **Table 12** for an overview).

In eight papers, TOWRE was used. Participants had to read aloud as many words or non-words in a list in 45 seconds for this task. Some studies included the same participants, therefore, in three out of five study populations there were significant positive correlations between performance on the TOWRE word and non-word scores and word and sentence perception in quiet (r = 0.41–0.49, $p < 0.05$; adding model to predict anomalous sentences p = 0.010, df = 32) (Moberly et al., 2018a,c, 2021; Pisoni et al., 2018; Moberly and Reed, 2019; Skidmore et al., 2020; Tamati et al., 2021). More specifically, when performing a regression analysis, Moberly et al. (2018a) found that only TOWRE word and non-word score was related to word and sentence perception in quiet (WQ: r^2 = 0.312, p = 0.001, non-words: r^2 = 0.173, p = 0.014, SQ: Harvard: r^2 = 0.175, p = 0.015, PRESTO: r^2 = 0.187, p = 0.011). Lastly, Moberly et al. (2021), found a significant positive correlation with word perception in quiet for participants with an intermediate and high degree of auditory sensitivity (intermediate: rho = 0.48, p = 0.03, high: rho = 0.42, p = 0.05).

The remaining tasks used to study speed of lexical and phonological access: the WRAT, "preoperative speechreading of sentences," "Lexical Model Oriented (LEMO) subtest of internal homophonic word reading" and non-word repetition task were only applied in one study each. The results varied and showed significant positive (Cohen's d = −1.23, p = 0.0039) (Völter et al., 2021), negative (r = −0.872, p = 0.002) (Hay-McCutcheon et al., 2005) and non-significant relationships (Moberly et al., 2017a; Skidmore et al., 2020).

3.3.4. Degraded receptive language

Degraded receptive language is captured with the Text Reception Threshold (TRT) task. This is a visual analog of the Speech Reception Threshold (SRT) task, where sentences are masked using different visual patterns. The participant needs to try and read the sentences and is scored based on the degree of masking at which they are able to repeat 50% of the words correctly. This task was used in three included studies (Haumann et al., 2012; Kaandorp et al., 2017; Völter et al., 2021) (see **Table 12** for an overview). In one of the three papers the TRT was measured preoperatively (Haumann et al., 2012). Results of these papers assessing performance the TRT and a very similar fragmented sentences test task were highly variable: both non-significant results (Kaandorp et al., 2017), significantly positive (Cohen's d = −0.94 to 1.57, p = 0.0021–0.0002; r^2 = 0.157, $p < 0.001$) (Moberly et al., 2018c; Völter et al., 2021) and negative relations (SN modulated: TRT random dots r = −0.23, r^2 = 0.05, p = 0.036, TRT random bars r = −0.27, r^2 = 0.07, p = 0.012, SN modulated: TRT random dots r = −0.29, r^2 = 0.09, p = 0.007, TRT random bars r = −0.28, r^2 = 0.08, p = 0.009) (Haumann et al., 2012) were found.

4. Discussion

This scoping review aimed to provide a comprehensive overview of the current literature on the relationship between both neurocognitive factors and brain activation patterns, with speech perception outcomes in postlingually deafened adult CI users. Fifty-four papers were included and divided into three categories: (1) literature discussing different brain activation patterns in better and poorer CI performers, (2) literature relating performance on cognitive tasks to speech perception outcomes, and (3) literature relating performance on cognitive language tasks to speech perception outcomes.

4.1. Brain areas recruited in better CI performers

Overall, literature studying brain activation patterns in CI listeners demonstrated that better performers in quiet or noise showed increased activation in the left frontal areas and temporal cortex when passively listening to noise, speech and non-speech stimuli, and actively to semantically correct and incorrect sentences. The frontal lobe is thought to be involved in several speech-related functions, such as semantic generation, decision making and short-term memory (Mortensen et al., 2006; Strelnikov et al., 2013), while the temporal cortex is the main hub for auditory and speech processing. However, activity in the premotor cortex and parietal cortex showed less consistent links with performance. These areas are involved in planning movement and spatial attention, respectively (Breedlove and Watson, 2013).

Moreover, cross-modal activation in the visual occipital cortex during speech perception was seen in better performers. Conversely, visual stimuli activating the auditory temporal cortex was observed in poorer performers. This suggests that learning auditory speech perception with a CI is facilitated by visual cues, yet visual cues should not be the main input for the auditory cortex. In practice, provided the beneficial activation in the visual cortex is higher than the activation induced by visual stimuli in the auditory cortex, speech perception in quiet is more successful. This occurrence of cross-modal activation might be related to duration of deafness and plasticity postimplantation (Buckley and Tobey, 2010; Sandmann et al., 2012; Song et al., 2015a; Chen et al., 2016, 2017; Han et al., 2019).

Subsequently, Lazard et al. (2010, 2011) and Lazard and Giraud (2017) investigated both the involvement of the visual cortex during listening and cross-modal activation in the auditory cortex in CI candidates. They found that performance after implantation depended on activation of either the dorsal route or the ventral route during sound imagery tasks, indicating the use of phonological and speech sound properties, or the use of lexico-semantic properties, respectively. This confirmed the importance of maintaining both the temporal and occipital cortex for normal sound or language processing [such as phonological processing and the integration of visual cues (visemes) with phonological properties] even if the input is not auditory. It seems that if only fast semantic- or lexical-based strategies become the default during the time of deafness, it is hard to return to incorporating original slow speech sound-based strategies once implanted, which contributes to poorer performance. Future research may provide further insights into what causes CI listeners to use different speech perception strategies engaging different brain areas, leading to better or poorer outcomes.

4.2. Cognitive factors related to speech perception outcomes

Several observations were made from the literature studying cognitive performance in CI listeners and its association with speech perception outcomes.

First, non-verbal intelligence, assessed using the Ravens Matrices task, was positively related to word or sentence perception in quiet in most studies (9 out of 13) (Moberly et al., 2017c, 2018c, 2021; Mattingly et al., 2018; Pisoni et al., 2018; Moberly and Reed, 2019; O'Neill et al., 2019; Skidmore et al., 2020; Zhan et al., 2020; Tamati and Moberly, 2021; Tamati et al., 2021). The Ravens task is thought to, amongst other things, involve the ability of inducing abstract relations as well as working memory (Carpenter et al., 1990). Since it is suggested that several basic cognitive functions are involved in performing the Ravens task, it is unclear whether one of these cognitive functions underlie the observed relationship with speech perception performance (Mattingly et al., 2018). Studies that used other tasks to measure the same domain failed to provide additional evidence for the association of the cognitive subdomain non-verbal intelligence with speech perception outcomes (Collison et al., 2004; Holden et al., 2013; Moberly et al., 2016b).

Second, performance on auditory and visual working memory tasks was unrelated to speech perception outcomes in most studies (11 of 15) (Holden et al., 2013; Moberly et al., 2016b, 2017a,b,c, 2018c, 2021; Moberly and Reed, 2019; Skidmore et al., 2020; Tamati et al., 2020; Zhan et al., 2020; Bosen et al., 2021; Tamati and Moberly, 2021; Luo et al., 2022). When both modalities were combined in the working memory task, or more verbal aspects were added, significant correlations with word and sentence perception, both in quiet and noise, appeared to be more prevalent. However, there were only a limited number of studies assessing these types of working memory and thus more data is required to draw any conclusions. Interestingly, Luo et al. (2022), performed a more extensive verbal working memory task, including a cued and uncued working memory condition. When corrected for temporal and spectral resolution, only a significant positive correlation remained between performance in the uncued condition and word perception in noise, but not sentence perception in noise. This suggests that while top-down information is less available, as in the uncued condition of the working memory task (compared to the cued condition), similar working memory processes are at play as during word perception in noise (compared to sentence perception in noise). More research is needed to confirm whether a specific type of working memory is involved in particular speech perception tasks, in the same way that working memory is thought to be modality-specific (Park and Jon, 2018). Working memory processes would enable the listener to retain relevant information while listening to speech [as suggested by the ease of language understanding model (ELU) (Rönnberg et al., 2013)].

Third, cognitive inhibition was generally unrelated to word perception in quiet; a negative relationship was only observed in people with a high degree of auditory sensitivity or after adaptation to speech (Moberly et al., 2021; Tamati and Moberly, 2021). The relationship with sentence perception in quiet was less clear and in several papers negative relationships were observed (3 of 7) (Moberly et al., 2016b, 2017b, 2018a,c; Moberly and Reed, 2019; Tamati et al., 2020; Zhan et al., 2020). This possibly indicates that inhibiting information is engaged more in sentence perception compared to word perception. In theory, sentences contain more information than single words, and interfering information needs to be suppressed while items are retained in working memory (Rönnberg, 2003). It should be noted, however, that since most of these studies were performed in the same lab within the same participant sample, the results should be considered carefully. Additionally, only one main task, the Stroop task, was used to assess cognitive inhibition. It is possible that by implementing the Flanker task more often, different results might be observed, as both tasks measure different facets of inhibitory control (Knight and Heinrich, 2017).

Fourth, performance on standard recall tasks assessing the cognitive domain learning and memory in general did not to correlate with speech perception performance (Holden et al., 2013; Moberly et al., 2017a; Pisoni et al., 2018; Hillyer et al., 2019; Kessler et al., 2020; Skidmore et al., 2020; Tamati et al., 2020; Völter et al., 2021; Ray et al., 2022; Zucca et al., 2022). This is contrary to expectations, as the relevance of these skills is often emphasized in speech perception models (Rönnberg et al., 2013). One explanation for this discrepancy could be that these tasks are not reflective of the use of memory and learning for everyday speech perception. The fact that scores on subtests of the CVLT showed significant positive correlations with sentence perception in quiet and noise (Pisoni et al., 2018; Ray et al., 2022), might already give an example of a test or scoring method more representative of memory and learning skills involved in speech perception. Compared to simple word and picture recall tasks, this test calculates specific scores on, for example, semantic clustering or recall consistency.

Although these studies provide some indications, for many of the cognitive functions there is no or insufficient data to make any inferences. Often, one task is applied only within a single study or results are inconsistent. This is true for social cognition, the general cognitive measures, attention, processing speed, flexibility, audio-visual and verbal working memory, and perceptual-motor function. Moreover, most studies do not report any power analysis, which further increases the unreliability of results should the power be insufficient. One example where a greater sample size seemed to lead to clearer outcomes was for the general cognitive measures. These did not predict word perception in quiet with a sample size of 15 (Zucca et al., 2022). However, research including a larger sample size (df = 32) (Wazen et al., 2020) did show the effectiveness of a quick cognitive assessment for predicting sentence perception in quiet and noise preoperatively. Furthermore, it might be beneficial to consider social cognition, the only cognitive domain currently not covered in the literature. This domain might be of value to CI listeners, as better social skills might lead to more social exposure and therefore more listening practice (Knickerbocker et al., 2021). Therefore, it seems that it would be worthwhile to include this cognitive domain in future research.

4.3. Language skills related to speech perception outcomes

Language is the most interesting cognitive domain in the context of the current paper, as speech perception is part of this domain. According to the outcomes of the included papers, vocabulary was not associated with speech perception performance (7 out of 10 papers) (Collison et al., 2004; Kaandorp et al., 2015, 2017; Shafiro et al., 2016; Moberly et al., 2017a; Kessler et al., 2020; Tamati et al., 2020; Völter et al., 2021). For both verbal fluency and degraded language perception, only a few papers were included, which did not allow to make any inferences about these cognitive skills (Haumann et al., 2012; Finke et al., 2016; Kaandorp et al., 2017; Moberly et al., 2018c; Kessler et al., 2020; Völter et al., 2021; Zucca et al., 2022). The last skill, speed of lexical and phonological access, was often shown to be significantly positively correlated with word and sentence perception when assessed using TOWRE (3 of 5 study populations) (Moberly et al., 2018a,c, 2021; Pisoni et al., 2018; Moberly and Reed, 2019; Skidmore et al., 2020; Tamati et al., 2021). Overall, it seems that in adult CI users, rather than lexical knowledge, the ability to form words quickly and efficiently from phonemes or written text is crucial for speech perception outcomes (even if bottom-up information is incomplete).

4.4. Suggestions for future research

This literature overview points toward some cognitive factors predicting or failing to predict speech perception performance. Unfortunately, a considerable number of reviewed studies showed inconsistent results. As more studies are needed to validate the conclusions above, possible reasons for inconsistency and suggestions to improve future studies are provided:

First, tasks capture scores in different manners when evaluating a cognitive skill. For example, a significant positive correlation was found when measuring response time per trial in an attention task, but not when measuring accuracy within a prespecified time frame (Moberly et al., 2016b; Hillyer et al., 2019; Völter et al., 2021). Similarly, some tasks are more engaging compared to others which aim to assess the same cognitive skills. This might lead to differences in validity between these tests. For example, of two measures assessing attention, the TMT-B requires more use of semantic knowledge compared to pattern matching. Future studies might consider using different measures assessing the same cognitive skills, or one task under different conditions, to determine what feature of the task is relevant for assessing a certain cognitive skill in relation to speech perception outcomes.

Second, the time of assessment might influence results. Significant positive correlations of performance on the TMT-A with speech perception were found when measured preoperatively (Zucca et al., 2022), but similar measures performed postoperatively did not show such a relationship with speech perception outcomes (Hua et al., 2017; Völter et al., 2021). Performing the same cognitive test before and after implantation could provide more insight in this respect. Furthermore, it might provide more granular information on causal relationships, which is valuable for clinical purposes.

Third, the speech perception measures used and the mode of presentation might explain inconsistent findings. Many studies reported cognitive measures to be related to sentence perception outcomes (in noise), rather than word perception outcomes (in quiet). However, it is unclear whether adding noise to words or sentences causes particular cognitive skills to be engaged, as many studies measure words in quiet and sentences in noise only. Measuring all four possible conditions might also be important to create a general classification system for better and poorer performers, which in turn can help to better generalize results. For example, it has been observed that poorer performers in quiet are poorer performers in noise, but better performers in quiet might be poorer performers in noise (Walia et al., 2022). Understanding the underlying causes leading to either poor performance in quiet or noise is needed, as this might lead toward different treatment options. In addition to the speech perception task, the extent to which bottom-up information during this task is not accessible, might also lead to the use of different cognitive strategies. Therefore, including measures of auditory sensitivity (as in Moberly et al., 2021) might be valuable. Furthermore, presentation mode (whether speech is presented in CI alone, or best aided condition) should be clearly stated. Unfortunately, this is overlooked in many of the included papers. Therefore, based on the included literature, it is impossible to make any inferences regarding the influence of listening condition on the use of specific cognitive skills. Indicating the test conditions in detail, or even including different testing conditions in future studies, like Hua et al. (2017), might be insightful.

Fourth, as mentioned in the introduction, the different cognitive domains and factors are not independent of each other. In fact, some tasks are used specifically to measure two different cognitive factors. Therefore, results based on correlation analysis, whereby each of the cognitive task scores are correlated separately with speech perception outcomes, should be interpreted with caution. It might be more informative to more often use alternative statistical analyses, such as regression analysis, instead. This could reveal any mediation of specific cognitive factors or cognitive scores explaining more of the variance in speech perception outcomes. Furthermore, as discussed before, many of the included studies do not report their power calculations, nor do they provide all statistical values. Ensuring sufficient power and consistently reporting statistical values (including effect sizes and values of non-significant results) will improve interpretation of results.

Lastly, while it is useful to look at papers which investigate either brain activation patterns or performance on cognitive and language tasks, it could be highly valuable to combine both neuroimaging techniques and behavioral measures within studies. We believe this could be beneficial as these measures could validate each other, as well as provide information on underlying neurocognitive processes involved in the observed behavior.

4.5. Limitations

The main limitation of this scoping review is that the number of papers for several neurocognitive domains is limited and their methods and dependent/independent variables are highly variable. Conclusions, therefore, are only based on a limited number of papers that cover the same cognitive domain or function. Secondly, as stressed previously, many questions remain as to why results of different papers do not agree. Furthermore, no risk of bias assessment was performed. This makes the conclusions drawn prone to being influenced by biases, whether coming from the authors of the included literature or from interpretation by the authors of this scoping review. Implementing the above-mentioned suggestions could improve evidence in future research and bring more clarity on the topics discussed in this review.

5. Conclusion

In this scoping review, a comprehensive overview of literature on the relationship between cognitive factors and speech perception outcomes in adult CI users was given. This literature showed that the use of higher-order cognitive functions, recruiting the frontal cortex, the use of visual cues, recruiting the occipital cortex, and the temporal cortex still available for auditory processing, are beneficial for postlingually deafened adult CI users in relation to speech perception outcomes. Cognitive assessments indicate that performance on non-verbal intelligence tasks positively correlated with speech perception outcomes. Performance on auditory or visual working memory, learning, memory and vocabulary tasks were unrelated to speech perception outcomes and performance on the Stroop task unrelated to word perception in quiet. However, many uncertainties regarding the explanation of inconsistent results and the small number of studies limit the extent of these conclusions. Additional research is needed to validate current findings. Only then will they potentially be used as a guide for counseling and rehabilitating adult CI users.

Author contributions

LB, BP, EM, and WH contributed to the conception and design of the study. LB and NT collected the data. LB, NT, BP, and WH curated and interpreted the data. LB wrote the first draft of the manuscript. NT, BP, EM, and WH revised the manuscript critically. All authors read and approved the submitted version.

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Conflict of interest

LB and BP were employed by Cochlear Ltd. NT was affiliated with Cochlear Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Cocktail-party listening and cognitive abilities show strong pleiotropy

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Introduction: The cocktail-party problem refers to the difficulty listeners face when trying to attend to relevant sounds that are mixed with irrelevant ones. Previous studies have shown that solving these problems relies on perceptual as well as cognitive processes. Previously, we showed that speech-reception thresholds (SRTs) on a cocktail-party listening task were influenced by genetic factors. Here, we estimated the degree to which these genetic factors overlapped with those influencing cognitive abilities.

Methods: We measured SRTs and hearing thresholds (HTs) in 493 listeners, who ranged in age from 18 to 91 years old. The same individuals completed a cognitive test battery comprising 18 measures of various cognitive domains. Individuals belonged to large extended pedigrees, which allowed us to use variance component models to estimate the narrow-sense heritability of each trait, followed by phenotypic and genetic correlations between pairs of traits.

Results: All traits were heritable. The phenotypic and genetic correlations between SRTs and HTs were modest, and only the phenotypic correlation was significant. By contrast, all genetic SRT–cognition correlations were strong and significantly different from 0. For some of these genetic correlations, the hypothesis of complete pleiotropy could not be rejected.

Discussion: Overall, the results suggest that there was substantial genetic overlap between SRTs and a wide range of cognitive abilities, including abilities without a major auditory or verbal component. The findings highlight the important, yet sometimes overlooked, contribution of higher-order processes to solving the cocktail-party problem, raising an important caveat for future studies aiming to identify specific genetic factors that influence cocktail-party listening.

KEYWORDS
cocktail-party listening, genetics, genetic correlation, cognition, hearing threshold, hidden hearing loss

1. Introduction

Ordering drinks at a bar, listening to announcements in an airport terminal, and chatting in a crowded space are all real-world examples of the cocktail-party problem (1), in which listeners must segregate the acoustic mixture reaching their ears into its constituent sounds and attend to the sounds of interest (2). Among the most challenging cocktail-party problems are those involving multiple simultaneous talkers (3). These situations are also the most critical for successful real-world hearing, as listeners report difficulties in following conversations in noisy environments more than any other kind of hearing problem [e.g., (4)]. It is therefore crucial to understand why some listeners find these situations more challenging than others.

Psychoacoustical studies provide a remarkably clear picture of which acoustic features are exploited to solve the cocktail-party problem (5, 6), and functional neuroimaging studies have made considerable progress in delineating the neural implementation of cocktail-party listening [e.g., (7)], at least in typical listeners. What is less clear is how and why listeners show such large individual differences in their cocktail-party listening abilities. Possible factors include basic sound sensitivity, peripheral auditory processing, and supramodal (i.e., cognitive) abilities. Regarding sound sensitivity, hearing impairment is obviously a major limiter of all hearing abilities, including cocktail-party listening, but while hearing aids are highly effective at improving sound sensitivity and speech intelligibility in quiet or steady-state noise in hearing-impaired listeners, their benefit in more realistic, cocktail-party-like situations falls short, suggesting that simply increasing overall audibility is not sufficient to solve the cocktail-party problem (8). Furthermore, performance on multitalker cocktail-party listening tasks differs dramatically among listeners with HTs in the normal or near-normal range [e.g., (9–12)]. These findings make it clear that cocktail-party listening and sound sensitivity are quite distinct.

Regarding peripheral auditory processing, a single mechanism has garnered particular interest in recent years. Non-human animal studies have shown that cochlear synaptopathy, or loss of the connections between hair cells and auditory-nerve fibers, may degrade the temporal representations of suprathreshold sounds in the absence of elevated HTs (13). Cochlear synaptopathy can be induced by moderate amounts of noise exposure [e.g., (14)] and occurs naturally *via* normal aging [e.g., (15)]. Several non-invasive electrophysiological correlates of cochlear synaptopathy have been proposed, which can be applied to living humans (16, 17). However, cochlear synaptopathy as an explanation of poor cocktail-party listening in humans remains controversial because the extent to which synaptopathy correlates with multitalker listening tasks or self-reported real-world hearing problems is unclear [e.g., (18)].

Prior studies make it abundantly clear that listeners' cocktail-party listening abilities correlate with their cognitive abilities. Studies reporting such correlations have employed a variety of experimental designs, ranging from comprehensive psychophysical and cognitive assessments in small samples [e.g., (19)] to cursory assessments in huge samples [e.g., (20)]. In a metaanalysis of 25 individual studies, Dryden et al. (21) estimated an overall moderate correlation between speech-in-noise performance and cognitive abilities. Their analysis collapsed across various speech-in-noise tasks, cognitive measures, and listeners with and without hearing impairment. The authors concluded that there were not clear differences in correlations as a function of the target stimulus or masker type, but they did conclude that some cognitive domains were more strongly correlated with speech-in-noise performance than others: the cognitive domains considered, in order of strongest to weakest correlation, were processing speed, inhibitory control, working memory, episodic memory, and crystallized intelligence. These conclusions should be interpreted somewhat cautiously, as Dryden et al. noted, because of the considerable heterogeneity in study designs [similarly, see (22)]. Nevertheless, it is interesting to note that these correlations did not seem to be stronger for cognitive tasks with a prominent auditory or verbal component, suggesting that these relationships were not due to common method variance (23).

Previously, we explored whether genetic factors influenced cocktail-party listening (24). We measured speech-reception thresholds (SRTs) in a cocktail-party listening task where listeners reported target sentences mixed with time-reversed masker sentences from different talkers. Listeners were recruited from large pedigrees as part of the Imaging Genomics of the Aging Brain (IGAB) study. Quantitative genetic analyses suggested that just over half of the variance of SRTs was due to additive genetic factors. This estimate of heritability did not appear to be influenced by environmental factors that were shared among relatives (e.g., current household), and was robust to the inclusion and exclusion of hearing-impaired listeners. Furthermore, the genetic correlation between SRTs and HTs, or the correlation between their latent additive genetic influences, was not significantly different from 0, although it was significantly different from 1. This result suggested that the genetic factors influencing cocktail-party listening were largely distinct from those influencing sound sensitivity, which was consistent with the idea that normal sound sensitivity is not sufficient to solve the cocktail-party problem, as mentioned earlier. Overall, the findings suggested that future studies could identify specific genetic variants that influence cocktail-party listening—and by extension, real-world hearing problems—in listeners without clinical hearing impairment.

It remains to be established whether the genetic factors influencing cocktail-party listening overlap with those influencing cognitive abilities. In the present study, we explored this open question by estimating the phenotypic and genetic correlations between SRTs, HTs, and various cognitive abilities in listeners from the IGAB study. This sample was randomly ascertained with respect to hearing, meaning that some of them had hearing loss. The sample also represented a cross-section of the adult lifespan, including both young and old adults. Our primary aim was to estimate correlations between SRTs, HTs, and cognitive abilities. Although such correlations have been estimated before [cf. (21)], all previous studies estimated phenotypic correlations only. Other novel features of the present study were that we measured a wide range of cognitive abilities, rather than focusing on just one or a few specific tasks or abilities [e.g., working memory; (25)], and the sample size was large compared to other studies that measured many cognitive abilities in the same listeners [e.g., (19)].

2. Materials and methods

2.1. Listeners

The IGAB study recruited 493 listeners, 304 of whom were genetically female. Listeners ranged from 17 to 91 years old, with a median age of 47.8 years, and belonged to 54 pedigrees of varying size. The largest pedigree had 91 members. Reported familial relationships were verified based on autosomal markers.

Listeners were not recruited or excluded based on any criteria except that they must have participated in at least one prior genetic study. These studies were the San Antonio Family Heart Study [SAFHS; (26)]; the San Antonio Family Gallbladder Study [SAFGS; (27)]; and the Genetics of Brain Structure and Function Study [GOBS; (28)]. SAFHS occurred across three recruitment phases between 1992 and 2007. To be eligible for SAFHS, an individual had to be Mexican American, aged 40–60 years, have a spouse willing to participate, and have at least six adult (>16 years old) offspring and/or siblings. SAFHS also recruited the spouses of these participants (if they were Mexican American), their first-, second, and third-degree adult relatives, and Mexican American spouses of those relatives. SAFGS was conducted between 1998 and 2001 and recruited additional Mexican American families in a similar way, except that the initial proband always had type-2 diabetes. Since this disorder has a lifetime prevalence approaching 30% in this population, the recruitment strategy employed in SAFGS represented effectively random sampling for other diseases, behaviors, and abilities. GOBS was conducted between 2006 and 2016 and re-recruited SAFHS and SAFGS individuals, as well as their previously unrecruited adult offspring. Thus, all listeners were sampled from the same community.

All listeners provided written informed consent on forms approved by the institutional review board at the data-collection site, University of Texas Health Science Center at San Antonio, as well as review boards at the University of Texas Rio Grande Valley and Boston Children's Hospital.

2.2. Overview of the assessments

We attempted to conduct the auditory and cognitive assessments described in the following sections on all listeners in the IGAB study. Usually, a listener completed these assessments during a single laboratory visit, although occasionally a listener was unable to complete one or more of them, for various reasons. During the same visit, listeners completed a brief structured interview to determine their medical histories, the mini-mental state examination [MMSE; (29)], and the clinical dementia rating (CDR) staging instrument (30). Listeners completed other assessments to collect demographic information, physical variables, and biological samples, but these were not relevant to the present goals and are not described here.

Most listeners spoke English as their first language and their assessments were conducted in English. However, a small proportion of listeners spoke Spanish as their first language, and these individuals completed Spanish translations or versions of each assessment if such a translation/version was available. Spanish translations/versions were available for most cognitive assessments, but notably not the cocktail-party listening task. We therefore only analyze data from English-speaking listeners here (see the next section).

Auditory and cognitive assessments were performed under the supervision of a member of the research team in a quiet testing room using a laptop with an integrated digital-to-analog converter and a touchscreen display. The cocktail-party listening task and hearing test were conducted with connected headphones (Sennheiser HD 25 Pro), while the cognitive tests used the laptop's integrated loudspeakers. Listeners made their responses using the keyboard, the touchscreen, or orally, depending on the assessment.

2.3. Exclusions

During their medical interviews, one listener reported multiple sclerosis, two reported Parkinson's disease, two reported Alzheimer's disease, one reported non-Alzheimer's dementia, 15 reported strokes, and three reported another neurological disorder or brain trauma. Several listeners were suspected to have at least mild cognitive impairment based on the neurological assessments: 12 listeners scored below 24 on the MMSE, and three listeners had CDR global scores and/or sum of boxes scores above 1 and/or 4.5, respectively. It became apparent during their assessments that eight listeners were illiterate. Six listeners were Spanish speakers. While none of the above features were exclusion criteria for the IGAB study *per se*, we have excluded these listeners from the present study (40 exclusions in total).

2.4. Cocktail-party listening task

For several reasons outlined in our previous article (24), we opted to develop a novel cocktail-party listening task using synthetic speech and time-reversed maskers. Briefly, the task was time-efficient, as listeners made multiple responses to a single brief sentence per trial [cf. (31)], and performance could not be improved by paying attention to the syntactic structure or semantic content of the sentences [cf. (32)]. Synthetic speech using realistic voice models (33) allowed the construction of a very large corpus with coarticulation across words, and reversed maskers prevented some listeners from becoming confused about the task demands.

The task was similar to the every-other-word paradigm devised by Kidd et al. (34). On each trial, the listener heard a target sentence starting with the name "Jane" followed by four variable words: a verb, a number, an adjective, and a noun. There were eight possible variable words per position (verbs: "bought," "found," "gave," "heard," "held," "kicked," "saw," "threw;" numbers: "two" to "ten" excluding "seven;" adjectives: "big," "blue," "cold," "hot," "black," "old," "red," "small;" nouns: "bags," "cards," "gloves," "hats," "pens," "shoes," "socks," "toys"). Listeners reported the variable words per target sentence *via* a graphical user interface on the touchscreen display, with one button per word.

Target sentences were presented at an average sound pressure level (SPL) of 60 dB and mixed with two random masker sentences constructed from the same corpus but with a different name ("Pat" and "Sue") and with the constraint that no word could occur more than once on a given trial. Masker SPLs were manipulated to achieve a desired signal-to-noise ratio (SNR) with the targets. Maskers were time-reversed and aligned to have simultaneous onsets with the targets. All sounds were presented diotically.

On the first trial of the task, the SNR was 40 dB (i.e., maskers were 20 dB SPL). On following trials, SNRs were decreased and increased by 2 dB for every correct and incorrect selection, respectively, on the immediately preceding trial. For example, if a listener selected three variable words correctly (i.e., made one error) on the first trial, the SNR on the second trial was 40 – 2 – 2 – 2 + 2 = 36 dB. It is straightforward to show that this procedure converges asymptotically on the SNR value that yields a 50% chance of a correct response, assuming a constant psychometric function (35). The task was always terminated after 30 trials. SRTs were estimated by taking the mean of all SNR values excluding the SNR on the first trial, which was always 40 dB and therefore uninformative, and including the theoretical 31st trial, whose SNR could be calculated based on listeners' responses to the 30th trial.

2.5 Hearing test

As described in our previous article (24), the hearing test measured HTs for 0.5-, 1-, 2-, 4-, 8-, and 12.5-KHz pure tones in both ears. Each trial in the hearing test comprised a 2-s interval which equiprobably contained or did not contain a monaural 1-s pure tone whose amplitude was modulated at 100% depth using a 2-Hz full-wave rectified sinusoid. On each trial, listeners pressed the space bar if they heard a tone during the interval. Trials were organized into separate blocks for each frequency and ear. The lowest frequency tested was 0.5 KHz because previous work suggests that HTs measured inside and outside of a sound-attenuated chamber are largely equivalent at or above this frequency, whereas lower-frequency HTs may be unreliable (36). Within a block, the first tone had a fixed level of 60 dB hearing level (HL) and the levels of subsequent tones were manipulated using a single interval adjustment matrix (37) with an adjustment factor of 10 dB up to the second reversal and 4 dB afterward. Blocks were terminated after six reversals. HTs were defined as the quietest sound heard per frequency and ear. Better-ear average (BEA) HTs were calculated using all frequencies except 12.5 KHz.

2.6. Cognitive tests

Cognitive assessments were administered using the latest version of our in-house computerized cognitive battery, Charlie, which we have used in prior studies [e.g., (38, 39)], and is the successor of the South Texas Assessment of Neurocognition (STAN), which was used in the GOBS study [e.g., (40)]. Charlie contains many of the same tests as STAN but was updated to run using modern hardware (e.g., touchscreen computers). Individual tests and their associated dependent variables are described below. Tests were completed in the order they are described.

2.6.1. Orientation

The first test in the battery was a simple measure of visual search speed. On each trial, a red square appeared in a random position on the touchscreen and listeners touched the square as quickly as possible. There were 15 such trials in total. This test was originally developed to introduce the listener to the touchscreen device and ensure that they could operate it correctly (hence the name "orientation"), but we found that it yielded meaningful cognitive data in a previous study (39). The test yielded a single dependent variable, namely the log-transformed time taken to complete all trials.

2.6.2. Trail-making test (TMT) part A

This test was a computerized analog of part A of the classic trail-making test (41), which measures visual search and processing speed. During the test, numbers 1 to 26 appeared inside circles that were randomly positioned on the touchscreen. Listeners touched the circles, one by one, in ascending numerical order, as quickly as possible. After touching an appropriate circle, a line appeared that connected the current circle to the previous circle, forming a trail between them. Upon touching an incorrect circle, listeners heard a brief feedback sound instead. The tested ended after the final circle was touched. The dependent variable was the log-transformed completion time.

2.6.3. TMT letter

This test was identical to the TMT part A, except that the circles contained letters of the alphabet instead of numbers, and listeners touched them in ascending alphabetical order. It was intended to serve as an intermediate condition between parts A and B of the classic trail-making test, since poor performance on part B could be caused by poor literacy. Again, the dependent variable was the log-transformed completion time.

2.6.4. TMT part B

This test was a computerized analog of part B of the classic trail-making test, which measures set shifting and executive functioning. Twenty-six circles, each containing a number or letter, appeared in random positions on the screen. Listeners touched them in alternating ascending numerical and ascending alphabetical order (1, "a," 2, "b" ...) as quickly as possible. The dependent variable was the log-transformed completion time.

2.6.5. Matrix reasoning

This test used the same stimuli as the progressive matrix-reasoning test that appears in the Wechsler adult intelligence scale [WAIS; (42)], which measures non-verbal abstract reasoning. On each trial, listeners saw a visual puzzle or matrix with a piece missing, and touched the missing piece from four alternatives presented below it. The dependent variable was the total number of correct responses.

2.6.6. Visuospatial memory

This test measured visuospatial short-term memory capacity using a change-localization test, similar to the one used by Johnson et al. (43). On each trial, four items with random shapes, positions, and colors appeared on the touchscreen for a brief period, then disappeared for a longer period. After the second period, three of the items reappeared, and a fourth item with a novel shape and color appeared in the position previously occupied by the missing item. Listeners touched the new item. The dependent variable was the total number of correct responses.

2.6.7. Emotion recognition

This test was identical to the ER-40, which is widely used in psychiatry research to index the ability to judge emotions in facial expressions (44). On each trial, listeners saw a color photograph of a static face expressing a happiness, sadness, anger, fear, or no emotion. Listeners touched the word describing the corresponding emotion from the five alternatives. The dependent variable was the total number of correct responses.

2.6.8. California verbal learning test

This test was a modified and abridged version of the adult CVLT, second edition (45), which measures episodic verbal learning and memory. On each trial, listeners heard 16 words spoken aloud and then repeated out loud as many of them as possible. Oral responses were recorded by the administrator. There were five trials, and the same 16 words were heard in the same order each time. The dependent variable was the total number of correct responses summed over trials.

2.6.9. Forward span

This classic measure of verbal short-term memory capacity is found in many standardized cognitive batteries, such as the WAIS. Listeners heard sequences of digits and repeated them out loud. Oral responses were recorded by the administrator. The dependent variable was the improved mean span metric proposed by Woods et al. (46).

2.6.10. Backward span

This is a more challenging variant of forward span in which listeners repeated sequences of digits in reverse order. Oral responses were recorded by the administrator. The dependent variable was the improved mean span metric.

2.6.11. Letter–number sequencing

This is the classic measure of verbal working memory capacity—as opposed to short-term memory capacity, since it requires the ability to manipulate as well as recall remembered items —found in many cognitive batteries, including as the WAIS. Listeners heard sequences of letters and digits, and repeated them back in alternating ascending numerical and alphabetical order. Oral responses were recorded by the administrator. The dependent variable was the improved mean span metric.

2.6.12. Wechsler test of adult reading

This is a widely used test of reading ability (47). Listeners attempted to correctly pronounce words from a list of 50 words of increasing difficulty. Oral responses were recorded by the administrator. The dependent variable was the total number of correct responses.

2.6.13. Controlled oral word association test letter

This is the traditional "fas" variant of the COWAT, which measures verbal fluency (48). Over three trials, listeners said as many unique real words beginning with a specific letter as possible, discounting proper nouns, in 1 min. The letters were "f," "a," and "s" on the first, second, and third trials, respectively. Oral responses were recorded by the administrator. The dependent variable is the total number of valid responses.

2.6.14. COWAT animal

This is another variant of the COWAT, which measures semantic verbal fluency (49). Listeners named as many unique animals as possible in 1 min. Oral responses were recorded by the administrator. The dependent variable is the number of valid responses.

2.6.15. Digit symbol

This is a two-alternative forced-choice computerized variant of the digit–symbol substitution test (38), which measures processing speed. Listeners were presented with a key of symbols and digits at the top of the screen, which persisted across all trials. On each trial, they saw a new random digit and random symbol, and judged whether they made a correct pair according to the key. The dependent variable is the number of correct responses made within two 90-s blocks, multiplied by overall accuracy; the multiplicative term served to penalize individuals who responded quickly but with poor accuracy.

2.6.16. Facial memory

This test measures facial recognition memory. During a learning phase, listeners saw 20 monochrome photographs of strangers' faces, presented sequentially. During a recognition phase, listeners were presented with faces, one per trial, that were equiprobably one of those from the learning phase or entirely novel. On each trial, listeners made an old/new judgement. The dependent variable is the number of correct responses.

2.6.17. Continuous performance test

This is the identical-pairs version of the widely used continuous performance test, which measures sustained attention (50). On each trial, listeners see a row of three random symbols for a brief period and respond when all three symbols match those from the immediately preceding trial. The dependent variable is the number of hits, or matches correctly reported.

2.6.18. Logical memory

This was identical to the logical memory test from the Wechsler memory scale (51), which measures verbal episodic memory. This test contained three parts. In the first part, listeners immediately recalled details of two short passages. In the second part, listeners recalled the passages after a delay. In the third part, listeners answered yes or no questions regarding the passages. The dependent variable was the total raw score.

2.7. Quantitative genetic analysis

2.7.1. Univariate models

A univariate quantitative genetic model attempts to explain the phenotypic (or observed) variance of a single focal trait in terms of ensemble genetic and environmental factors. Under the standard assumptions of quantitative genetics (52), the focal trait vector, denoted by $\boldsymbol{y}$, follows a multivariate normal distribution, $\boldsymbol{y} \sim N(\boldsymbol{\mu}, \boldsymbol{\Omega})$. The mean of this distribution, denoted by $\boldsymbol{\mu}$, is given by $\boldsymbol{\mu} = \boldsymbol{X\beta}$, where $\boldsymbol{X}$ is a design matrix of fixed-effect nuisance covariates, such as age and sex, and $\boldsymbol{\beta}$ is a vector of their corresponding regression coefficients. The covariance matrix, denoted by $\boldsymbol{\Omega}$, is given by $\boldsymbol{\Omega} = 2\boldsymbol{\Phi}\sigma^2_{\mathrm{G}} + \boldsymbol{I}\,\sigma^2_{\mathrm{E}}$, where $\boldsymbol{\Phi}$ is the matrix of kinship coefficients between listeners (determined by their pedigrees), σ^2_{G} is the additive genetic variance (a free parameter), $\boldsymbol{I}$ is an identity matrix, and σ^2_{E} is the environmental or residual variance (another free parameter).

Narrow-sense heritability (53) is given by $h^2 = \sigma^2_{\mathrm{G}} \,/\, (\sigma^2_{\mathrm{G}} + \sigma^2_{\mathrm{E}})$ and can be thought of as an effect size for the genetic effect, as it represents the proportion of phenotypic variance explained by additive genetic factors. For example, if $h^2 = 1$, the trait would be completely determined by such factors; if h $h^2 = 0.5$, half the trait's phenotypic variance would be determined by such factors. Because we often wish to test the statistical significance of h^2, it can be convenient to reparameterize the equation for the covariance matrix as $\boldsymbol{\Omega} = [2\boldsymbol{\Phi}h^2 + \boldsymbol{I}\ (1 - h^2)]\sigma^2$, so that h^2 and the phenotypic standard deviation, denoted by σ, are free parameters. This allows us to construct a null model where $h^2 = 0$. The null and alternative models are both fitted to the data *via* maximum likelihood estimation, and a likelihood ratio test (LRT) is constructed to obtain a p-value for the test of heritability.

We fitted univariate quantitative genetic models to SRTs, HTs, and the 18 individual cognitive measures (i.e., 20 models in total). Fitting was done using the SOLAR software package (54). The purpose of these analyses was to check if all traits were heritable, as we expected based on previous studies. Before model fitting, traits were rank-based inverse-normal transformed to ensure that they were normally distributed and reduce the influence of outliers. All models contained an intercept, age, age^2, sex, an age $\times$ sex interaction, and an age^2 $\times$ sex interaction as fixed-effect covariates. All of these fixed effects were included in every model, including bivariate and trivariate models (described below), regardless of their statistical significance.

2.7.2. Bivariate models

A bivariate quantitative genetic model is an extension of a univariate model that considers two traits simultaneously. The equations are available elsewhere [e.g., (52)]. Crucially, bivariate models provide not only heritability estimates for two traits, but also estimates of their phenotypic, genetic, and environmental correlations. The phenotypic correlation, denoted by ρ_{P}, is the correlation between the phenotypes (i.e., observed values)—it is exactly like the more commonly understood Pearson's product–moment coefficient and its values can be interpreted the same way; for example, $\rho_{\mathrm{P}} = 0$ represents independence and $\rho_{\mathrm{P}} = \pm 1$ represents complete correlation. The genetic correlation, denoted by ρ_{G}, describes the correlation between the traits' latent additive genetic factors. Again, $\rho_{\mathrm{G}} = 0$ represents independence (of the underlying genetic factors) and $\rho_{\mathrm{G}} = \pm 1$ represents complete correlation (between the genetic factors, also called complete pleiotropy). Note that ρ_{P} and ρ_{G} are guaranteed to converge only when both traits are perfectly heritable; therefore, ρ_{G} can be exactly ± 1, implying complete pleiotropy, even if ρ_{P} is not, due to non-genetic factors (e.g., measurement error) influencing the traits. Finally, the environmental correlation, denoted by ρ_{E}, describes the correlation between the traits' non-genetic components. Since measurement error is a major non-genetic component, environmental correlations are the most difficult to interpret (and often the least interesting) of the three correlation types.

Under the default parameterization, ρ_{G} and ρ_{E} are free parameters, allowing null models where $\rho_{\mathrm{G}} = 0$ or $\rho_{\mathrm{E}} = 0$ to be fitted and LRTs to determine whether traits are significantly genetically or environmentally correlated. Another possibility is to test whether traits show incomplete pleiotropy, using a null model where $\rho_{\mathrm{G}} = \pm 1$. While ρ_{P} can be estimated deterministically, the model also can be reparameterized so that ρ_{P} is a free parameter, which allows an LRT of phenotypic correlation.

We fitted bivariate models in which one trait was always SRTs, and the other was either HTs or an individual cognitive measure (i.e., 19 models in total). Per model, we performed LRTs to test whether ρ_{P} differed from 0, ρ_{G} differed from 0, ρ_{G} differed from ± 1, where the sign matched that of the ρ_{G} estimate, and ρ_{E} differed from 0.

Bivariate models can handle incomplete data; that is, when one individual has a value for one trait but not the other, allowing maximal use of all available data.

2.7. 3. Endophenotype ranking

The endophenotype ranking value (ERV) is a helpful metric for ranking trait pairs (40). It is defined deterministically as ERV $= |\sqrt{h^2_1}\sqrt{h^2_1}\rho_{\mathrm{G}}|$, where h^2_1 and h^2_2 are heritabilities of two traits. This quantity represents the phenotypic covariance of the traits explained by the same genetic factors, and balances the strengths of the genetic signals and the strength of their genetic relationship. It is sometimes called bivariate heritability (55). We estimated ERVs for all SRTs and HTs, as well as all SRT–cognition trait pairs (19 ERVs in total).

2.7.4. Correction for multiple comparisons

All p-values were corrected for multiple comparisons by applying a single-step false-discovery rate (FDR) adjustment at the 0.05 level (56).

3. Results

3.1. Heritabilities

Table 1 shows narrow-sense heritability estimates for all traits. SRT and HT heritability estimates ($h^2 = 0.553$ and h^2

TABLE 1 Results from the univariate and bivariate quantitative genetic analyses.

Trait	N	h2	ρP	ρG	ρE	ERV
SRTs	400	**0.553 (0.135)**				
COWAT letter	442	**0.534 (0.117)**	**−0.436 (0.0424)**	**−0.980 (0.153)**	0.0977 (0.181)	0.532
Digit symbol	438	**0.598 (0.123)**	**−0.409 (0.0452)**	**−0.864 (0.100)**	0.323 (0.277)	0.496
TMT part B	439	**0.460 (0.125)**	**0.442 (0.0424)**	**0.906 (0.143)**	0.0109 (0.179)	0.457
Logical memory	342	**0.689 (0.149)**	**−0.429 (0.0480)**	**−0.698 (0.121)***	0.0683 (0.303)	0.431
TMT letter	441	**0.357 (0.104)**	**0.416 (0.0436)**	**0.963 (0.146)**	0.0408 (0.144)	0.428
LNS	435	**0.329 (0.110)**	**−0.458 (0.0410)**	**−1 (n/a)**	−0.0524 (0.147)	0.426
CVLT	405	**0.676 (0.142)**	**−0.435 (0.0434)**	**−0.696 (0.143)***	−0.0462 (0.235)	0.426
Backward span	416	**0.514 (0.119)**	**−0.438 (0.0439)**	**−0.745 (0.128)**	−0.0821 (0.191)	0.397
WTAR	406	**0.770 (0.109)**	**−0.508 (0.0400)**	**−0.570 (0.121)***	−0.448 (0.193)	0.372
Orientation	442	**0.239 (0.120)**	**0.240 (0.0481)**	**1 (n/a)**	−0.165 (0.143)	0.363
CPT	356	**0.416 (0.150)**	**−0.242 (0.0523)**	**−0.729 (0.172)***	0.244 (0.205)	0.349
TMT part A	441	**0.267 (0.106)**	**0.373 (0.0465)**	**0.900 (0.149)**	0.0449 (0.144)	0.345
Matrix reasoning	432	**0.414 (0.125)**	**−0.427 (0.0427)**	**−0.708 (0.159)***	−0.186 (0.156)	0.339
COWAT animal	442	**0.692 (0.105)**	**−0.330 (0.0472)**	**−0.538 (0.149)***	−0.0231 (0.207)	0.333
Forward span	432	**0.400 (0.130)**	**−0.420 (0.0433)**	**−0.696 (0.196)***	−0.234 (0.141)	0.327
Facial memory	442	**0.406 (0.127)**	**−0.421 (0.0433)**	**−0.648 (0.142)***	−0.202 (0.164)	0.307
Emotion recognition	409	**0.394 (0.122)**	**−0.340 (0.0462)**	**−0.634 (0.152)***	−0.0691 (0.166)	0.296
Visuospatial memory	433	**0.257 (0.122)**	**−0.389 (0.0438)**	**−0.698 (0.219)***	−0.230 (0.136)	0.263
HTs	405	**0.337 (0.131)**	**0.311 (0.0472)**	0.362 (0.210)*	0.284 (0.151)	0.156

h^2, narrow-sense heritability; ρ_P, phenotypic correlation; ρ_G, genetic correlation; ρ_E, environmental correlation; ERV, endophenotype ranking value; SRT, speech reception threshold; COWAT, controlled oral word association test; TMT, trail-making test; LNS, letter–number sequencing; WTAR, Wechsler test of adult reading; CPT, continuous performance test; CVLT, California verbal learning test; HT, hearing threshold. In the third, fourth, and sixth columns from the left (heritabilities, phenotypic correlations, and environmental correlations, respectively), the leftmost value in each cell is the parameter estimate, the parenthetical is the standard error of that estimate, and a bold value indicates that an estimate was significantly different from 0 at the FDR-corrected level. The same is true for the fifth column from the left (genetic correlations), except that an asterisk also indicates that an estimate was significantly different from ±1 (whichever is closer to the parameter estimate). Note that sometimes the ρ_G estimate was exactly ±1: in these cases, the estimate converged to a parameter boundary and standard errors could not be computed (hence "n/a"), though statistical tests could still be performed.

=0.337, respectively) were extremely similar to those we reported previously in a slightly smaller sample of the same listeners (24). Cognitive measures had a range of heritabilities, with orientation being the weakest ($h^2 = 0.239$) and WTAR being the strongest ($h^2 = 0.770$). This pattern of heritability estimates for cognitive traits was consistent with the pattern we reported in the GOBS study, which was conducted about a decade ago and involved the same individuals and their close relatives (40, 57). All heritabilities were significantly >0 at the FDR-corrected level ($5.12 \leq \chi^2 \leq 48.5$; $1.62 \times 10^{-12} \leq p \leq 0.0118$; $1.01 \times 10^{-11} \leq p_{\text{FDR}} \leq 0.0174$).

3.2. Phenotypic correlations

The phenotypic correlation between SRTs and HTs was positive, indicating that larger (worse) SRTs were associated with larger (worse) HTs, and significantly different from 0 at the FDR-corrected level [$\rho_P = 0.311$; $\chi^2_{(1,N=405)} = 35.8$; $p = 2.14 \times 10^{-9}$; $p_{\text{FDR}} = 1.06 \times 10^{-8}$]. This is consistent with our previous study (24).

Phenotypic SRT–cognition correlations ranged from weak (SRT–orientation $\rho_P = 0.240$) to strong (SRT–WTAR $\rho_P = -0.508$), but most of them were stronger than the SRT–HT correlation (see Table 1). All SRT–cognition correlations were significantly different from 0 at the FDR-corrected level ($19.8 \leq \chi^2 \leq 94.2$; $2.84 \times 10^{-22} \leq p \leq 8.42 \times 10^{-6}$; $2.67 \times 10^{20} \leq p_{\text{FDR}} \leq 2.40 \times 10^{-5}$). SRT–cognition correlations were negative for all cognitive measures that were based on accuracy, where a lower score reflected poorer performance, and positive for all time-based measures, where a larger score indicated worse performance.

3.3. Genetic correlations

The genetic correlation between SRTs and HTs was positive, but not significantly different from 0 at the FDR-corrected level [$\rho_G = 0.362$; $\chi^2_{(1,N=405)} = 2.36$; $p = 0.125$; $p_{\text{FDR}} = 0.161$]. However, it was significantly different from 1 [$\chi^2_{(1,N=405)} = 7.74$; $p = 0.161$; $p_{\text{FDR}} = 0.00445$]. In other words, the hypothesis of no pleiotropy could not be rejected, but the hypothesis of complete pleiotropy could, suggesting that the genetic influences on SRTs and HTs were at least partially distinct. This result is consistent with our previous study (24).

All genetic SRT–cognition correlations were strong and significantly different from 0 at the FDR-corrected level ($0.538 \leq |\rho_P| \leq 1$; $7.19 \leq \chi^2 \leq 28.7$; $8.60 \times 10^{-8} \leq p \leq 0.00734$; $4.04 \times 10^{-7} \leq p_{FDR} \leq 0.0113$). SRT–LNS and SRT–orientation correlations were estimated to be exactly ±1 (a parameter boundary). Genetic correlations were always in the same direction as their corresponding phenotypic correlations, but were always stronger. For some cognitive measures, the correlation was not significantly different from ±1 at the FDR-corrected level.

3.4. Environmental correlations

None of the environmental correlations were significantly different from 0.

3.5. ERV ranking

Traits are presented in descending order of their ERV in Table 1. COWAT letter, digit symbol, TMT part B and logical memory had the highest ERVs, whereas visuospatial memory, emotion recognition, facial memory, and forward span had the lowest, although the range was rather narrow (see Table 1). All cognitive measures outranked HTs in terms of ERVs.

4. Discussion

In a previous study, we found that SRTs were heritable (24). That study as well as previous studies also found that HTs were heritable [e.g., (58, 59)]. Although it was not our goal to replicate such discoveries here, the results of the present study were entirely consistent with these previous findings. It is already well established that cognitive abilities are heritable, and the pattern of heritability estimates in the present study were similar to those in a previous family study we conducted a decade ago (40, 57). In the present study, as in other quantitative genetic studies, the goal was not to identify associations between specific genetic variants and these traits. Therefore, the results do not tell us which genes are involved in cocktail-party listening, sound sensitivity, or cognitive abilities. However, significant heritability estimates do suggest that such genes exist and are potentially discoverable *via* techniques such as linkage or association analysis, which we have applied previously to cognitive abilities [e.g., (57, 60)]. We intend to conduct such analyses on hearing traits in future studies.

As we found in our previous study, both phenotypic and genetic correlations between SRTs and HTs were modest (24). Only the phenotypic correlation was significantly different from 0, though the genetic correlation was significantly different from 1. Thus, while SRTs and HTs were at least phenotypically correlated, there was at most a modest overlap in their genetic factors. These results lend further support to the idea discussed earlier, namely that in groups of listeners with typical HTs, sound sensitivity does not play a critical role in cocktail-party listening. Our findings also extend this idea by suggesting that the genetic factors influencing cocktail-party listening are mostly different from those influencing sound sensitivity in such samples. This line of reasoning may lead to two further speculations. The first is that future genetic studies could seek to identify specific genetic factors for cocktail-party listening abilities in samples of people without (or at least, not ascertained for) clinical hearing impairment. The second is that it complicates the interpretation of studies that do not explicitly disentangle cocktail-party listening and sound sensitivity. For instance, a genome-wide association study conducted in the UK Biobank identified several risk loci for self-reported hearing problems (61). However, because this study did not measure HTs, people in the affected group were probably a mix of listeners with clinical hearing impairment and listeners who experienced hearing problems yet had normal HTs [e.g., (62)]. The authors compensated for this limitation by performing an additional association analysis of hearing-aid use. As expected, this second analysis yielded some but not all the same loci as the first. Importantly, the results of this study were somewhat different to those of other genome-wide association studies in which listeners' medical records were available and therefore included confirmed cases of clinical hearing impairment, or studies where HTs were available [e.g., (63)]. Thus, there is a clear need for objective measures of both SRTs and HTs in future genetic studies.

The main finding of the present study was that SRTs were strongly genetically correlated with all cognitive abilities. Some of these correlations could not be distinguished from ±1 statistically. Others were estimated to be exactly ±1, which can happen under quantitative genetic models because the optimization procedure hits a parameter boundary; these estimates would likely converge away from the boundary given more data. From these results, we conclude that there is extremely strong pleiotropy between SRTs and cognitive abilities, perhaps as much pleiotropy as between pairs of cognitive abilities. All genetic SRT–cognition correlations were stronger than the genetic correlation between SRTs and HTs—we found this result very surprising, as we expected the opposite to be true a priori.

When we ranked cognitive measures by their ERVs, or covariance with SRTs explained by shared genetic factors, a measure of verbal fluency (COWAT letter) came out on top, followed by a measure of processing speed (digit symbol), a measure of set shifting and processing speed (TMT part B), and a measure of verbal episodic memory (logical memory). It is interesting that at least two of the four measures involved processing speed—digit symbol and the TMT are classic processing-speed measures, and one could argue that the COWAT relies on processing speed as well, as it requires making verbal responses as quickly as possible. This is consistent with the metanalysis by Dryden et al. (21). Processing speed is more susceptible to age-related decline than any other cognitive domain (64), raising the possibility that the commonly observed age-related increases in SRTs (8, 65) could be tied to older listeners' declining processing speed. Two of the four tests (COWAT and logical memory) involved recalling verbal information from long-term memory; it is not immediately clear why such tasks would outrank those involving verbal working memory. The lowest-ranked measures (visuospatial memory, emotion recognition, facial memory, and TMT part A) were all primarily visual in nature, although the difference between the smallest and largest ERV was not enormous.

The role of cognitive abilities in cocktail-party listening has been explored in previous studies. Some studies of this kind have focused on a single cognitive domain, such as verbal working memory [e.g., (25)], and individual studies that involved more comprehensive cognitive batteries tended to have small sample sizes [e.g., (19)]. A notable exception is the study by Moore et al. (20), which explored the relationships between performance on a cocktail-party listening task (the digit-triplet test) and a battery of cognitive tests in around 90,000 listeners from the UK Biobank. The authors reported that higher SRTs were associated with worse performance on all cognitive measures, though the raw correlation coefficients were not reported, which makes it difficult to determine the strengths of these associations. Based on our own investigation of the UK Biobank dataset, which revealed that the digit-triplet test had poor test–retest reliability (24), we suspect that the correlations were quite weak. In a metaanalysis of 25 previous studies, Dryden et al. (21) estimated an overall moderate correlation between speech-in-noise performance and cognitive abilities, collapsed across various speech-in-noise tasks, cognitive measures, and listeners with and without hearing impairment. The authors reported correlations with specific cognitive domains. In descending order of strength, these were processing speed, inhibitory control, working memory, episodic memory, and crystallized intelligence. This order does not match our ERV-based order exactly, although in both cases, processing speed appeared to be particularly important.

There is increasing interest in the role of peripheral auditory processing during cocktail-party listening. In particular, cochlear synaptopathy has emerged as a compelling putative mechanism by which the temporal representations of sounds may be disrupted within the peripheral auditory system, degrading cocktail-party listening and leading to real-world hearing problems, without greatly affecting sound sensitivity (13, 16). Crucially, however, there is limited evidence of correlations between putative measures of cochlear synaptopathy and performance on cocktail-party listening tasks or self-reported real-world hearing problems in humans [e.g., (18)]. Measurement insensitivity may be at least partly to blame for these mixed results; that is, non-invasive assays of cochlear synaptopathy may not yet be sensitive enough to yield observable correlations. However, our results suggest an additional possibility, namely that large individual differences in cognitive abilities—which almost always go unmeasured in such studies—may mask these relationships. Future studies seeking to discover relationships between aspects of peripheral auditory function and cocktail-party listening may be better placed to do so if they also measure and adjust for individual differences in listeners' cognitive abilities.

The present study had a few potential limitations. The first was the use of time-reversed maskers. As we discussed previously (24), rendering maskers unintelligible by time-reversing them simplified the task instructions and eliminated some potential sources of confusion, which reduced floor effects and produced SRTs that were better suited to quantitative genetic analysis in this sample. However, one could argue that SRTs measured with time-reversed maskers have less ecological validity than SRTs measured with time-forward maskers because listeners do not encounter time-reversed speech in the real world. This limitation may be important if the masking caused by time-reversed maskers is substantially different in nature to that caused by time-forward maskers, but this does not appear to be true (66). Another potential limitation was that SRTs and HTs were measured using consumer-grade equipment (rather than audiometric equipment) in an ordinary quiet testing room (rather than a sound-attenuated booth). These features make it difficult to compare our listeners' raw SRTs and HTs to those from other psychoacoustic studies, and probably caused them to be higher overall, as well as adding some amount of additional measurement error. However, since the data were transformed prior to analysis, absolute SRT and HT values did not influence our results.

The present study considered the *genetic* factors that jointly influence cocktail-party listening, sound sensitivity, and cognitive abilities, but not the potential *environmental* factors. For example, noise exposure could cause worse SRTs and worse HTs. Unfortunately, we were unable to estimate noise exposure in individual listeners in this study. Previously, we derived an index of neighborhood noise levels based on transportation noise, but this was not associated with either SRTs or HTs (24). Another possible environmental factor that could jointly influence cocktail-party listening, sound sensitivity, and cognitive abilities is cardiovascular health, but we did not observe any correlations with various cardiovascular measures, such as body mass index, in this study. We did find strong effects of sex and age, as expected, and all results reported in the present study controlled for these effects.

In conclusion, the present study revealed that the genetic influences on cocktail-party listening overlap considerably with those on cognitive abilities, including abilities that are not primarily auditory or verbal in nature. These results may have important implications for future studies exploring the physiological and psychological factors that influence real-world hearing problems, as well as their genetic and/or environmental etiologies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the University of Texas Health Science Center at San Antonio and Boston Children's Hospital. The patients/participants provided their written informed consent to participate in this study.

Author contributions

Study concept and design: SM, DG, and JB. Acquisition, analysis, or interpretation of data: SM, EK, AR, MW, AH, AG, PF, RO, JP, SK, and RD. Drafting of the manuscript and statistical analysis: SM. Critical revision of the manuscript for important intellectual content: SM, EK, JM, AR, MW, AH, AG, PF, RO, JP, SK, HG, RD, JC, JB, and DG. Obtained funding and study supervision: DG and JB. Administrative, technical, or material support: SM, MW, AH, DG, and JB. All authors contributed to the article and approved the submitted version.

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Patient perceptions of cognitive screening in adult audiology services: A qualitative exploration

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Introduction: Both hearing loss and dementia are extremely pervasive, especially amongst older adults. As hearing loss and dementia have common symptoms, misdiagnosis can be common, and failure to address hearing loss for people with dementia could accelerate cognitive decline. The timely detection of cognitive impairment is clinically important, however the use of cognitive assessments in adult audiology services is a hotly debated topic. Although the early detection of cognitive impairment may improve patient care and quality of life, patients attending audiology services for hearing assessment might not expect to be asked questions about their cognition. The aim of this study was to qualitatively explore patient and public perspectives and preferences on the use of cognitive screening within adult audiology services.

Methods: Quantitative and qualitative data were gathered from an online survey and a workshop. Descriptive statistics were applied to quantitative data and an inductive thematic analysis was performed on free-text responses.

Results: In total, 90 respondents completed the online survey. Overall, cognitive screening in audiology was reported to be acceptable to participants (92%). A reflexive thematic analysis of the qualitative data reported four themes: i) knowledge of cognitive impairment and screening, ii) implementation of cognitive screening, iii) impact of screening on patient and iv) contributions to future care and research. A workshop was held with five participants to discuss and reflect on the findings in more detail.

Discussion: Participants found cognitive screening to be acceptable within adult audiology services providing audiologists had suitable training, and sufficient explanation and justification were provided. However, implications such as additional time and staff resource and supplementary training for audiologists would be required to address participants concerns.

KEYWORDS

cognitive screening, adult aural rehabilitation, hearing loss, cognitive impairment, qualitative research, mild cognitive impairment

1. Introduction

Hearing loss is a major public health issue. The World Health Organization (WHO) estimates that globally, 466 million adults have disabling hearing loss with numbers projected to rise to 700 million by 2050 (1). In the United Kingdom (UK), one in five adults are affected, which makes it the second most common disability in the UK (2). The prevalence and severity of hearing loss increases with age. More than 40% of people aged over 50 years live with hearing loss, increasing to more than 70% of those aged 70 years or older (3). Restrictions in communication arising from hearing loss can affect an individual's interpersonal relationships, educational and career opportunities as well as their ability to interact with services, including healthcare. The combination of all these factors can affect psychological health and wellbeing through social and emotional withdrawal (4–6). Additionally, the estimated risk of dementia for those with untreated hearing loss compared to those without is twice as likely for those with mild hearing loss, three times greater for those with moderate hearing loss and five times greater for those with severe hearing loss (7). Ultimately, hearing and communication difficulties can have a significant impact on an individual's quality of life.

Cognition refers to the mental processes involved in acquiring knowledge and comprehension through thought, experience, and the senses (8). Cognitive abilities describing the change in function over our lifespan are categorized into crystallized and fluid intelligence. Crystallized intelligence refers to skills that are well-practiced and familiar such as vocabulary and general knowledge (9). These remain stable or gradually improve over time, peaking in the late 60s to early 70s (10). On the other hand, fluid cognition signifies a person's innate ability to process, learn and manipulate new information (10, 11). Examples include executive function, processing speed, memory, and psychomotor ability. Fluid cognitive abilities typically peak in the third decade of life and exhibit a continuous decline into the later years of life (10). Hearing, or listening in noise, relies on peripheral hearing, central auditory processing and cognition (e.g., attention and working memory) (12, 13). Cognition plays a role in listening, with greater working memory and attention skills associated with better speech in noise understanding for people with hearing loss (14, 15).

Dementia is an umbrella term used to describe the progressive and gradual decline in cognitive function with severe effects on social and physical activities. It has been estimated to affect almost one million adults in the UK, rising to 1.6 million people by 2050 (16). The symptoms of dementia can vary depending on the cause, but its main clinical manifestations can be categorized into cognitive and psychological changes. Cognitive changes can include difficulties in communication, visual and spatial abilities, reasoning, problem solving, coordination, memory loss and confusion or disorientation (17). On the other hand, psychological changes include personality changes, depression, anxiety, inappropriate behavior, paranoia, agitation, and hallucinations (18). Mild cognitive impairment (MCI) is the earliest stage of dementia and approximately 80% of MCI patients develop dementia within 6 years of diagnosis (19).

Current hypotheses suggest that there are three main possible mechanisms through which hearing loss is associated with cognitive decline (20). First, in individuals with a hearing loss, greater cognitive resources may be necessary to process auditory signals, thus increasing cognitive load and depleting cognitive reserve (21). Second, some studies suggest structural changes in the brain structure of individuals with hearing impairment (22). Finally, both hearing loss and cognitive decline are independently associated with social isolation (23). Another possibility is that both hearing loss and cognitive impairment are caused by a common mechanism, or that the association is multifactorial (24). Global populations are aging at an unprecedented rate and numbers are expected to accelerate in the coming decades (25). Society will be required to adapt and restructure across all sectors to accommodate for the shift in age demographics (26). There are over 11 million people aged 65 and over in the UK and this will have increased to 13 million people or 22% of the population in the next 10 years (27). With the increase in number and proportion of aging individuals, the number of people affected by both dementia and/or hearing loss is also expected to increase. Hearing loss has been identified as the largest modifiable mid-life risk factor for dementia (28). As hearing loss is highly prevalent and can be managed through aural rehabilitation, early detection of hearing loss represents an opportunity to address potentially causal mechanisms of cognitive decline (24).

Hearing loss and cognitive impairment can present similarly. This can cause increased difficulty in distinguishing the true cause of these symptoms over time. Examples of overlapping symptoms include short-term memory problems, difficulty in understanding and following conversations and social withdrawal (23, 29–31). Individuals with cognitive impairment/dementia commonly have trouble processing speech in the presence of competing background noise and may also struggle to express their hearing difficulties or communication challenges. Family or carers may misinterpret these difficulties as related to dementia rather than a potentially correctable hearing problem (32, 33). The combination of these factors can present challenges and then cause misdiagnosis and delay in presentation to healthcare professionals. This may further delay provision of the correct treatment and have a greater impact patient's quality of life. Ongoing studies are investigating whether addressing hearing loss, by providing amplification or alternative intervention can prevent, slow, or reverse cognitive decline in individuals with hearing loss (34–36). In the United States, the Aging and Cognitive Health Evaluation in Elders (ACHIEVE) randomized controlled trial, is the first to evaluate the efficacy of a best-practice hearing intervention in delaying cognitive decline in older adults with untreated hearing loss (37). A recent meta-analysis reported that the use of hearing devices in individuals with hearing loss was significantly associated with a reduction in cognitive decline and an improvement in cognitive testing scores (38). However, evidence remains inconclusive (21, 39, 40) due to lack of longitudinal research (41).

Cognitive screening tests are short tests which can be used to assess how well the brain is functioning. They are designed to test our cognition (or thinking abilities), such as memory, language, judgement, and the ability to learn new things. Such tests comprise part of the assessment of possible dementia but are not in themselves sufficient to make the diagnosis due to their lack of specificity. There are many other reasons for low scores on cognitive testing, for example they are usually verbally administered, as such people with hearing loss tend to perform worse than individuals with normal hearing (42). However, some cognitive screening tests have been adapted for people with hearing loss for example by removing verbal items or presenting items visually (43, 44). Nonetheless, cognitive testing is usually regarded as an essential tool, to either to raise the possibility of a cognitive disorder or to quantify its degree. It has been proposed that cognitive screening tests could be used in audiology clinics to aid early detection of cognitive impairment or dementia for onward referral and support. Such tests could guide audiological care through interventions such as hearing aid programming and follow up. There are many factors which need to be considered before cognitive screening could be implemented in audiology services. For example, consideration should be given to the purpose of the screening, how it would be conducted, any necessary training and the procedure for onwards referral with health services, this list is by no means exhaustive. In addition to any practical and clinical considerations, it is important to understand whether cognitive screening is acceptable to patients attending adult audiology services.

This study aims to explore patient perceptions of cognitive screening delivered within UK adult audiology services by analyzing free-text responses from an online survey and a workshop.

2. Materials and methods

2.1. Study design

This study reports a qualitative analysis of free-text answers from an online survey of 90 participants in the UK and a workshop.

2.2. Ethical approval

Ethical approval was obtained from the University of Nottingham Faculty of Medicine and Health Science Research Ethics Committee (FMHS 438-0122). All participants provided informed electronic consent.

2.3. Participants and recruitment

Participants were included if they were (i) aged 18 years or older, (ii) had a diagnosis of dementia or mild cognitive impairment and/or a hearing condition (e.g., hearing loss), or (iii) were receiving care as a person living with dementia or mild cognitive impairment and/or a hearing condition or (iv) were a carer/communication partner providing support to someone who is living with dementia/mild cognitive impairment and/or a hearing condition.

It is important to consider the perspective of stakeholders such as carers or family members of people living with hearing loss and/or dementia who may support the individual to attend clinical appointments and complete tests. Thus, this research includes the perspective of key stakeholders including both carers and communication partners of people living with dementia and/or hearing loss.

Participants were recruited using purposive sampling; this included contacting participants from the National Institute for Health and Care Research (NIHR) Nottingham Biomedical Research Center (BRC) research participant database *via* email and through using social media channels (e.g., Twitter and a blog post). The first authors (EB, PT) monitored the sample during data collection (45) and recruitment ceased when data saturation was obtained (46). Data saturation occurred when the first authors (EB, PT) identified no new patterns pertinent to the research question within the online survey responses (47).

2.4. Data collection

2.4.1. Online survey

Participants completed a 15-min questionnaire through an online platform (JISC Online Surveys, https://www.onlinesurveys.ac.uk). First, participants were provided with an electronic Participant Information Sheet with a description of the study's aim and the researchers contact details in case participants wished to ask any questions or had concerns. Next, participants completed an electronic consent form and provided basic demographic data. Participants were asked to complete three questions regarding their opinions on the use of cognitive screening in adult audiology services. Participation was voluntary and participants could withdraw at any time by exiting the online survey without giving a reason.

The questions were developed by the research team (EB, PT, HH) in consultation with a Patient Research Partner (JS) to consider how they might be interpreted by the participants. The questions are listed in Box 1.

The first question was a close-text response; possible response options were "Yes" and "No". The second and third questions allowed participants to reflect on their personal perceptions of cognitive screening in adult audiology services. The analysis focused on the free-text responses to the open-ended questions. Data were collected between 21st September and 5th October 2022.

2.4.2. Workshop

Participants who completed the online survey were invited to register their interest to attend an online workshop to explore the findings from the online survey in greater depth. The workshop provided an opportunity to explore the topic of cognitive screening in audiology services, using two different data collection methods (i.e., a survey and a workshop). The collection of data about the

BOX 1 Online survey questions.

1. If you went to get your hearing tested, would you be happy for someone to ask you questions about your memory?
2. How would this make you feel?
3. Do you have any other thoughts you would like to share with us?

research question using different methods is a form of qualitative triangulation, which is an established strategy for enhancing the rigor of qualitative research (48). The workshop took place on 14th November 2022, for two hours, and was facilitated by the first two authors (EB and PT) and consisted of two steps. First, workshop participants were asked to reflect on the online survey questions listed in Box 1. Second, participants were asked to review and respond to the findings of the qualitative analysis of the online survey by reflecting on the themes and sub-themes from the reflexive thematic analysis. The process of data triangulation allowed participants to reflect and elaborate on their survey responses and provide in-depth feedback on the survey themes. The workshop was video recorded online using Microsoft Teams and transcribed verbatim to capture the findings. The analysis process is described below.

2.5. Patient and public involvement

A Patient Research Partner (JS), an individual with lived experience of hearing loss, was involved in the design and conduct of this research. JS contributed to writing the blog post, reviewing the online survey questions, and the content of the workshop. She also provided comments on the final manuscript prior to submission.

2.6. Data analysis

Demographic information and information collected from close-ended questions were analyzed using descriptive statistics. Anonymised identification codes were assigned to the survey participants (e.g., SP1) and the workshop participants (e.g., WP1). Written informed consent was obtained from study participants for the publication of anonymous direct quotes.

A reflexive thematic analysis of the free-text responses to the online survey was conducted following Braun and Clarke's (49–52) six-step process on the free-text responses from the online survey. This method was chosen as it offers a flexible yet robust and well-established system to gain a detailed account of qualitative data. The process followed is detailed in Table 1.

TABLE 1 Phases of thematic analysis.

Step	Phases	Description of the process
1	Familiarizing yourself with your data	Transcribing data (if necessary), reading and re-reading the data, noting down initial ideas
2	Generating initial codes	Coding interesting features of the data in a systematic fashion across the entire data set, collating data relevant to each code
3	Searching for themes	Collating codes into potential themes, gathering all data relevant to each potential theme
4	Reviewing themes	Checking if the themes work in relation to the coded extracts (Level 1) and the entire data set (Level 2), generating a thematic "map" of the analysis
5	Defining and naming themes	Ongoing analysis to refine the specifics of each theme, and the overall story the analysis tells, generating clear definitions and names for each theme
6	Producing the report	The final opportunity for analysis. Selection of vivid, compelling extract examples, final analysis of selected extracts, relating back of the analysis to the research question and literature, producing a scholarly report of the analysis

The first author (EB) a researcher with expertise in dementia and hearing loss research, who has formal training in qualitative methods and first author (PT), a medical student, independently familiarized themselves with the free-text responses of the full data set and developed a list of initial codes. All initial codes were collated using Microsoft Excel. Any responses containing multiple meanings was assigned as many codes as appropriate. After completion of their independent lists, both researchers (EB and PT) discussed and reviewed each coding decision together. Discrepancies were resolved through discussion until a consensus was reached. Subsequently, the two authors met to generate and refine the overarching themes and subthemes. Themes and sub-themes were then checked against the raw data to ensure they represented the participants' responses. Data summaries were presented to the research team members (JS, EH, HH, TD) as part of a peer debriefing process to discuss insights obtained from the survey and to refine the qualitative analysis. Subsequently, all authors (EB, PT, JS, EH, PB, HH, TD) provided feedback on the narrative.

2.6.1. Workshop analysis

The workshop provided an opportunity to explore the online survey questions in greater depth with a sub-set of participants. Specifically, participants at the workshop engaged in member reflection, which entailed reviewing and providing feedback on the survey themes and reflecting and elaborating on their survey responses (53). Data from the workshop were analyzed using a primarily deductive thematic approach. According to Braun and Clarke (52, 54), thematic analysis is conducted at a point on the continuum between primarily inductive analyses, which prioritize data-driven meaning, and primarily deductive analyses, which prioritize analyst-based or theory-based meaning (55, 56). Deductive approaches can be used to explore the evidence for, explicate, and amend existing themes from previous research (57, 58). Even primarily deductive analyses often use inductive elements, such as inductive coding, generating inductive subthemes within deductive themes, or generating both inductive and deductive themes (55, 57–59). In the present study, the primarily deductive analysis was used to explore the themes derived from the online survey data in greater depth and to identify any additional themes stemming from the workshop data. The analysis entailed applying codes from the online survey analysis to the workshop data, as well as generating new codes for any workshop data that did not conform to the pre-existing codes. This analysis was conducted by two members of the research team (PB and EH) using Microsoft Word. EH was a researcher with expertise in hearing loss research and qualitative methods and PB was a nursing student.

3. Results

3.1. Demographic profile

The demographic profile of survey takers is shown in Table 2. Fifty-four participants (60%) were female with an overall mean age of 66.6 years ± 14.1. Of the 90 survey participants, 82 (92%) individuals self-reported as living with a hearing condition (e.g., hearing loss and/or tinnitus) and four (4%) as living with a cognitive condition (e.g., mild cognitive impairment). Of the sample, 10 participants identified that they were a carer of someone living with a cognitive condition and two reported being a communication partner of someone living with hearing loss.

3.2. Disposition toward cognitive screening in audiology clinics

Overall, the majority of survey takers (83 participants, 92.2%) indicated that they were willing to be screened for cognitive impairment in an adult audiology clinic.

3.3. Qualitative analysis

Four themes were identified describing patient perceptions of cognitive screening in adult audiology services: (1) knowledge of cognitive impairment and screening; (2) implementation of cognitive screening; (3) impact of screening on patient; and (4) contribution to future care and research. Each of these themes comprised several subthemes (Table 3). Generally, the themes were derived from the online survey data and were supported by the workshop data. One additional subtheme was generated through the analysis of the workshop data (Subtheme 2.4).

TABLE 2 Participant characteristics.

	Online survey	Workshop
Number of participants	90	5
Age		
25–34	6	-
35–49	6	-
50–64	32	1
≥ 65	46	4
Mean (SD)	66.67 (14.14)	75.20 (11.34)
Sex		
Male	36	3
Female	54	2
Male:Female	1:1.5	1.5:1
Ethnicity		
White (British, Irish, Other White Background)	87	5
Asian or Asian British	2	-
Mixed	1	-
Occupation		
Full-time employed	22	-
Part-time employed	11	-
Part-time carer	1	-
Retired	51	4
Student	1	-
Other	4	1
Level of education		
Secondary school up to 16 years	15	1
Higher or secondary or further education	18	2
College or University	38	-
Post-graduate degree	19	2

3.3.1. Theme 1: Knowledge of cognitive impairment and screening

The first theme refers to participants' existing knowledge of the relationship between hearing loss and cognitive impairment, the implications of using cognitive screening for the early detection of cognitive impairment and the consequences of untreated hearing loss.

3.3.1.1. Sub-theme 1.1: Awareness and perceived risk of cognitive impairment

Most participants reported that they were aware of the link between untreated hearing loss and the impact this may have on cognitive impairment. Participants reported how this knowledge related to how acceptable they felt cognitive screening in adult audiology services to be:

> *I'm happy to do this as I've read magazine articles about the impact hearing loss can have on long term cognitive function.* SP53
>
> *I've been aware of this idea that there's a...potential link between your levels of hearing and cognitive function...My consultant said to me... "If you delay with hearing aids...the part of your brain that's involved in hearing...it's not being used, so it kind of dies away". So, for me, I think I'd be quite happy to be asked questions about memory in screening.* WP4

Sources of knowledge regarding this topic included authoritative sources, such as the Royal National Institute for Deaf People (RNID) and healthcare professionals.

However, the suggestion that hearing loss could be linked to dementia was viewed negatively by several participants:

TABLE 3 Themes/sub-themes.

Theme	Subtheme
1. Knowledge of cognitive impairment and screening	1.1. Awareness and perceived risk of cognitive impairment 1.2. Early detection and intervention
2. Implementation of cognitive screening	2.1. Understanding and justification of screening 2.2. Delivery of screening 2.3. Patient concerns about cognitive screening 2.4. Relationship with the audiologist
3. Impact of screening on patient	3.1. Emotional associations with screening 3.2. Holistic care 3.3. Interest in cognitive screening
4. Contribution to future care and research	4.1. Future care and research 4.2. Professional awareness and training

> *I wouldn't particularly like it. Two reasons. 1. I don't like the implied assumption that hearing impairment leads to memory loss. 2. Also, it's something I have never considered. I don't like the thought of such a possibility being planted in my mind.* SP26
>
> *Scared about the future, as I understand there are links to hearing loss and early-onset dementia.* SP3

This particularly related to the fear and stigma surrounding developing cognitive impairment or dementia.

> *One the main disadvantages is you're going to worry about it…I'd want to…reassure people that it's not necessarily a bad thing, but…you might well trigger something in someone by not knowing…their…own personal experiences…of dementia.* WP4

Nonetheless, some participants viewed cognitive screening as a reasonable precaution for people whom they perceived to have potential risk-factors, such as those with a family history of dementia, past medical history and/or being of a certain age.

> *I've always experienced hearing loss…but I've never come across the fact that there was a relationship between that and cognition and that would probably have been very helpful a few years ago if I knew that there were something of that nature happening, particularly when you get into your 80s, you become more aware that that there is possibly something that could be…related to it.* WP5
>
> *Having got to [a certain age], I'm beginning to feel that things like memory are important and that we need to…keep an eye on ourselves and…friends of similar ages to find out if problems are occurring.* WP3

However, some participants raised the issue that cognitive screening would perhaps not be appropriate for people of a younger age:

> *At what age would…you suggest that this started? Would it end up being anybody who has a hearing loss is tested for cognitive impairment? I have a son…and he's very proud of his hearing aid…but I think he would be very, very put off by the thought of having cognitive testing [at] his age.* WP3

3.3.1.2. Subtheme 1.2: Early detection and intervention

One of the reported benefits of cognitive screening was the ability to detect cognitive impairment earlier on in the care pathway, thus enabling access to potential treatment:

> *…any cognitive impairment could be picked up and mitigated to some extent, as soon as possible. So, I would be glad of the questions.* SP34
>
> *The sooner dementia is diagnosed the better the chances of treatment.* SP38
>
> *I never, ever…thought that hearing loss would be associated with a cognitive impairment…People should be made more aware of that rather than wait until it's too late and by the time you actually get a…diagnosis, you may well be in the stages where you're not aware enough to actually do anything about it.* WP1

Receiving an earlier diagnosis of cognitive impairment and subsequent pathway to treatment was viewed positively by those who reported personal experiences of caring for someone living with dementia:

> *Since I was carer for my mother who had Alzheimer's I would be only too pleased to be assessed because the earlier the treatment the better if any is needed.* SP64
>
> *Having looked after my late husband with Parkinson's/ Lewy body dementia, my feelings would only be positive that it may contribute to earlier diagnoses.* SP6

One workshop participant described their personal experience of dementia and hearing loss, and how the symptoms of both conditions often masked each other:

> *My father-in-law…[had] dementia and…hearing problems…It was very, very difficult at times to find out whether it was his hearing aids that were playing up…or whether it was actually…dementia…I would be personally quite happy for anybody to try and link one with the other or to isolate one from the other…If they can isolate that you haven't got the hearing problem and it is…dementia related, I think you're actually removing one of the…obstacles for forward treatment.* WP1

Participants tended to regard hearing loss as readily mitigated but, in contrast, did not offer any suggestions as to what might help the management of cognitive impairment.

> *It's much more important to deal with the hearing loss than it is to worry about cognition…Whatever you do about tracking cognition, hearing loss is what you can do something about and…it's much more prevalent.* WP2

3.3.2. Theme 2: Implementation of cognitive screening

Many responses related to how cognitive screening could/should potentially be implemented within an adult audiology service. These mainly focussed on interactions between patients and audiologists during a hearing appointment, particularly when discussing cognitive testing, and how cognitive screening would fit into the patient care pathway for example how the results might be used. Patients also raised several concerns about the practical implementations of cognitive screening.

3.3.2.1. Subtheme 2.1: Understanding and justification of screening

Most responses highlighted the importance of providing an adequate explanation and justification of why cognitive screening was being conducted, to patients, prior to administering any test:

> *If it were done without explanation, I'd be confused, and probably feel insulted. However, if there were a reason given which made sense in the context of the appointment then that would be fine.* SP38
>
> *Without a succinct explanation it would be a matter of trust rather than seeing a benefit to myself or others.* SP86
>
> *If you give a decent explanation, which is the fact that... there is a... link between hearing loss and dementia, then people will [be] very happy to answer those straightforward questions.* WP2

The explanation of cognitive screening was viewed as particularly important; participants described how they did not associate a hearing assessment with anything relating to cognition. Therefore, it would be necessary for the audiologist to take the time to carefully explain and justify why cognitive screening tests needed to be conducted. Without this aspect some participants reported that they would feel apprehensive about the screening. As one participant put it "*the attitude of the questioner is key*" (SP27). Two workshop participants recommended that audiologists frame cognitive screening in a way that emphasizes the positive aspects and that minimizes alarm.

> *If it's pitched [as] screening, it's no different from having your blood pressure checked... If you can pitch it in such a way that people understand it as part of a general health screening, rather than something that's specific to them [so] that they don't feel picked upon... It's not something that... they're exhibiting as such... It's part of a general screening that's preventative that [is available to] everyone who comes within the orbit of the audiology department.* WP4
>
> *I went recently for general health screening test and... the phrase that was used... was maintaining active independence, so it was positioned for me as a positive thing... I think the way that you present these tests as being something that... you can be in control of... is much more positive than the idea that it's going to... identify something that's wrong with you, so the presentation of it... is really key.* WP4

One participant stated that they would like the opportunity to ask the audiologist questions about the screening. Although participants emphasized the need to understand *why* the screening was being conducted, some still stated that they would feel concerned about the outcome of the results if they indicated that the patient had any impairment.

3.3.2.2. Subtheme 2.2: Delivery of screening

The delivery of cognitive screening manifested in two different ways. First, participants emphasized the mode of delivery of the screening tests, for example, if they were to be delivered orally:

> *It would be interesting to find out if the tests are via audio [and] if they allow for the hearing loss, and taking time to hear and process the request. Vs. for example visual or written tests.* SP46

Reference was made to the impact hearing loss may have on a verbal cognition test, for example responding incorrectly if unable to hear or mishearing the questions asked. As one participant noted "*if the patient cannot understand the test, how can you make a satisfactory diagnosis?*" (SP3). One workshop participant emphasized the importance of having a short yet informative cognitive assessment.

> *It desperately depends what questions you've been asked... The full standard test for... mild cognitive impairment is... quite a long-winded process: 20 minutes or so. I presume that that is not the sort of thing you are proposing... The whole of this discussion does depend... on a... relatively short and simple and screening process... Are there meaningful tests [that are] relatively brief?* WP2
>
> *I don't understand how you could get a short cognitive test that would be... meaningful... This process needs to start by... defining... the possible tests... Having participated in cognitive testing... it's not a short process... Its impact is significant... on the patient... Let's hear about the cognitive test, which could be at all sensibly added into [a hearing assessment].* WP2

Similarly, another workshop participant recommended that cognitive testing should be incorporated into hearing assessments to ensure the process is informative and streamlined.

> *If there's some way of putting [cognitive testing] in with an audiology test... Once something has been devised that will tie the two together, at least from the audiologist side of things, they can roll out that. [Then we can say] "It's not a hearing problem that's causing the lack of understanding"... which points it toward the other way... When you have the GP test of [cognition], it doesn't rule out the hearing side... An audiologist... [is] in a position to say that... "Your hearing is fine. There is another problem."* WP1

Finally, it was highlighted how participants were keen to know what would happen to result of the screening tests and the potential referral pathway onwards if the tests indicated a certain level of impairment. It was suggested that patients should have surety that they would receive further practical support and input from either General Practitioners (GPs) or memory clinics, if required.

> *We can get different [clinicians] each time... I have found, because I've had many operations in my time, is that the way that the computer system works within the health service... as long as the data goes to a GP... then it can be very helpful in the way things are processed from there.* WP5
>
> *I would quite like to be given some... information to take away with me at that point... I have always... managed my own hearing loss... so I'm quite used to doing that... [I would prefer] feedback... in person on the day, or at least some information about where... these results might lead... because the idea that it might go via the GP is... probably good if you have a proactive GP, if you can get an appointment, if you can access them. But otherwise, I think it's good if you... have an awareness yourself.* WP4

3.3.2.3. Subtheme 2.3: Patient concerns about cognitive screening

Concerns about cognitive screening centered on two primary areas: (i) the qualifications of the person administering the test and (ii) the accuracy of the test. Patients suggested that audiologists may require additional training to deliver this type of testing, as they felt that cognition would not be their primary area of expertise. In addition, cognition, or cognitive impairments, were highlighted by respondents as being a condition associated with stigma. Therefore, audiologists would have to be equipped with the necessary skills to be able to discuss and communicate with patients about this topic in a sensitive way.

> *Only if the audiologist had been suitably trained in dealing with a very sensitive topic.* SP38

In some circumstances, participants felt that additional input would be required from healthcare professionals outside of the audiology department, for example from a GP. One participant noted:

> *If I was worried about my memory, I would ask the doctor, or blank it. I would not want anyone asking me about memory whilst testing my ears. If you had lost some hearing that is bad enough without me thinking that the tester is thinking I have lost my memory as well.* SP36

In addition, several participants described how they would want any concerns to be followed up by the "*professionals qualified to help*" (SP1).

It was reported that sensory impairment, such as hearing loss, could influence the result of the cognitive screening test, as certain conditions may mask each other. Moreover, participants living with hearing loss described how listening fatigue impacts their ability to process and answer questions accurately. As discussed previously, an inability to hear an oral cognitive test will likely impact the result. Some participants emphasized how this could result in misleading assumptions about patients' cognition:

> *My hearing [loss] results in a lot of information in conversations being incomplete and or inaccurate as I rebuild and guess at missing words. So poor memory can be seen as the issue where my memory is ok but the original information, I heard is inaccurate. Someone not recognizing this could make incorrect assumptions resulting in a poor and misleading diagnosis.* SP28

One participant described how having a carer attend alongside could provide additional information, rather than solely relying on patient reports or measures.

3.3.2.4. Subtheme 2.4: Relationship with the audiologist

Several workshop participants felt it was important for the audiologist to establish a good relationship with the patient, including developing a sense of trust and understanding, before carrying out cognitive testing.

> *My initial reaction would be that... [cognitive testing] could be useful, but it depended very much on what the audiologist or whoever I was talking to was like and how much I felt they understood the situation. It's a big leap of faith in a way, isn't it?* WP3

Two workshop participants noted that cognitive testing could be detrimental to audiologist-patient relationship and deter patients from attending audiology appointments, especially if the testing is not handled in a sensitive manner.

> *I know nobody who has got dementia who didn't have worries about it a long before they were in any sense properly diagnosed and I think there is a significant danger... to be dealt with that... by asking the question... you'll turn them off audiology.* WP2
>
> *I also have a... friend who's deaf, who is absolutely terrified of the audiologist and... that sort of testing would probably push her over the edge of never going back to an audiologist..., which would make the original problem much worse...You do have to be very careful about the questions you ask.* WP3

It is crucial to ensure that cognitive testing does not deter patients who may already be reluctant to have their hearing assessed and managed due to the considerable stigma associated with hearing loss and hearing aids.

> *What you've got here really is a... double whammy in that there's so much negativity around... hearing loss in general that it's... seen still as a kind of a weakness. People don't think twice about wearing glasses now, but they would think twice about wearing hearing aids... You almost [need to get] over that... negativity about hearing loss before you can even deal with... the cognitive... loss as well, so I can see why people will just kind of run away screaming from... the idea of either of them.* WP4

A barrier to establishing sufficient trust is the lack of continuity such that patients rarely encounter the same audiologist across different appointments.

> *You just cannot get that continuity where the person you've perhaps spoken to in the first place did understand the problem that you were describing, then you've got to start completely again with somebody who may not pick it up on the same wavelength.* WP1

3.3.3. Theme 3: Impact of screening on patient

The majority of participants reported an emotional reaction to the thought of cognitive screening. Most of the emotions had negative associations but, despite this, some participants described how they were interested in the results of the screening and could understand how it could contribute to a holistic view of care.

3.3.3.1. Subtheme 3.1: Emotional associations with screening

Many participants reported a strong emotional reaction to the thought of cognitive screening being conducted within the context of an adult audiology hearing appointment. Participants described how they would feel irritated as they felt questions about cognition did not relate to the purpose of their visit to audiology:

> *I'd probably feel slightly irritated if I was asked questions which did not relate to the purpose of my visit.* SP7

Issues of cognitive impairment provoked feelings of concern and worry in many participants. This manifested as "*embarrassment*" about failing the test and thus being perceived as lacking cognitive capability. In addition, emotions such as "*worry*", "*anxiety*" and "*apprehension*" were mentioned with respect to the screening test potentially uncovering a cognitive impairment:

> *Scared about the future, as I understand there are links to hearing loss and early-onset dementia.* SP33

Nonetheless, a small number of participants reported that cognitive testing would have no impact on them at all.

> *The diagnosis... of cognitive impairment... brings enlightenment, if I can put it that way... It's better to know than not know, whatever it may be.* WP2

3.3.3.2. Subtheme 3.2: Holistic care

Some participants considered that screening cognition could contribute to providing holistic care, by considering the assessment of more than one condition. This presented in two ways, first that screening could be used as an "*indicator for current or future health issues*" (SP7). Second, that it could provide "*a more rounded image of health and cognition*" (SP58), rather than focussing on health conditions independently.

> *Your symptoms that... you're worrying about... may not be to do with cognitive impairment. They may just be do something like stress or... hearing so that [cognitive testing] can be positioned as something that is reassuring as much as it's diagnostic.* WP4
>
> *[Through cognitive testing] you can look at the way that it's impacting your life and get... tips at the initial stages... for how you can deal with... early cognitive impairment and prevent things like depression becoming an issue, so... it can be helpful to know this as a way of being prepared and also to... avoid mental health issues.* WP2

It was suggested that an understanding of a patient's cognition could help the audiologist when speaking to patients about their hearing loss:

> *Establishing a patient's ability regarding memory loss might help the audiologist when talking to a patient about their hearing loss.* SP38

Some participants described how the results of the screening could be monitored at each hearing appointment to detect changes over time. Additionally, one respondent suggested that screening cognition during hearing appointments may be a way of detecting people who are reluctant to go their GP to raise any potential issues about cognitive impairment.

3.3.3.3. Subtheme 3.3: Interest in cognitive screening

Despite the emotional reactions reported by participants, a common view was that they would be interested in having their cognition screened:

> *I would be interested to find out more about my memory and how it compares to others of my age if any testing is being done.* SP70

This was mainly described in the context of having results of the test conveyed to patients at the time of screening. Some participants stated that they would be "*curious*" about the results and "*would be happy to receive any results or find out if problems are showing*" (SP57). One workshop participant suggested that it would raise awareness of any cognitive problems, and thus patients would be in a better position to manage it:

> *I've never even really heard of the word [cognition] before this... If you're not aware of any problem, then you can't deal with it so... if somebody said to me "You've got a slight problem now and this is the way you ought to deal with it"... that would be extremely helpful.* WP5

The same participant described how patient awareness of cognitive problems, through screening in audiology, would be useful on both a personal and public level:

> *I think it's got to be a very positive thing because... it's about other people having the perception of what is wrong with you. That becomes helpful even to the person who's suffering.* WP5

3.3.4. Theme 4: Contribution to future care and research

A common theme of participants was that cognitive screening could contribute to their future care, both within audiology and the health and social care system more generally. Reference was also made to the potential to impact future research.

3.3.4.1. Sub-theme 4.1: Future care and research

The acceptability of cognitive screening was related to participants' perceptions that the results could benefit either themselves in the short term, by identifying additional health concerns and/or access to treatment, or others by contributing to future research. One survey participant suggested that the results of the cognitive screening could be recorded and used in "*future examinations*" (SP12). Potential avenues for future research included a better understanding of the link between hearing loss and cognition:

> *If the answer was to further the understanding of health conditions/my condition and might lead to the development of new/improved treatments or it was for tailoring existing treatment for my condition, I would feel very pleased that I had contributed.* SP60

3.3.4.2. Sub-theme 4.2: Professional awareness and training

Several workshop participants advised that an important direction for future care and research is to raise awareness of hearing loss and hearing aids. For example, one participant stated that there should be greater knowledge amongst the public of hearing loss and dementia as both individual and co-existing conditions.

> *One of the other really important things about…the contribution to future care and research is just the general raising of awareness…through either articles in the press and the media…Then throughout the population you have…increased awareness of…these issues as individuals, but also the combined impact of the two issues together.* WP4

Three workshop participants reported that care home staff need greater awareness of and training in hearing loss, including an understanding of how it can affect many people living with dementia.

> *Those of us here who have hearing loss…know it's important but within the care system, it's a relatively smaller thing…Training, training, training of the care home system is what is needed…far more than worrying about diagnosing people with cognitive impairment at hearing tests…Probably a very significant proportion of people in care homes with dementia are…suffering from age-related hearing loss…It comes back to this training, training, training within the care home system.* WP2

It is particularly important for care home staff to have the knowledge and skills to carry out hearing aid maintenance. However, training alone may be insufficient. They also need the resources and facilities to support hearing aid use and maintenance, such as readily available supplies of batteries.

> *One of the problems we had with my mother-in-law when she was in a care home was that nobody actually understood how hearing aids worked and regularly they were left in the drawer and there were no batteries in them…That can be a very, very, very big problem and I don't know how you solve that, because even if you train people, they forget the next day.* WP3
>
> *[My] father-in-law eventually went into a care home…He was wearing hearing aids…but we'd go in there and we would think he's just looking blank…[The] hearing aids… had batteries that just hadn't been changed…Within the care system…little things like hearing aid batteries and the tubes…if they're not checked regularly, then these [residents] that they've got both the cognitive problem and the hearing problem are sitting in a room just looking at other people, day in and day out…There should be a system within the care system for them to be checked and tested…and at least had batteries available for them.* WP1

4. Discussion

This study qualitatively explored patient perceptions of conducting cognitive screening in adult audiology services. It found that overall, cognitive screening was acceptable to most participants. However, there were some caveats concerning the implementation of cognitive screening in clinical practice. These centered around the qualifications and experience of the audiologist in delivering cognitive tests, conveying the results to participants and the potential implications for future care for example, onwards referral to primary care. The relationship and trust between the audiologist and patient could also play an important role in ensuring that patients feel comfortable with cognitive screening.

The acceptability of cognitive screening, appeared to be linked to participant awareness of the link between cognitive impairment and hearing loss (7). In addition, participants' age, or their perception of aging, was related to their views on the appropriateness of cognitive screening. For example, older respondents highlighted the known relationship between cognition and aging, thus were more likely to report positive views of cognitive screening compared to younger respondents. The Lancet commission on Dementia (28) highlighted that untreated hearing loss is the largest mid-life modifiable risk factor for dementia. Further research is needed to understand the potential benefits of detecting hearing loss in mid-life and fitting of hearing aids to ascertain whether intervention can improve or delay cognitive decline.

In addition, recent international practice recommendations for the management of hearing and vision impairment in people living with dementia advocates for improving the awareness and knowledge of the implications of comorbid sensory and cognitive impairment with both the public and healthcare professionals (60). As hearing loss and dementia are both progressive conditions, cognitive screening in adult audiology services could offer an opportunity to monitor an individual's level of cognitive function over time, as suggested by participants in this study. Some researchers have suggested the development of auditory cognitive stress tests' to detect early stages of neurodegeneration (61). Identifying untreated hearing loss in individuals with cognitive impairment could have benefits including improved communication and quality of life (62). It may be that people living with cognitive impairment require additional support or adaptions in order to use their hearing aids. It remains an open question as to whether earlier intervention for hearing loss could help to prevent or delay cognitive impairment. There are encouraging signs in the literature (63), but there is a lack of prospective research to demonstrate such benefits. In any case, in order to be able to undertake such studies requires early identification of hearing problems. The findings in this study suggest that patients feel that audiologists may require further specialist training to explain, administer, interpret and discuss cognitive screening tests with patients. This study supports evidence which emphasizes the importance of trust between audiologists and their patients (64), and would be pertinent when discussing potentially a sensitive topic such as cognitive impairment. Previous research suggests that audiologists typically focus on hearing aids, spending less time addressing psychosocial concerns in patients (65). In particular, patient-centered communication and shared decision making have both been identified as areas for improvement for audiologists (66). Barriers to addressing psychosocial concerns, such as loneliness, have been suggested to include a lack of time, training and continuity (67).

Consistent with existing literature, participants reported concerns about the confounding effect that hearing loss may have on cognitive assessments which are delivered orally. Previous research has demonstrated that measures of cognition may be underestimated if sensory impairments are not considered or adjusted for (68, 69). Efforts have been made to develop or adapt cognitive tests for people with hearing impairment (70, 71). However, a scoping review of cognitive screening and assessment tools adapted for people with sensory impairment found that the sensitivity and validity of these instruments is poor (44). It is important to keep in mind that screening tools only allow healthcare professionals a snapshot view into an individual's cognitive state at the time of administration, so that the results may be unreliable. Brief cognitive tests, such as the Mini-Mental State Examination (72), often have cut-off scores for determining the presence of cognitive impairment but these should be viewed with caution. Similarly, in this study participants with hearing loss highlighted how it is important to consider patient's hearing status prior to screening, as the results of an oral test may not be accurately represented. There are other factors which may influence test performance including vision impairment, age of participant, level of education and mood. Future research is still required to develop reliable tools for identifying cognitive impairment which take into account the effects of hearing loss.

Previous findings have suggested that identification of cognitive impairment can help inform audiological management in this population, programming of hearing aid devices and settings and longer-term care planning (73); however, this was not reflected in the present study. Most of the support for cognitive screening emerging from this study emphasized that it would potentially enable an earlier diagnosis and thus access to treatment and support which could mitigate further cognitive decline. Results from this study highlight how patients would be keen to ensure longer-term support and follow up if any cognitive impairment were to be discovered which currently may not be readily available. In the UK there is limited post-diagnostic support for people living with MCI/dementia despite evidence-based guidance suggesting the use of interventions to promote cognition, independence and wellbeing (74, 75). Moreover, a recent report by the Alzheimer's Society highlighted how a lack of post-diagnostic support results in more frequent crisis such as health deterioration and hospitalization for the person with dementia as well as carer breakdown (74). More so than ever, post-diagnostic support for people living with dementia has been adversely impacted by the COVID-19 pandemic (76). The lack of post-diagnostic support is similar in National Health Service (NHS) audiology services. In the UK, only half of services offered follow up appointments to their patients, despite two-thirds of patients reporting the need for further support (2).

This study is not without limitations. Participants were recruited purposively, from social media and from a database of individuals who have previously registered their interest in participating in research. Thus, the results may be more representative of adults who are more knowledgeable about hearing research compared to the general population. In addition, the sample was mainly White British ($n = 87$), comprised of mostly retired individuals ($n = 51$) demonstrating a lack of ethnic and sociodemographic diversity. Although this sample is not representative of the age structure of the whole UK population, it does represent an age group that is likely to have most concern about hearing loss and the development of cognitive impairment.

This study also had various strengths. In particular, this was a high-quality qualitative study that was carried out in accordance with best practice recommendations. Specifically, several techniques for enhancing the trustworthiness and rigor of qualitative research were utilized (48, 77). One such technique was qualitative triangulation, or collecting data about the research question using different techniques (i.e., a survey and a workshop). This process also gave us the opportunity to carry out member reflection whereby the workshop participants could reflect and elaborate on their survey responses and provide in-depth feedback on the survey themes. Furthermore, the data analysis was conducted using an established procedure (49, 52). The quality of this analysis was further strengthened via peer debriefing, which included two authors independently analyzing the data and comparing their results and all authors providing feedback on the thematic analysis. We also carried out disconfirming evidence analysis, which entails reporting notable cases that contradict the overall patterns, trends, or themes. For example, we noted that though many participants felt that they would have a negative emotional reaction to cognitive screening, a minority thought that they would be unaffected.

This study demonstrates that although cognitive screening in audiological assessments were generally acceptable to our participants, several changes would be needed before it could be introduced into routine adult audiology practice in future. Indeed, screening for dementia in asymptomatic patients is not currently advised by Public Health England (78), and a change to this recommendation would require a clearer evidence base of benefit. It is also likely, that additional time and staff resources would be necessary to address some of the concerns highlighted in this study. Audiologists may require supplementary training to deliver this form of specialized test for patients with hearing loss. Additional time would be required during appointments to discuss the purpose of and conduct the screening test and explain the results to patients. There are still questions to be raised if cognitive screening were to be embedded in clinical practice. As the scope of this project was to focus on the acceptability of screening for patients, we acknowledge that this is only one consideration in the potential implementation of cognitive screening into audiological clinical practice, and that many other factors would need to be considered to inform potential implementation. Future research should be undertaken to investigate challenges, starting with audiologist perceptions of cognitive screening including their attitudes and beliefs, as well as practical considerations.

5. Conclusions

To our knowledge this is the first study to explore patient perceptions on this topic. Although acceptable to patients, the findings suggest that if cognitive screening were to be incorporated into clinical audiology practice, audiologists would require sufficient time within appointments to discuss and explain the rationale for screening as well as information on the potential benefits. Although, evidence to inform best practice is still currently lacking, this study provides a first step toward identifying a patient-centered approach to cognitive screening within audiological care.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This study involving human participants was reviewed and approved by the University of Nottingham Faculty of Medicine and Health Science Research Ethics Committee (FMHS 438-0122). Electronic informed consent to participate in this study was provided by all participants.

Author contributions

The study was conceived by EB. EB, EH, HH, and TD designed the study. EB and PT collected the data, analyzed the online survey data, and wrote the draft manuscript. EH and PB analyzed and reported the workshop data. All authors critically reviewed and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fneur.2023.1143128/full#supplementary-material

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Cortical responses correlate with speech performance in pre-lingually deaf cochlear implant children

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Introduction: Cochlear implantation is currently the most successful intervention for severe-to-profound sensorineural hearing loss, particularly in deaf infants and children. Nonetheless, there remains a significant degree of variability in the outcomes of CI post-implantation. The purpose of this study was to understand the cortical correlates of the variability in speech outcomes with a cochlear implant in pre-lingually deaf children using functional near-infrared spectroscopy (fNIRS), an emerging brain-imaging technique.

Methods: In this experiment, cortical activities when processing visual speech and two levels of auditory speech, including auditory speech in quiet and in noise with signal-to-noise ratios of 10 dB, were examined in 38 CI recipients with pre-lingual deafness and 36 normally hearing children whose age and sex matched CI users. The HOPE corpus (a corpus of Mandarin sentences) was used to generate speech stimuli. The regions of interest (ROIs) for the fNIRS measurements were fronto-temporal-parietal networks involved in language processing, including bilateral superior temporal gyrus, left inferior frontal gyrus, and bilateral inferior parietal lobes.

Results: The fNIRS results confirmed and extended findings previously reported in the neuroimaging literature. Firstly, cortical responses of superior temporal gyrus to both auditory and visual speech in CI users were directly correlated to auditory speech perception scores, with the strongest positive association between the levels of cross-modal reorganization and CI outcome. Secondly, compared to NH controls, CI users, particularly those with good speech perception, showed larger cortical activation in the left inferior frontal gyrus in response to all speech stimuli used in the experiment.

Discussion: In conclusion, cross-modal activation to visual speech in the auditory cortex of pre-lingually deaf CI children may be at least one of the neural bases of highly variable CI performance due to its beneficial effects for speech understanding, thus supporting the prediction and assessment of CI outcomes in clinic. Additionally, cortical activation of the left inferior frontal gyrus may be a cortical marker for effortful listening.

KEYWORDS

cochlear implant, cortical activation, cross-modal reorganization, speech understanding, functional near-infrared spectroscopy

1. Introduction

A cochlear implant (CI) is currently the only FDA-approved biomedical device that can restore hearing for the majority of individuals with severe-to-profound sensorineural hearing loss (SNHL). Despite the fact that speech restoration with a CI has generally been successful in cases of deaf children (Nikolopoulos et al., 2004; Wiley et al., 2005; Sharma and Dorman, 2006), there is still a great deal of variability in CI post-implantation results (Niparko et al., 2010; Geers et al., 2011), particularly when listening to speech amid background noise (Saksida et al., 2022). It is unknown why some implanted children experience poor speech perception following implantation. Several factors such as rehabilitative communication strategy, age at onset of hearing loss, duration of deafness, age at cochlear implantation, experience of hearing aid use, and duration of CI experience contribute to speech perception outcomes, but huge variance in auditory skill development remains unexplained in children with CIs (Zeng, 2004; Tomblin et al., 2005; Lin et al., 2008; Niparko et al., 2010; Tobey et al., 2013). Therefore, seeking an accurate predictor or measure is extremely important to assist clinicians in better anticipating clinical outcomes, tracking subsequent adaptation to the restored auditory input, ultimately aiding clinical settings, supporting adequate and timely rehabilitation, and implementing interventions.

It has been proposed that auditory-to-visual cross-modal plasticity driven by hearing loss may play a significant role in understanding and predicting the potential benefits of post-lingually adult CI users (Doucet et al., 2006; Sandmann et al., 2012; Strelnikov et al., 2013; Song et al., 2015; Anderson et al., 2017; Fullerton et al., 2022). This neuroplasticity could provide adaptive benefits after hearing deprivation by enhancing the abilities of non-auditory skills, such as superior visual speechreading skills (Rouger et al., 2007); on the other hand, it was also demonstrated to correlate with behavioral measures of speech performance (Strelnikov et al., 2013; Anderson et al., 2017; Fullerton et al., 2022). Those adult CI research literature showed that cross-modal plasticity may be another factor affecting speech perception outcomes in cochlear implanted children. However, it remains unclear how such cortical reorganization of brain regions might influence hearing restoration in pre-lingually deaf children after implantation.

In children who are pre-lingually deaf, deprivation of auditory input during sensitive periods impedes the normal development of central auditory pathways and is associated with heightened sensitivity to visual stimuli observed in auditory brain regions. This cross-modal plasticity was believed to be harmful to CI outcomes because it prevented the auditory cortical areas from processing newly introduced auditory stimuli (Lee et al., 2001; Giraud and Lee, 2007; Lee et al., 2007). The reason why cochlear implantation should be performed as early as possible was probably because early implantation could prevent cross-modal takeover of auditory regions (Lee et al., 2007). However, in recent years, this view was thought to be overly simplistic (Heimler et al., 2014). Instead, the activation of auditory cortical areas by visual speech may not hinder the recovery of the auditory sense following implantation but may help preserve important language networks, which may improve CI results (Lyness et al., 2013; Mushtaq et al., 2020). Therefore, it is necessary to explore the relationship between cortical cross-modal activation and speech outcomes in CI children further. Functional near-infrared spectroscopy (fNIRS), an emerging brain-imaging technique, is considered to be one of the most suitable means of neuroscience research for people with hearing loss or hearing devices, due to its advantages of being CI compatible, noninvasive, quiet, safe for repeated use, unrestrictive and tolerant of movement artifact (Hoshi, 2003; Kiguchi et al., 2007; Dieler et al., 2012). Evidence related to using fNIRS to explore cortical plasticity in CI adults with post-lingual deafness has demonstrated its validity and feasibility (Olds et al., 2016; Anderson et al., 2017; Zhou et al., 2018). The purpose of this study was to apply fNIRS to examine the influence of cross-modal plasticity in defined regions of interest (ROIs) on speech understanding in a large sample of pre-lingually deaf CI children with a more diverse range of speech abilities.

Previous neuroimaging studies examining visual takeover of auditory regions in CI children often used low-level visual stimuli such as checkerboards (Corina et al., 2017) and pictures (Liang et al., 2017). Compared to those visual non-speech materials, speech stimuli contain more information and are more representative in terms of communication and language. In the case of post-lingually deaf CI adults, cross-modal activation of auditory cortex by visual speech was demonstrated to be beneficial for speech performance with a CI (Anderson et al., 2017; Fullerton et al., 2022). Unlike post-lingually acquired deafness, pre-lingually deaf children who did not have an experience of using visual cues when listening to speech may show different results between response of auditory cortex to visual speech and speech understanding after implantation. Additionally, it has been controversial whether visual speech (lip-reading) should be used in current CI rehabilitation strategies due to the correlation between cross-modal plasticity and CI outcomes. Therefore, visual speech (lip-reading) was used as the visual stimulus in this study. Bilateral superior temporal gyrus (STG, Brodmann area 22) and left inferior frontal gyrus (LIFG, Brodmann areas 44 and 45), as well as bilateral inferior parietal lobes (IPL, Brodmann areas 39 and 40), were defined as ROIs beforehand because activation of fronto-temporal–parietal regions, particularly the network dominated by STG, was involved in speech comprehension in CI recipients (Lee et al., 2005; Anderson et al., 2017; Zhou et al., 2018) and normally-hearing (NH) subjects (Wijayasiri et al., 2017; Defenderfer et al., 2021; Lawrence et al., 2021). In brief, increased visual processing in STG is associated with variable auditory performance with a CI (Strelnikov et al., 2013; Chen et al., 2016; Anderson et al., 2017; Zhou et al., 2018; Anderson et al., 2019; Mushtaq et al., 2020), and either LIFG (Wong et al., 2008; Obleser and Kotz, 2010) or IPL (Lawrence et al., 2018; Mushtaq et al., 2021) is crucial for improving speech recognition under challenging listening situations, such as listening to speech in background noise or recovering meaning from degraded speech.

The aims of the present study were to (i) examine the impacts of bilateral STG activation to visual speech on speech understanding in children with CIs (and a group of NH controls); (ii) explore underlying mechanisms of the relationship between cross-modal brain plasticity and speech performance after implantation; and (iii) measure activities in LIFG and IPL during listening to speech with two levels. To achieve these aims, we implemented a fNIRS experiment using a block design and examined cortical responses in defined ROIs during three conditions: auditory speech in quiet (SIQ), auditory speech in noise (SIN), and visual speech. We hypothesized that: (i) pediatric CI users would elicit stronger cross-modal responses to visual speech in auditory brain regions compared with NH controls because of early auditory deprivation; (ii) NH listeners would elicit stronger responses to auditory speech than CI users to reflect retained auditory processing specialization of the auditory cortex; and (iii) the amplitude of LIFG and IPL activation would vary according to speech condition. To our knowledge, this is the first fNIRS study to describe neural activation of fronto-temporal–parietal networks in a representative sample of pediatric CI recipients with pre-lingual deafness.

2. Materials and methods

2.1. Participants

The study protocol was approved by Chongqing General Hospital and conformed to the declaration of Helsinki. Before taking part, all participants' accompanying guardians signed informed consent forms, and subjects were also asked to verbally assent to attend. CI users were contacted through the Chongqing Integrated Service Center for Disabled Persons. NH controls were school-age students or acquaintances of the project's researchers, who were recruited through word-of-mouth or online advertisements. Ages between 6 and 12 years old, native Mandarin speakers, healthy, and self-reported or parent-reported normal or corrected-to-normal vision were common inclusion criteria across both groups. Exclusion criteria were any known language, cognitive, or motor disorder; a history of brain injury; and any active external or middle ear disease. Additionally, to eliminate discrepancies in handedness, the Edinburgh Handedness Inventory (Oldfield, 1971) was used to confirm that each individual was right-handed.

In order to rule out the side of implantation as a contributing factor in the analysis, only CI users with a right-ear implant were engaged. All of the participants in the CI group were pre-lingually deaf children who had used their right-ear implants for more than 1 year. CI participants were questioned about their deafness, including the etiology of deafness, age at onset and duration of deafness, history of hearing aid use, age at CI activation and duration of CI use. Briefly, all children received hearing screening at birth and had no genetic damage to organs other than the ear. In patients with congenital or early-onset deafness (later than at birth) caused by meningitis (three subjects), auditory neuropathy (two subjects), congenital malformation of inner ear (one subjects) and enlarged vestibular aqueducts (four subjects). Only a small percentage of children underwent genetic screening due to family financial reasons, and two of them had unspecified genetic causes of deafness. The etiology of hearing loss was unknown for 26 subjects. Twenty-four of the children had used hearing aids prior to CI, while the remaining 14 had not. However, the duration of hearing aid use was extremely varied, ranging from complete absence to continuous bilateral use. Table 1 presents the details regarding CI participants.

The NH listeners recruited for this study were age and gender matched with CI recipients. These children were healthy and had pure-tone air conduction thresholds of $\leq$20 dB SPL at 0.5, 1, 2, and 4 kHz in both ears.

Forty-three pre-lingually deaf children with CI and 41 NH subjects participated in this study. Two CI children withdrew from the fNIRS examination because they could not tolerate the optodes on their heads. Moreover, three CI children and five NH children were excluded due to excessively poor channel quality. Eventually, available data was obtained from 38 pre-lingually deaf CI children (mean age 6.86 ± 0.70 years, range 6.01–8.19 years, 11 females) and 36 control subjects (mean age 7.04 ± 0.89 years, range 6.05–8.87 years, 14 females) participated in the study. There were no significant differences in age and gender between the two groups (both $p > 0.05$). This sample size was determined using data from earlier fNIRS investigations with CI recipients utilizing similar stimuli (Anderson et al., 2017; Zhou et al., 2018; Anderson et al., 2019; Mushtaq et al., 2020). Along with it, the Hiskey-Nebraska Test of Learning Aptitude (H-HTLA) was used to assess intelligence, and none of the subjects were intellectually disabled. All participants were fluent in Mandarin Chinese similar to the Chongqing dialect.

2.2. Speech understanding test

Prior to neuroimaging testing, the auditory speech perception abilities of all participants were measured in a soundproof room in which the background noise level was less than 30 dBA. A GSI free-field loudspeaker was used to deliver auditory stimuli, and the speech processor program in the CI user was configured in clinical settings throughout the test. CI users who had an implant or a hearing aid in the left ear were instructed to remove the device. Open-set disyllabic words from Mandarin Speech Perception (MSP) material (Zhu et al., 2012) were used to obtain a measure of speech perception. This material consisted of 10 standardized lists, each including 35 words recited by a female talker. MSP words were delivered to participants at a presentation level of 65 dBA. To prevent ceiling effects, these words were presented both in quiet and in steady, speech-shaped noise, with signal-to-noise ratios (SNRs) of 10 dB. For each condition, a list was randomly selected out of a group of 10 lists, each list with 35 words, and a disyllabic word was randomly selected from the list. Following each word presentation, the participant was told to pay close attention to the words and try their best to repeat back every word. A licensed audiologist scored participants' responses to MSP words according to the proportion of words they correctly identified. No lists were repeated within test subjects.

At the start of the speech perception test, all participants completed a short practice that was performed simply and not scored to ensure that they all understood the procedure of behavioral measures. Notably, no participant received the same word more than once, and none of the subjects received any feedback at any point in the experiment.

2.3. fNIRS stimuli

The HOPE corpus, which was used to generate speech stimuli during the acquisition of fNIRS measurements, is a corpus of Mandarin sentences with paired babble noises that are similar to Bamford-Kowal-Bench (BKB) sentences (Xi et al., 2012). This material comprised digital audiovisual recordings of 160 sentences that were transcribed in a sound-attenuating test booth at the Chinese PLA General Hospital, Beijing, and were male-spoken, phonemically-balanced. There were between six and eight words in each sentence, with three or four of those being defined as keywords. An illustration of a sentence with keywords underlined is: "她看见一只兔子/She recognized a rabbit./" We selected 63 sentences from

TABLE 1 Demographic characteristics of CI users, including speech understanding scores.

Subject ID	Gender	Age (years)	Onset (months)	Duration (months)	HA history	CI age (years)	CI side	CI duration (months)	MSP (quiet, %)	MSP (SNR10dB, %)
CI_01	Female	6.83	18	8	Yes	2.14	B	57	80	65.7
CI_02	Female	7.84	12	28	Yes	3.28	R	55	21.4	10.7
CI_03	Male	6.56	At birth	14	Yes	1.17	R	66	94.3	87.1
CI_04	Female	6.01	At birth	18	Yes	1.47	R	55	58.6	7.1
CI_05	Male	7.23	10	52	Yes	5.10	R	26	71.4	51.4
CI_06	Male	6.30	At birth	24	Yes	1.94	R	53	91.4	87.1
CI_07	Female	7.91	28	33	Yes	5.01	R	35	31.4	0
CI_08	Male	6.96	At birth	33	Yes	2.73	R	52	92.9	80
CI_09	Male	6.13	12	7	Yes	1.55	R	56	40	4.3
CI_10	Female	6.55	At birth	43	No	3.56	R	36	94.3	78.6
CI_11	Male	6.13	18	15	No	2.72	R	42	88.6	54.3
CI_12	Male	7.15	14	48	No	5.12	R	25	60	40
CI_13	Male	8.15	12	36	No	3.92	R	52	25.7	7.1
CI_14	Male	8.19	18	26	No	3.66	R	55	88.6	84.3
CI_15	Male	6.57	At birth	19	Yes	1.59	R	61	38.6	0
CI_16	Male	7.98	At birth	61	No	5.03	R	36	17.1	0
CI_17	Male	7.28	At birth	30	No	2.44	R	59	75.7	75
CI_18	Male	7.88	At birth	54	Yes	4.42	R	42	71.4	65.7
CI_19	Female	6.22	At birth	20	Yes	1.64	R	56	50	8.6
CI_20	Female	6.30	At birth	12	No	1.00	R	64	94.3	75.7
CI_21	Male	6.77	At birth	38	Yes	3.15	R	44	94.3	77.1
CI_22	Female	6.30	17	3	No	1.65	B	57	95.7	82.9
CI_23	Male	6.36	19	11	Yes	2.51	R	47	72.9	72.9
CI_24	Female	6.02	12	4	No	1.38	B	57	77.1	75.7
CI_25	Male	6.46	18	34	Yes	4.33	R	26	15.7	12.3
CI_26	Male	6.07	18	14	Yes	2.67	R	41	24.3	0
CI_27	Male	6.70	18	28	Yes	3.80	R	35	47.1	42.9
CI_28	Male	8.16	24	16	Yes	3.32	R	59	90	75.7
CI_29	Male	6.95	18	12	Yes	2.52	R	54	95.7	87.1
CI_30	Male	6.84	12	24	Yes	2.94	R	47	45.7	35.7
CI_31	Male	6.24	16	7	Yes	1.94	R	52	74.3	63
CI_32	Male	6.89	35	8	No	3.56	R	41	67.1	67.1
CI_33	Male	6.69	24	21	No	3.72	R	36	84.3	74.3
CI_34	Female	6.74	34	10	Yes	3.67	R	37	75.7	62.9
CI_35	Female	6.02	At birth	31	No	2.59	R	42	72.9	65.7
CI_36	Male	6.15	12	14	No	2.19	R	48	78.6	51.4
CI_37	Male	7.46	12	20	Yes	2.66	R	58	64.3	51.4
CI_38	Male	7.84	12	21	Yes	2.73	B	62	71.4	35.7

Age, natural age (years); Onset, age at onset of bilateral hearing loss (months); Duration, duration of bilateral hearing loss (months); CI age, age at cochlear implantation (years); CI side, side of cochlear implantation; B, bilateral; R, right; CI duration, duration of CI use since activation of CI device in right side (months); HA history, Experience of hearing aid use before implantation; MSP, Mandarin Speech Perception; SNR, signal-to-noise ratio.

the material to use for testing, so there were seven sentences in each of the nine blocks. To draw the participant's attention, a sentence including an animal was contained in every block. Except for specific sentences involving animals, which were subsequently distributed at random to each block, all sentences were chosen randomly from the corpus.

The experiment included a visual and an auditory session. For the auditory session, we designed two listening conditions: SIQ and SIN, where the auditory speech cues were presented but the visual speech cues were not shown. First, sentences were digitally isolated from their respective lists into 4-s trials using Adobe Audition editing software. Subsequently, in SIQ trials, babble noise in the right channel was removed, and only male-spoken Mandarin sentences in the left channel were retained. SIN trials were created by first modifying the 4-s noise in the right channel to reflect a total root-mean-square (RMS) amplitude value of 10 dB lower than the total RMS of the individual sentence to generate a specific SNR (+10 dB). Next, the babble noise and Mandarin sentences were mixed in the left channel. For the visual session, we adopted visual speech (i.e., lip-reading), where the visual speech cues of the recording were shown but the auditory speech cues were muted. The visual stimuli consisted of lip-reading of HOPE sentences and were also edited from their respective lists into 4-s trials using Adobe After Effects software according to the auditory stimuli. The background of the two auditory speech conditions was uniform, and the talker's mouth was replaced with a fixation cross. Only this uniform background and fixation cross were used during rest intervals.

2.4. fNIRS paradigm

The speech stimuli were presented in a pseudorandom block design, with a baseline of 25 s followed by 9 blocks of stimuli that alternated between SIQ, SIN, and visual speech stimuli (Figure 1A). A no-stimulus period (rest) with a duration of 25 s was incorporated between those blocks to allow the haemodynamic response produced by the stimulation block to return to a baseline level. Each block contained seven sentences, evenly spaced to fill a 28-s block duration. Participants were told to pay attention to the talker and make an effort to comprehend what the talker was saying throughout these blocks. For the visual condition, participants were instructed to fixate on the location of the talker's mouth. For the auditory conditions and rest periods, participants were instructed to look at the centrally positioned fixation cross and to minimize saccades as much as possible. To maintain attention to the speech stimuli throughout the experiment, an attentional trial was presented after each of the blocks. Two alternative animal pictures were presented on either side of the fixation cross 0.5 s after the presentation of each block, in which one animal in the picture had appeared in the previous block and the other animal in the picture almost rhymed with the correct animal. Participants were required to select the animal picture that appeared in the immediately preceding sentences they had just heard by pressing one of two buttons. They had up to 6 s to respond; otherwise, the pictures would disappear. We used this task only to ensure that subjects could focus their attention during the neuroimaging test phase, but the behavioral task results were not included in the analysis.

Before fNIRS scanning, participants first completed a brief familiarization run to make sure they understood the experimental procedure. The familiarization blocks contained sentences that were different from those delivered during the fNIRS measurements and the behavioral assessment in order to prevent preexposure to the experimental stimuli. This practice task was redone several times if the subject made mistakes until the researcher confirmed that the participant understood the task completely. Notably, speech stimuli in speech understanding tests differed from those in the corpus, which helped to limit training effects within and across testing sessions.

2.5. fNIRS measurements

The experiment was performed in the same booth as the speech perception test, with lights out in the room while collecting data. Participants were situated comfortably at a distance of 75 cm from a computer (Thinkpad E480) display unit, which was utilized to present visual stimuli. Auditory stimuli were delivered through a GSI free-field speaker placed directly on the monitor at a presentation level where sound intensity was coordinated at 70 dB SPL (A-weighted) as measured by a sound level meter when the subjects were absent. Although ear inserts do improve the SNR for the delivery of auditory stimuli, sound field presentation was more effectively and accurately to represent "real-world" experience with spoken communication (Hervais-Adelman, 2012). Before the experiment, participants removed their hearing device in the left ear if they had one. The stimuli of the study were presented through the Eprime3.0 (Psychology Software Tools, Inc., Pittsburgh, PA, United States) tool. Brain activity was non-invasively measured using a Hitachi ETG-4100 (Hitachi Medical Corporation, Tokyo, Japan) optical topography system, which emitted infrared light at wavelengths of 695 and 830 nm and sampled at a rate of 10 Hz, as well as used frequency modulation to minimize crosstalk between channels and wavelengths (Scholkmann et al., 2014).

A pair 3 × 5 optode arrays were placed over the left and right temporal regions, aiming to mainly cover the bilateral STG, LIFG, and bilateral IPL. Together, these consisted of 16 sources and 14 detectors with a 3-cm fixed source-detector gap, resulting in 44 measurement channels (22 per hemisphere). As shown in Figure 1B, to standardize array placement across participants, the middle optode on the bottom row was positioned close to the preauricular point and the middle optode on the top row was pointed in the direction of point Cz according to the 10–20 system (Klem et al., 1999). Importantly, there was some variation in how the external CI processor was positioned among the participants in the CI group, so that the external CI processor sometimes interfered with probe placement. In such cases, we positioned the headset over the processor. While this prevented certain channels from scalp contact, the data acquisition of the remaining channels was usable. To improve optode-scalp contact, we carefully removed redundant hair from underneath optodes with a small plastic illuminated tool, modified the angle of the optodes, and ran the signal check program that was pre-installed in the ETG 4100. Until all of the accessible channels passed the signal test, we did not move on to the next phase. To further guarantee the consistency of optode placement, a reference picture was taken once the position of the array had been settled upon. During imaging, individuals were required to keep as still as possible and avoid unnecessary head movements to reduce motion artifacts in the fNIRS data. Prior to starting the neuroimaging task during data collection, participants received verbal and written instructions. The task was then started at the participant's decision by pressing the spacebar on the keyboard. The onset and end of each stimulus were timed to match the beginning and finish of the incoming fNIRS data, and they were both recorded in an event file. Participants did not receive any feedback on their performance accuracy.

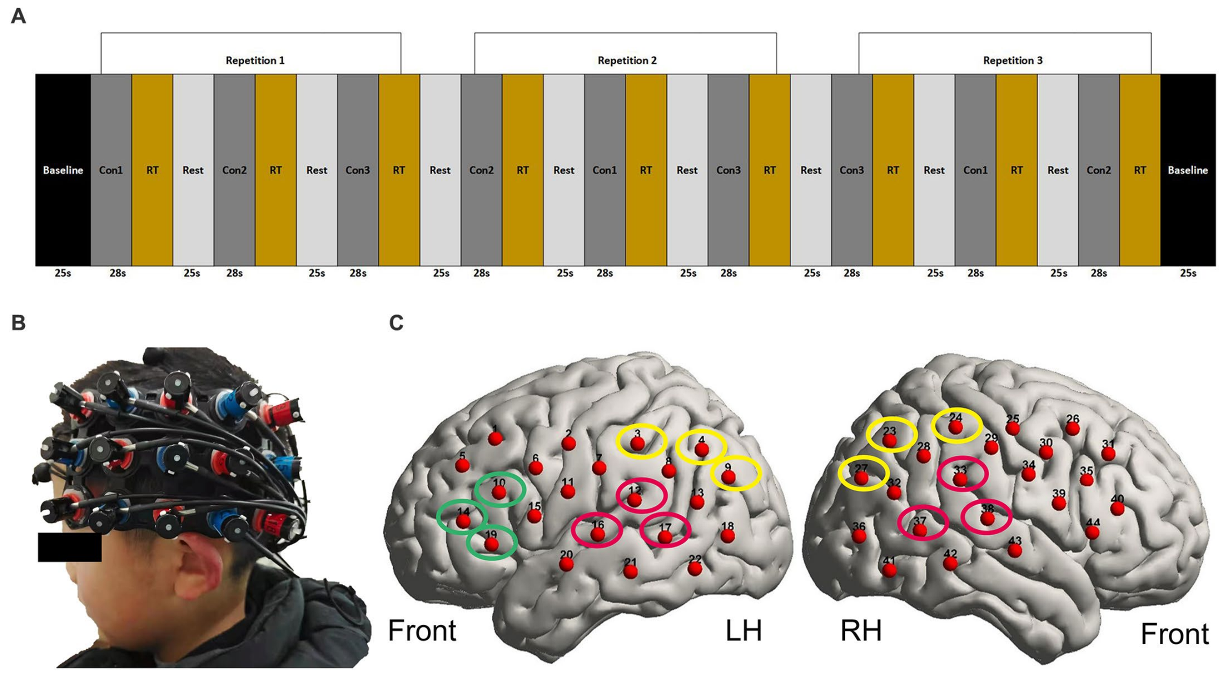

FIGURE 1
fNIRS paradigm and the localization of optodes. **(A)** Illustration of three repetitions of each stimulus type in pseudorandom order. Con1 represents SIQ (28s), Con2 represents visual speech stimuli (28s), Con3 represents SIN (28s), and RT represents the response time in which a behavioral task was presented. The baseline and rest periods lasted 25s each. **(B)** A photograph of the optode array holder placed on the head of one of the participants. The red and blue color coding on the holder indicates the locations of emitters and detectors, respectively. **(C)** fNIRS measurement channel locations on the brain cortex using a 3D digitizer. The channels outlined in red form bilateral STG. The channels outlined in green form LIFG. The channels outlined in yellow form bilateral IPL. LH, left hemisphere; RH, right hemisphere.

2.6. Processing of fNIRS data

2.6.1. fNIRS data for cortical activation

The fNIRS recordings were imported into MATLAB (R2013A; The MathWorks) for further analysis using HOMER2 (Huppert et al., 2009) and NIRS-SPM (Jong et al., 2008) toolboxes together with custom scripts. Pre-processing of the data was performed using HOMER2 software, and the fNIRS response amplitude was quantified using NIRS_SPM software.

Before processing of the data, the task-unrelated time intervals were removed first. Following that, because poor optode-scalp contact can be a limiting factor impacting fNIRS data quality, the scalp coupling index (SCI) approach introduced by Pollonini et al. (2014) and visual inspection were used to exclude channels from which data were unacceptable in quality. In order to maintain as many channels as possible for further statistical analysis, we established a flexible threshold of SCI ≥ 0.202 and decided to just remove the worst 5% of channels from the overall dataset.

Processing of the data for the retained channels proceeded as follows:

(a) The raw intensity signals from each channel were converted to changes in optical density using the HOMER2 hmrIntensity2OD function (Huppert et al., 2009).

(b) A correction strategy was chosen to reduce signal contamination since children may exhibit motion/muscle artifacts. We first used spline interpolation approach ($p = 0.99$, frame size = 10 s) to remove large spikes and baseline shifts in the data (Scholkmann et al., 2010). Second, we used the HOMER2 package's hmrMotionCorrectWavelet function (IQR = 0.7), which implements a condensed version of the algorithm proposed by Molavi and Dumont (2012). During experiments involving speech tasks, this function has been demonstrated to significantly reduce motion artifact (Cooper et al., 2012; Brigadoi et al., 2014). We did not include wavelet coefficients that were more than 0.7 times either the first or third quartile interquartile range. If the wavelet coefficients are normally distributed, this almost corresponds to the $\alpha = 0.1$ threshold used in assessing motion artifact corrections for fNIRS methods (Lawrence et al., 2021).

(c) Following motion-artifact correction, recordings were bandpass filtered with cut-off frequencies of 0.01 and 0.5 Hz for the lower and upper thresholds to reduce the physiological noise sources in the data, such as high-frequency cardiac oscillations, low-frequency respiration, and blood pressure changes (Dewey and Hartley, 2015; Yucel et al., 2021).

(d) The optical density data were transformed into estimated changes in HbO and HbR concentrations using the modified Beer–Lambert law after motion-artifact correction (Huppert et al., 2009). We adopted a default value of 6 for the differential path-length factor at both wavelengths.

(e) An anti-correlation method (Yamada et al., 2012), which assumes that systemic noise-induced changes in HbO and HbR concentration are positively correlated but stimulus-related changes in HbO and HbR concentration tend to be negatively correlated, was used as the final stage of pre-processing to further reduce physiological interference. The HbO and HbR associated to the stimuli in channels were identified by maximizing the negative correlation between them (Cui et al., 2010).

(f) After completing the necessary pre-processing steps, we used the general linear model (GLM) approach to calculate the level of cortical activation (Schroeter et al., 2004). The stimulus time-course convolved with a canonical hemodynamic response function implemented in SPM 8 software (Wellcome Trust Centre for Neuroimaging, UCL, UK, 2009) together with its temporal and dispersion derivatives (Ho, 2012). Finally, we utilized the beta value to evaluate the impact of the stimulus on cortical response. The beta value was block averaged over three repetitions of each stimulus to obtain the mean hemodynamic response of each participant, channel, and stimulus condition. The estimated response amplitudes (ERAs) within each ROI were the mean beta values across the ROI measurement channels. Additionally, this study focused on HbO responses since they are more sensitive to changes in regional cerebral blood flow (Hoshi, 2007).

2.6.2. fNIRS data for functional connectivity

The Homer2 toolbox was used to process the data for the functional connectivity analysis together with custom scripts (Scholkmann et al., 2014). Consistent with the pre-processing of the activation analysis, including exclusion of channel, artifact rejection, motion correction, bandpass filtering (0.009–0.1 Hz), the Modified Beer–Lambert Law, and estimation of the hemoglobin concentrations. We used a different filter range for functional connectivity as compared to the activation analysis. This is because previous research has shown high coherence in a low-frequency range (0.009–0.1 Hz) (Sasai et al., 2011). Then the hemoglobin concentrations were segmented into an epoch corresponding to the window in which the stimulus was shown and a response was generated (−5 to +30s). It has indicated that the HbO data exhibits more robust coherence patterns and connectivity than HbR data; consequently, connectivity analysis was carried out using HbO data (Wolf et al., 2011). The coherence between all channels was evaluated for each participant employing epoch data within the frequency range of 0.009–0.1 Hz (Yucel et al., 2021). The resulting coherence values indicate the degree of similarity in signals between channel pairs during the outlined time window. A value closer to 1 suggests a higher degree of similarity, while a value closer to 0 suggests greater independence of signals (Fullerton et al., 2022). Coherence values for the ROI channels (Figure 1C) were averaged to estimate task-related connectivity during speech processing. Specifically, connectivity included coherence values between 7 ROI pairs: LSTG and RSTG, LSTG and LIFG, LSTG and LIPL, LSTG and RIPL, RSTG and LIFG, RSTG and LIPL, and RSTG and RIPL.

2.7. Definition of ROI

ROIs were pre-selected for this study. The main *a priori* "auditory" ROI targeted superior temporal regions considering recent fNIRS research on cross-modal brain plasticity in CI users (Olds et al., 2016; Anderson et al., 2017; Zhou et al., 2018; Anderson et al., 2019; Mushtaq et al., 2020) and comprised symmetrical channels 12, 16, and 17 in the left hemisphere (LH) and channels 33, 37, and 38 in the right hemisphere (RH). A pair of secondary *a priori* ROIs targeted "LIFG" regions (including channels 10, 14, and 19 in the LH) and "bilateral IPL" regions (namely channels 3, 4, and 9 in the LH and channels 23, 24, and 27 in the RH), the selection of which was based on their potential influence on effortful listening (Wong et al., 2008; Obleser and Kotz, 2010; Adank, 2012; Wild et al., 2012; Lawrence et al., 2018, 2021). In order to estimate channel positions on the cortical surface, the optode placement was recorded using the Hitachi ETG-4100's electromagnetic 3D Probe Positioning Unit, as illustrated in Figure 1C. First, the 3D digitizer system was used to record the positions of the optodes and anatomical surface landmarks (the left tragus, right tragus, nasion, inion, and Cz), which were then translated into MNI coordinates using MATLAB (R2013A; The MathWorks) with customized scripts. Finally, these coordinates were input into the NIRS-SPM toolbox to register fNIRS channels and project them to brain regions.

2.8. Statistical analysis

Both behavioral and fNIRS data were analyzed using IBM SPSS Statistics for Windows Version 25.0 software (IBM Corp., Armonk, New York). The reported *p*-values in all analyses were two-tailed, with a significance level set at $p < 0.05$ without any special instructions. Furthermore, we used the Bonferroni method to correct for multiple comparisons of *p*-values. Speech understanding was quantified as the percentage of words reported correctly (% correct). To make the data more suitable for statistical analysis, the rationalized arcsine transform was applied using SPSS 25 (Anderson et al., 2017). Subsequently, the transformed scores [rationalized arcsine units (RAUs)] were subjected to statistical analysis.

In each group, we employed two-tailed t-tests to evaluate cortical activation in a total of 44 measurement channels. Specifically, we contrasted each speech condition against a silent baseline and applied a false discovery rate (FDR) correction method (Benjamini and Hochberg, 1995) to adjust for multiple comparisons across all channels. To ensure high statistical rigor, we established an FDR-corrected threshold of $q < 0.05$ indicating statistical significance.

The cortical activation differences in each ROI were determined by analyzing the ERAs for the bilateral STG, bilateral IPL, and LIFG separately using three linear mixed models (LMMs). The first two LMMs included fixed effects of "group" (CI vs. NH or GCI vs. PCI), "stimulus type" (SIQ vs. SIN vs. visual condition), and "hemisphere" (LH vs. RH), with all two- and three-way interactions, as well as a random intercept for "participant." When specifically examining the cortical activation differences in LIFG, the models included fixed effects of "group," "stimulus type," and "group-stimulus type," along with a random intercept for "participant." The task-related functional connectivity differences between groups in each ROI pair were determined by analyzing the coherence values for SIQ, SIN, and visual condition separately using three LMMs, including fixed effects of "group" (CI vs. NH), "ROI pair" (7 pairs of ROI), group×ROI pair interaction, and a random intercept for "participant." Estimation of the model parameters was done through the restricted maximum likelihood (REML) approach. The *post hoc* Bonferroni's test was used for multiple comparisons during follow-up analyses.

Bivariate correlation analysis was conducted to examine the association between activation levels (ERAs) or coherence values and speech perception scores (RAU). Specifically, the parametric statistic

Pearson's correlation coefficient (r) was used to estimate the direction and strength of the linear relationship. Since the age-at-onset, duration of deafness prior to implantation, age-at-implantation, and duration of CI use are known clinical factors influencing CI outcomes (Zeng, 2004; Tomblin et al., 2005; Green et al., 2007; Lin et al., 2008; Niparko et al., 2010; Lazard et al., 2012; Blamey et al., 2013; Tobey et al., 2013), correlation analysis was also conducted between these factors and speech performance with a CI. If there were some correlations, partial correlation analysis would be used to control the impacts of these factors.

3. Results

3.1. Behavioral results: speech performance

All NH children scored 100% on both speech understanding tests, with the exception of one child who scored 98.29% in quiet and 97.14% in noise. In contrast, the deaf children with CIs displayed a huge amount of variability in their performance on the behavioral tests. A summary of the percentage of correctly identified words in both parts of speech perception test by each CI user is shown in Table 1. The scores ranged from 15.7 to 95.7% (mean 66.7% and SD 25.0%) in quiet and 0 to 87.1% (mean 50.4% and SD 30.7%) in noise. The wide variation in speech performance in the CI group is comparable with other data from international, large-scale research (Gifford et al., 2008; Blamey et al., 2013; Spahr et al., 2014), suggesting that the CI outcomes reported in the current study may be taken into account as representative of the general CI population. We considered those CI participants with word scores in quiet ≥88% and ≤ 50% (the top 11 and bottom 11 children from our cohort) to have good perception (good CI recipients, GCI) and poor speech perception (poor CI recipients, PCI), respectively. To avoid floor effects, the scores in quiet were selected for subsequent correlation analyses.

3.2. fNIRS results

3.2.1. Data pre-processing

Some unacceptable channels were removed after the fNIRS data pre-processing steps, which included the exclusion of channels with poor signal quality using the SCI method and the application of motion artifact correction. In CI group, a total of 150 channels out of 1,672 channels (9.0%) met the exclusion criteria and were thus excluded from further analysis. Of these, 39 out of 570 (6.8%) available ROI channels were unusable. In NH group, 120 of 1,584 channels (7.6%) were excluded for further analysis. Of these, 40 out of 540 (7.4%) available ROI channels were unusable.

3.2.2. Contrasts against silence

Figure 2 displays group-level activation maps for each condition compared to silence, for both groups. In the initial analysis, responses to stimuli were contrasted to the silent baseline, and tests were conducted on every individual fNIRS measurement channel. The NH group showed statistically significant activation ($q < 0.05$, FDR corrected) within channels overlying the right temporal gyri (Ch#38, 42) in SIQ and within channels overlying the left (Ch#16) and right (Ch#38, 42) temporal gyri in SIN. As expected, this group did not show any activation when responding to visual stimuli. The CI group showed larger activation in SIQ and the visual condition. Specially, statistically significant activation ($q < 0.05$, FDR corrected) was observed in channels overlying the left (Ch#12, 16) and right (Ch#33, 37, 38, 42) temporal gyri in SIQ, in channels overlying the right (Ch#38) temporal gyrus in SIN, and in channels overlying the left (Ch#12) and right (Ch#33, 37, 38, 42) temporal gyri in the visual condition. Additionally, during the processing of SIQ, CI children exhibited significant activation beyond the temporal cortex, localizing over LIFG (Ch#14). We used the mean values across the ROI measurement channels for subsequent analyses, as previous research on the reliability of fNIRS test–retest has consistently shown that averaging fNIRS response amplitude across a small number of channels located overlying a cortical ROI is more reliable than assessing it on a single-channel basis (Wiggins et al., 2016). Additionally, although there was no significant activation or deactivation within channels overlying IPL in both groups of children, we analyzed the cortical activation differences in IPL considering its potential to enhance speech recognition in challenging listening situations and the near-significant deactivation seen in NH group.

3.2.3. ROI statistical analyses in the NH and CI groups

To identify and address the experimental hypotheses, we used LMMs to compare differences in cortical activation for each ROI across all stimulus conditions between CI users and NH controls. The mean group-level ERAs for each ROI among conditions in both groups are shown in Figure 3.

To investigate cortical responses within STG, ERAs from the LH and RH were obtained from each participant for each condition (Figure 3A). These ERAs were then analyzed using a LMM with fixed effects of "group" (CI vs. NH), "stimulus type" (SIQ vs. SIN vs. visual condition), and "hemisphere" (LH vs. RH), along with all possible two- and three-way interactions. Furthermore, a random intercept for "participant" was included in the model. The results demonstrated that (i) there was a significant main effect of group ($F(1,72) = 4.882$, $p = 0.030$) and stimulus type ($F(2,360) = 7.447$, $p = 0.001$), (ii) there was a significant interaction between group and stimulus type ($F(2,360) = 4.604$, $p = 0.011$). Follow-up analyses for the group×stimulus type showed that (i) there was a significant difference in cortical responses to visual stimuli between CI users and NH subjects ($p = 0.001$), (ii) there were similar cortical response patterns between CI and NH participants for both levels of auditory stimuli (all $p > 0.05$), (iii) NH participants exhibited lower cortical activation in response to visual stimuli compared to SIQ ($p = 0.017$) or SIN ($p < 0.001$), and (iv) CI children displayed similar cortical responses across all conditions (all $p > 0.05$).

A second LMM was employed to examine cortical activation within IPL using the same parameter settings as in the STG analysis (Figure 3B). The results showed a significant main effect of hemisphere ($F(1,360) = 6.205$, $p = 0.013$); however, no significant interactions were observed between group and stimulus type or group and hemisphere (all $p > 0.05$).

A third LMM was used to investigate cortical activation in LIFG, with fixed effects of "group," "stimulus type," and "group×stimulus type," along with a random intercept for "participant" (Figure 3C). Significant effects were observed for group ($F(1,72) = 4.506$, $p = 0.037$)

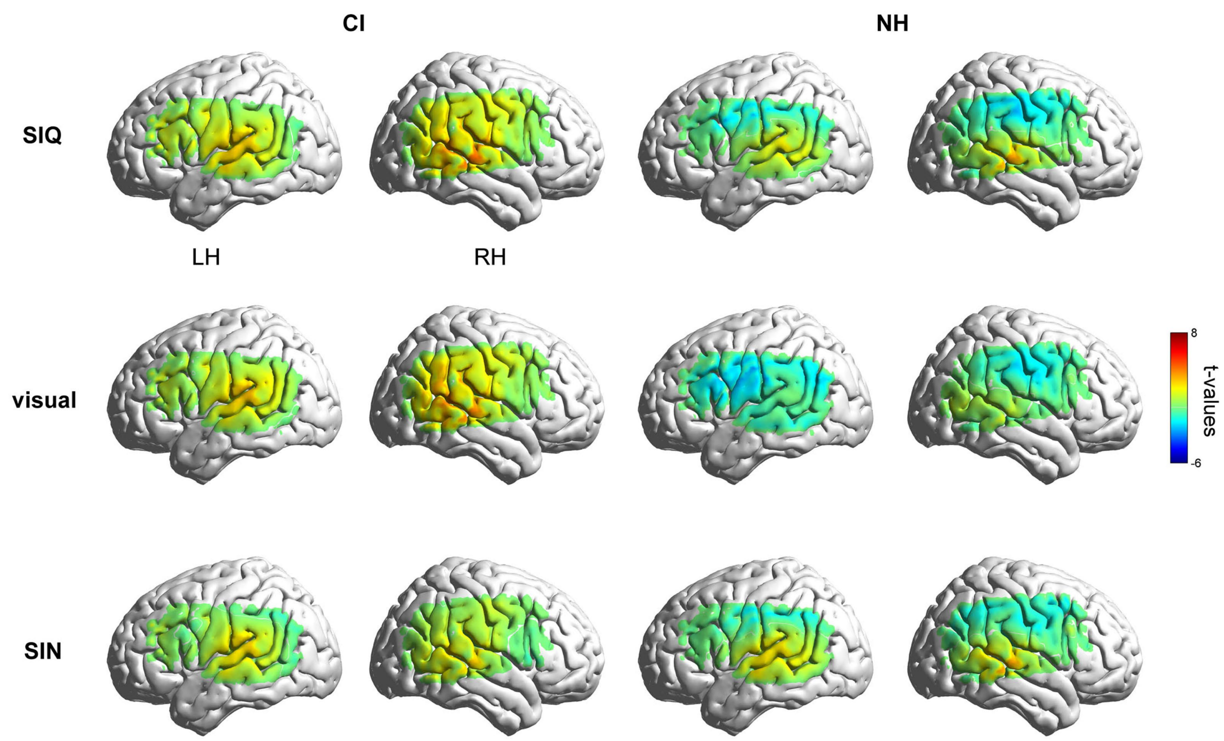

FIGURE 2
Group-level activation maps for CI and NH participants. Grand mean responses to each stimulus type were initially contrasted against the silence in the LH and RH, respectively. Note that the maps are interpolated from single-channel results, and the overlay on the cortical surface is for illustrative purposes only.

and the group×stimulus type interaction ($F(2,144) = 3.357$, $p = 0.038$). The *post hoc* analyses for the group×stimulus type interaction revealed that (i) there were significant differences between CI users and NH participants in their cortical responses to SIQ ($p = 0.022$) and visual stimuli ($p = 0.01$), (ii) CI children exhibited lower cortical activation in response to SIN compared to SIQ ($p = 0.019$), and (iii) NH participants displayed similar cortical responses across all conditions (all $p > 0.05$).

3.2.4. ROI statistical analyses within the CI group

Given the huge variability in behavioral test scores among CI users, we conducted formal statistical analyses to compare cortical responses between GCIs and PCIs. We used the same statistical methods as previously described in Part 3.2.3, employing three LMMs to investigate differences in cortical activation between these two groups. The group-level means of ERAs for each ROI across conditions in both groups are depicted in Figure 4.

The LMM results for the STG revealed a statistically significant main effect of group ($F(1,20) = 29.645$, $p < 0.001$) and a significant interaction between group and hemisphere ($F(1,100) = 10.779$, $p = 0.001$). The *post hoc* analyses showed that GCIs exhibited greater activation than PCIs across all types of stimuli, including SIQ ($p < 0.001$), SIN ($p = 0.009$), and visual stimuli ($p < 0.001$). Additionally, the GCI group demonstrated significant LH dominance in SIN ($p = 0.022$), while there was no significant difference in activation between LH and RH in the PCI group across all speech conditions (all $p > 0.05$). The LMM results for the IPL found no significant effects (all $p > 0.05$).

The LMM results for the channels covering LIFG showed a statistically significant main effect of group ($F(1,20) = 4.568$, $p = 0.045$), but no significant interaction occurred between group and stimulus type ($F(2,40) = 0.027$, $p = 0.974$).

3.2.5. Correlations with speech performance

We conducted Pearson correlation analyses between speech performance in quiet (RAU) and ERAs in each ROI (Figure 5). There was a positive correlation between speech understanding and bilateral STG (BSTG) activation to visual speech stimuli ($r = 0.764$, $p < 0.001$; Figure 5A). To investigate whether this association was hemisphere-specific, separate correlation analyses were conducted for left (LSTG) and right (RSTG) regions, which showed that both hemispheres contributed to the relationship (LSTG: $r = 0.665$, $p < 0.001$; RSTG: $r = 0.557$, $p < 0.001$; Figures 5B,C, respectively). This finding suggested greater cross-modal visual responsiveness in STG among GCIs compared to PCIs. Although age-at-onset, duration of deafness, age-at-implantation and duration of CI use are common factors influencing CI outcomes, only age-at-implantation exhibited a negative correlation with CI outcomes ($r = -0.346$, $p = 0.033$; Figure 5D); no factors were correlated with temporal activation by visual speech (all $p > 0.05$). Even when controlling for age-at-implantation using partial correlation analysis, a strong positive correlation between cross-modal activation and speech understanding remained ($r = 0.750$, $p < 0.001$). Furthermore, low-to-moderate correlations were found between CI outcomes and bilateral STG activation to SIQ ($r = 0.545$, $p < 0.001$; Figure 5E) and SIN ($r = 0.397$, $p = 0.014$; Figure 5F).

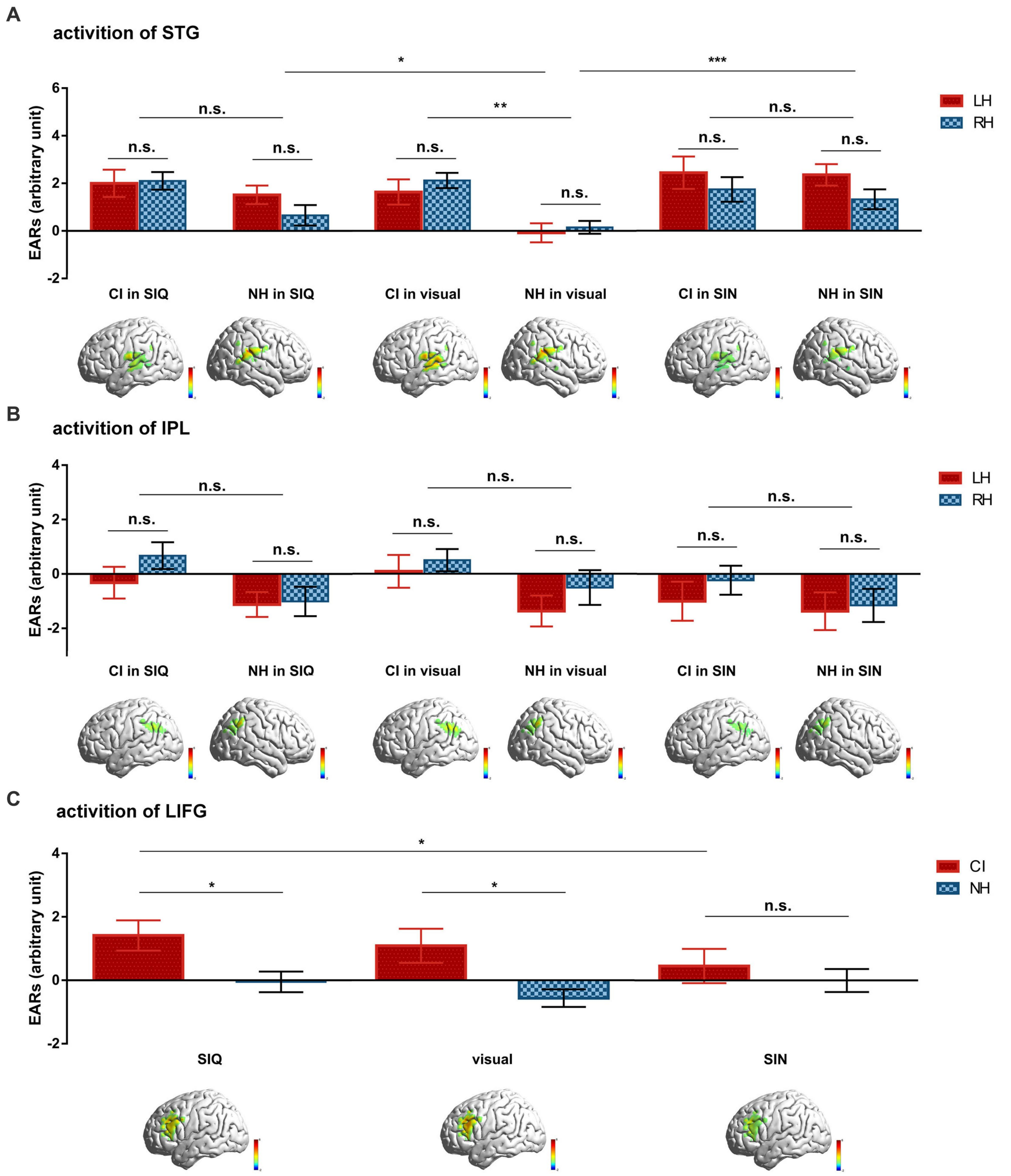

FIGURE 3
Differences in group-averaged ERAs for each ROI across all stimulus conditions between CI users and NH controls. **(A)** Cortical activation of STG. **(B)** Cortical activation of IPL. **(C)** Cortical activation of LIFG. Inset images below the statistics illustrate the differences in cortical activation maps for each ROI to corresponding stimulus between the two groups. Error bars represent standard error of the mean. Significance is marked as follows: **p*<0.05; ***p*<0.01; ****p*<0.001; n.s., not significant.

Interestingly, we found activation in LIFG in response to visual speech stimuli to be weakly correlated with CI outcomes ($r = 0.349$, $p = 0.032$; Figure 5G). Furthermore, we observed a nearly significant correlation between LIFG activation in response to SIQ and speech performance ($r = 0.314$, $p = 0.055$; Figure 5H). In contrast, we did not find any significant association between cortical responses in IPL and CI performance.

Overall, we believe that the results of the correlation analysis were largely consistent with those of the activation analysis, although only activation within STG in response to visual speech and SIQ remained significantly correlated with speech test scores for CI users when using the Bonferroni correction to reduce the possibility of type I errors during a series of correlation analyses. The absence of any noteworthy correlation between cortical responses in IPL and CI outcomes may be due to the unclear impacts of neural activity of IPL in this study. The activation response patterns in IPL were considerably disparate, even for GCIs, comprising both deactivation and activation responses. In the future, it will be necessary to expand the sample size and explore the effects of speech recognition accuracy on cortical activation in the parietal cortex in CI users further.

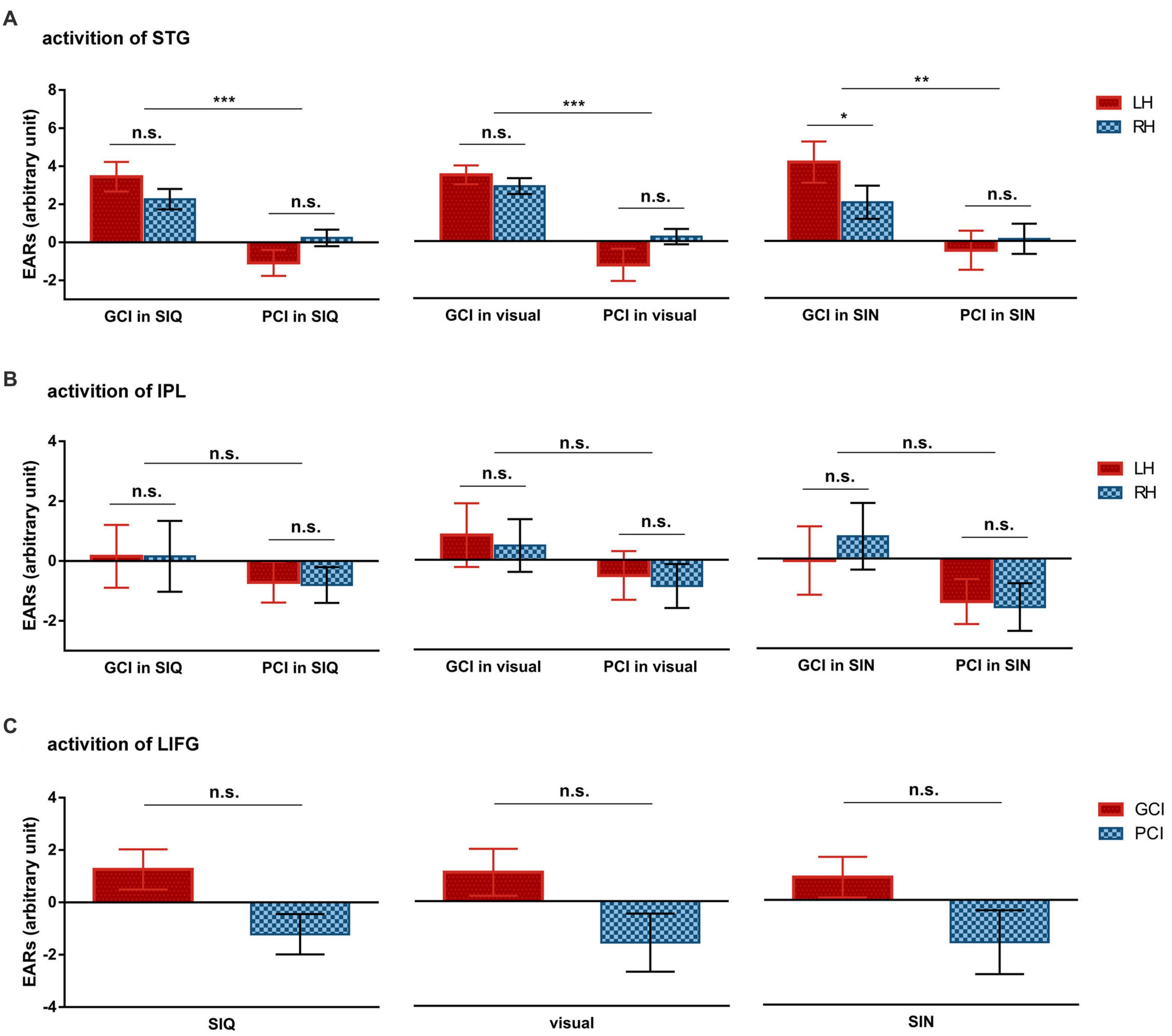

FIGURE 4
Differences in group-averaged ERAs for each ROI across all stimulus conditions between GCIs and PCIs. **(A)** Cortical activation of STG. **(B)** Cortical activation of IPL. **(C)** Cortical activation of LIFG. Error bars represent standard error of the mean. Significance is marked as follows: *p<0.05; **p<0.01; ***p<0.001; n.s., not significant.

3.2.6. Functional connectivity: statistical analyses between NH and CI groups

After demonstrating activation differences between CI children and NH controls, we further explored possible mechanisms by analyzing task-related functional connectivity between 7 pairs of ROI in response to visual and two levels of auditory speech stimuli within these two groups. Figure 6 displays the results of functional connectivity analysis for the CI and NH groups, respectively.

The LMM results for visual speech stimuli indicated a significant main effect of group ($F(1,72) = 7.701$, $p = 0.007$) and group×ROI pair interaction ($F(6,432) = 2.346$, $p = 0.031$). Further analysis of the group×ROI pair interaction revealed that the task-related functional connectivity differed significantly between the NH and CI groups in various ROI pairs, including LSTG and RSTG ($p = 0.018$), LSTG and LIFG ($p < 0.001$), LSTG and LIPL ($p = 0.037$) and RSTG and LIFG ($p = 0.031$), with stronger connectivity observed in CI children as compared to those with NH.

The LMM results for SIN revealed only a significant main effect of ROI pair ($F(6,432) = 3.172$, $p = 0.005$). In contrast, there were no statistically significant effects with respect to main effect of group or group×ROI pair interaction (all $p > 0.05$). Similarly, in terms of responses to SIQ, no statistically significant effects were found either (all $p > 0.05$).

To investigate the relationship between task-related functional connectivity and speech recognition ability, Pearson correlation analyses were performed for speech performance in quiet (RAU) and coherence values for each ROI pair in response to each stimulus type. However, no significant associations were found between task-related functional connectivity and CI outcomes (all $p > 0.05$).

4. Discussion

This study used fNIRS to investigate brain activation in pre-lingually deaf CI children to three types of speech stimulus and

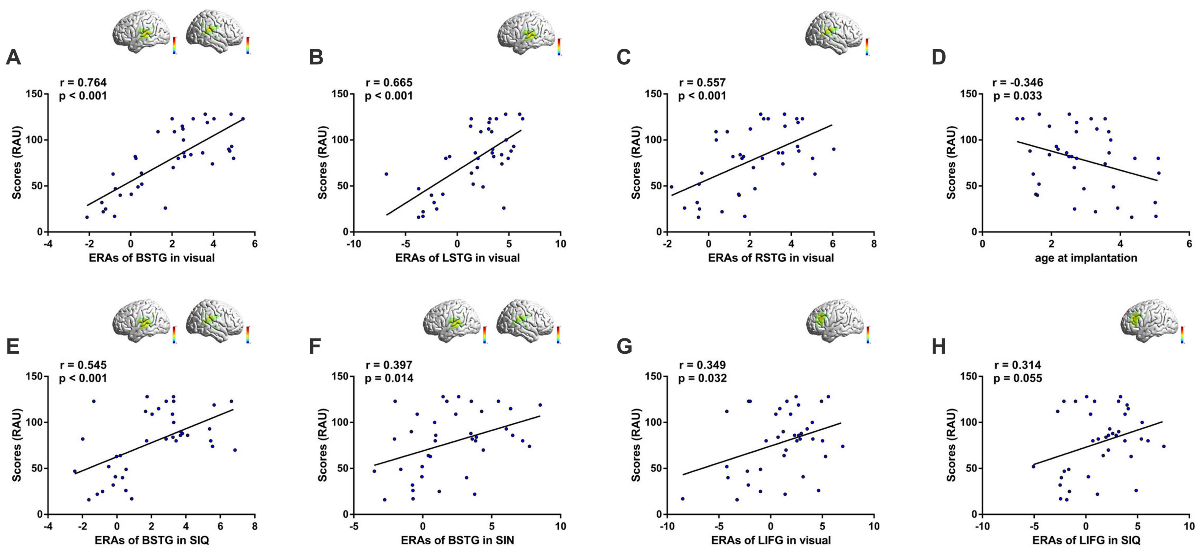

FIGURE 5
Cortical activation correlates with behavioral measures of speech perception. Inset images on the top right illustrate activation maps of the corresponding ROIs. **(A)** Correlation based on responses of bilateral STG (BSTG) to visual speech. **(B)** Correlation based on responses of LSTG to visual speech. **(C)** Correlation based on responses of RSTG to visual speech. **(D)** Correlation between age at implantation and CI performance. **(E)** Correlation based on responses of BSTG to SIQ. **(F)** Correlation based on responses of BSTG to SIN. **(G)** Correlation based on responses of LIFG to visual speech. **(H)** Correlation based on responses of LIFG to SIQ.

their correlations, especially visual cross-modal activation in STG, with behavioral speech perception after implantation. We aimed to extend previous findings to more representative CI children with pre-lingual deafness and to larger cortical regions with regard to speech understanding and effortful listening. The findings indicate that cortical responses of STG in CI children, especially those GCIs, were on average greater than those in NH group when processing all speech stimuli. Additionally, activation of STG was significantly correlated with behavioral speech test scores in quiet, with strong positive correlations observed between cross-modal activation within STG and CI performance. Specifically, better speech comprehension with a CI was associated with stronger STG activation in response to visual speech. A secondary analysis revealed that CI children, particularly GCIs, exhibited increased responses to all experimental speech stimuli in the LIFG region compared to NH controls. Additionally, there was a nearly significant correlation between LIFG activation in response to SIQ or visual speech and CI outcomes. The results suggest that visual cross-modal reorganization is at least one of the neural bases of poor speech perception in CI participants and that cortical activation of the LIFG may be a cortical marker for effortful listening. As far as we know, this is the first fNIRS research to describe neural activation of functional fronto-temporal–parietal networks involvement in speech comprehension and cross-modal reorganization in pre-lingually deafen CI children with a diverse range of speech abilities.

4.1. Cross-modal responses of auditory regions in CI users and in NH controls

The observation of significantly higher visual-evoked activation of auditory cortex in deaf CI users compared with NH controls aligns well with previously published data (Finney et al., 2001, 2003; Karns et al., 2012; Vachon et al., 2013). It remains a subject of debate regarding how such cross-modal reorganization of temporal regions may impact hearing restoration in pre-lingually deaf children after implantation. In this study, we involved pre-lingually deaf CI children with a more diverse range of speech abilities to study the relationship between cross-modal activation by visual speech stimuli and speech performance with CIs. To our knowledge, the sample size of this study, consisting of $n = 38$ CI participants, is the largest in this field and this increased sample size was expected to increase statistical power. It is interesting to note that our data did not support the theory that responsiveness of bilateral STG to visual speech was negatively correlated with CI success, but instead suggested that greater recruitment of auditory brain regions for processing visual speech would facilitate the restoration of hearing after implantation. Specially, participants with well-performing CIs achieved a greater cross-modal response than those with poorly performing CIs. Additionally, this positive relationship was not driven predominantly by one cerebral hemisphere. We also demonstrated that early implantation was closely related to better speech outcomes. However, this relationship seems not to be done by preventing cross-modal reorganization because there was no correlation between age-at-implantation and cross-modal activation. Perhaps one of the reasons is that early implantation contributes to the "normal" development of the auditory pathway during the sensitive period for auditory processing, or greater implantation age is linked to reduced gains from audiovisual integration (Stevenson et al., 2017). Another possibility is that there may be an undisclosed correlation between these two as the study did not examine cortical activation levels in deaf children before implantation. A more reasonable approach to identifying this correlation would be to

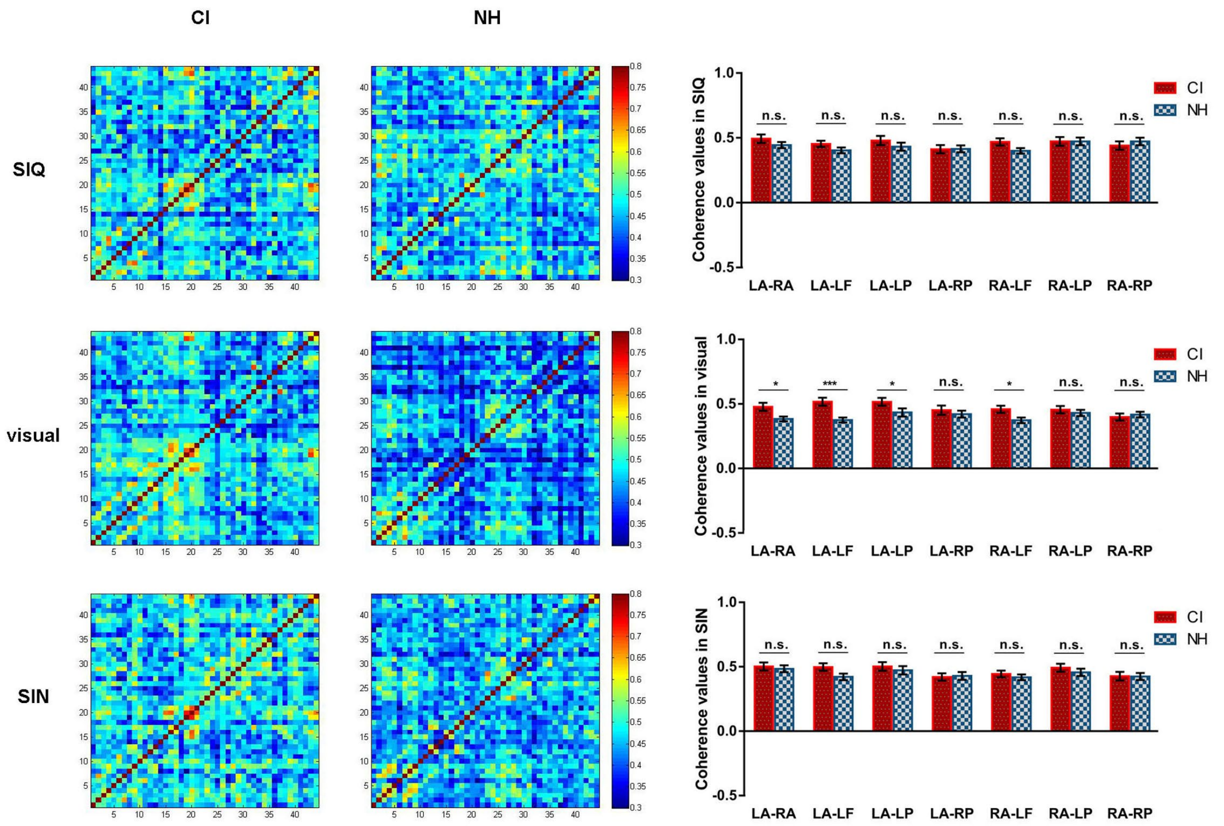

FIGURE 6
Differences in functional connectivity across all stimulus conditions between CI group and NH group. For each stimulus condition, the group-averaged coherence values of measuring channels are plotted separately for CI children (left column) and NH participants (middle column). The rightmost column shows the differences in coherence values for each ROI pair between the CI and NH groups. LA, LSTG; RA, RSTG; LF, LIFG; LP, LIPL; RP, RIPL. Error bars represent standard error of the mean. Significance is marked as follows: *p<0.05; ***p<0.001; n.s., not significant.

investigate cross-modal responses to visual speech preimplantation or to measure cortical changes from deafness to hearing recovery.

Recent research utilizing fNIRS have reported a comparable association between visual-evoked activation in the auditory cortex and speech perception with CI (Anderson et al., 2017; Mushtaq et al., 2020). In a longitudinal fNIRS study, Anderson et al. (2017) reported that enhanced visual cross-modal activation among individuals with CI correlated with better auditory speech understanding ability following implantation. However, unlike in the current study, Anderson et al.'s investigation included pre-lingually, peri-lingually, and post-lingually deaf adults, and the speech understanding was tested in the best-aided condition, which included hearing aids for many participants. Therefore, it remains unclear whether this association was driven by group disparities or residual hearing (Zhou et al., 2018). Mushtaq et al. (2020) subsequently investigated the activation of temporal cortex to visual and auditory speech stimuli in pre-lingually deaf CI children. The study confirmed that visual cross-modal plasticity provides adaptive benefits for restoring hearing with CI through an audiovisual mechanism. However, it remains uncertain whether the better speech skills in some pediatric CI users result from an innate ability to combine visual information with auditory input from birth or develop over time and with experience in those who already have good listening skills with CI.

Our findings fill in the gaps in this field and contribute to the existing evidence that a stronger visual processing ability in the auditory areas is positively related to successful CI outcomes (Jean-Luc et al., 2004; Strelnikov et al., 2013, 2015; Anderson et al., 2017; Mushtaq et al., 2020). Our study suggests that visual cross-modal reorganization was at least one of the neural bases of variable speech perception in pre-lingually deaf CI participants. Several potential reasons and mechanisms have been proposed to interpret the facilitative link between visual takeover of auditory brain regions and auditory speech understanding with CI. One possibility is an increase of the direct anatomical connection between visual and auditory cortical areas (Bizley et al., 2007; Chen et al., 2016) or a highly inherent correspondence between auditory and visual speech representations (Anderson et al., 2017). This supports the notion that CI users might become better at integrating auditory and visual speech cues as a compensatory mechanism (Mushtaq et al., 2020). Another proposal is that that vision may facilitate auditory perceptual learning by guiding top-down attention to auditory representations (Bernstein et al., 2013) or by assisting to decipher the degraded auditory speech when the incoming auditory signal is insufficient or in challenging listening environments (Strelnikov et al., 2009). Thirdly, it has been argued that the sensitive period for auditory processing should be viewed concurrently with the sensitive period for language processing (Lyness et al., 2013). Therefore, visual take-over of the auditory cortex after hearing deprivation could promote the development of language function in the critical period, which may be beneficial to the prognosis following CI (Lyness et al., 2013).

4.2. Intra-modal responses in CI users and in NH controls

We found that CI users processed auditory input similarly to NH children. Interestingly, further analysis revealed there was a stronger activation of STG in GCIs and a lower activation in PCIs, when compared to NH group. This is a little different from our experimental hypothesis and previous study (Olds et al., 2016) that the response of GCI should be similar to that of NH listeners to demonstrate "normal." The reason may be that GCIs required more neural activity to accurately decode degraded speech signals coded by a neuroprosthetic device than NH listeners did to decode natural speech signals (Yasushi et al., 2000; Mushtaq et al., 2020), while most PCIs may judge the process of decoding too difficult to succeed, resulting in decreased activity in auditory brain regions. Alternatively, perhaps the difference between pre-lingual and post-lingual deafness, or some other unknown factors led to this result. In any case, more research in this area is required to confirm this.

Our finding of a non-significant increase in STG responses to SIN compared to SIQ in both GCI and NH groups is consistent with the idea that greater neural activity in auditory regions was required in noise vs. quiet to maintain the same speech performance (Lawrence et al., 2021). However, for age-matched NH listeners, there was almost no difference between the noise condition of +10 dB SNR and the quiet condition, because the SRT of NH individuals is often lower than 0 dB SNR according to previous research (Chen et al., 2020). Furthermore, the +10 dB SNR condition was designed with high intelligibility where ceiling performance was presented in an adult fNIRS study (Defenderfer et al., 2021). This may also be the reason why the activation amplitude of STG or LIFG showed no significant distinction between these two conditions in the control group. On the contrary, in the cases of CI children, especially PCIs, both of the two auditory conditions were not easy for them, making them differ modestly in average score. We could infer that the lack of a significant difference in STG activation between the auditory conditions was due to the combined effects of lower speech recognition scores and higher neural activity under the noise condition in comparison to that under the quiet condition. Additionally, it is suggested that the intensity of the stimulus and the perception of the stimulus can play an important role in respect to the activation amplitude (Weder et al., 2018, 2020). Future work should also focus on identifying the mechanisms of brain activation by speech sounds with varying SNR.

While there were no significant differences in STG activation between LH and RH in either group, both the NH and GCI groups exhibited a tend of left hemisphere dominance when processing two levels of auditory stimuli. Additionally, a significant hemispheric lateralization was seen in the GCI group during their response to SIN. In contrast, PCIs did not show this similar left-hemispheric dominance for activation in STG. This seems supporting the finding of left-hemispheric dominance for language processing (Lazard et al., 2012; Paquette et al., 2015). Interestingly, a low-to-moderately positive correlation was demonstrated between between speech perception scores in CI children and STG responses to both SIQ and SIN, which implies that the STG is critical for auditory stimulus encoding and processing, as well as correlating with speech intelligibility (Pollonini et al., 2014; Olds et al., 2016; Lawrence et al., 2018; Mushtaq et al., 2021).

4.3. Potential cortical correlates of effortful listening

4.3.1. The role of LIFG In effortful listening

Previous research has identified frontal and pre-frontal cortical involvement in the processing of visual information in hearing loss (Rosemann and Thiel, 2018; Glick and Sharma, 2020). The current study also suggests that the LIFG showed significantly greater responses to visual sentences in the GCI group than those in the PCI and NH groups. The increased levels of LIFG activation to visual speech in GCIs might be due to a top-down mechanism to modulate visual cross-modal reorganization and speech perception outcomes. Similarly, PCIs and NH controls showed deactivation of LIFG in this condition, consistent with a lack of cross-modal reorganization. Alternatively, there may be a stronger task-related functional connection between LIFG and the auditory or visual regions in GCIs. Our data seem to support a prior finding from a PET study, which suggested that the deaf children who had developed greater executive and visuospatial functions subserved by the prefrontal cortex might be successful in auditory language learning after CI (Lee et al., 2005).

Additionally, we observed an obvious activation of the LIFG among GCIs when presented with SIQ and SIN stimuli, whereas the control group only showed slight LIFG activation in response to the SIN. The PCI group did not exhibit any LIFG activation in response to either the SIQ or SIN stimuli. As mentioned before, LIFG has been identified as one brain region potentially involved in effortful listening (Wong et al., 2008; Obleser and Kotz, 2010). This region supports the recovery of meaning from degraded speech or acoustically challenging speech by a greater level of top-down cognitive processing. The phenomenon is confirmed both in NH listeners (Sohoglu et al., 2012) and in hearing-impaired population with CIs (Sherafati et al., 2022). In our study, we chose an SNR of 10 dB, one reason is to correspond with the noise condition of behavioral test, and the other reason is that the average score of CI children was 50.6% in this condition, which was almost equal to SRT (defined as the SNR that produced 50% correct word recognition). However, the difficulty of speech recognition in the noise condition of +10 dB SNR for NH listeners was similar to that in a quiet environment, because speech scores in the two conditions were almost perfect. Previous studies have demonstrated that the SRT of NH individuals was far below +10 dB (the lowest SRT is −22.9 dB) (Chen et al., 2020) and speech in the +10 dB SNR condition was high intelligibility, with ceiling performance observed in NH adults (Defenderfer et al., 2021). This may be the reason why LIFG was not significantly activated in the control group under both the quiet and noisy conditions, or why no difference in LIFG activation was found in the control group between the two auditory conditions. Conversely, in cases of GCIs, greater activation of LIFG was possibly associated with more listening effort since they have to utilize more cognitive resources to effectively discriminate speech signals. Additionally, the slightly higher ERAs of LIFG to SIQ compared to the SIN in these children may be due to either suboptimal behavioral performance in quiet or the immature function of LIFG. The deactivation of LIFG for PCIs suggested that these individuals may identify the experimental trials as impossible and eventually "gave up" (Pichora-Fuller et al., 2016), like the response of the STG. Briefly, our results confirmed that the increase in LIFG brain activation may be a cortical marker for effortful listening, at least for CI children. Future work needs to set more different levels of SNR to validate the role of LIFG in recognizing degraded speech in children with CI and NH.

4.3.2. The role of IPL in effortful listening

Our data suggests that there were no significant differences in activation of IPL under all speech conditions between the CI and NH groups, or between the GCI and PCI groups. However, a global deactivation of this region was observed in response to each type of speech stimuli in both PCIs and NH participants. Conversely, in GCIs, we observed a global activation except for the LIPL response to SIN. It has been suggested that inferior parietal regions are part of the default mode network (DMN), which are preferentially more active during "rest" vs. engagement in an external task (Buckner et al., 2008), and the strength of deactivation within the DMN has been shown to correlate with task difficulty (Wild et al., 2012; Lawrence et al., 2018). Thus, we initially hypothesized that the level of deactivation may be greatest in CI group, particularly in GCI subgroup, similar to the activation trend of LIFG. Unexpectedly, the response patterns seemed to be completely different from what we expected. Indeed, IPL, beyond its role as an area of the DMN, is also known to be extensively involved in facilitating comprehension through the use of linguistic and semantic context (Obleser and Kotz, 2010; Golestani et al., 2013; Hartwigsen et al., 2015) and to form part of a functional fronto-temporal–parietal network supporting speech comprehension (Abrams et al., 2013). For instance, increased neural activity in IPL, especially in the angular gyrus of the left IPL, accompanies successful comprehension in challenging listening conditions (Bonner et al., 2013; Erb et al., 2013; Golestani et al., 2013; Clos et al., 2014). The precise role of bilateral IPL in this study is unknown. It seems likely that both deactivation of the DMN network and activation of the speech comprehension network may contribute to the response patterns in bilateral IPL in the current study because we could not explain the results using only one of networks. As such, further work is needed to clarify the role of IPL involvement in visual cross-modal reorganization and speech intelligibility among the hearing-impaired population.

4.4. Functional connectivity

We observed that CI children exhibited significantly higher task-related functional connectivity for visual stimuli than NH children in the main ROI pairs, particularly between the interhemispheric auditory cortex, between the auditory region and LIFG, as well as between the left auditory area and LIPL. This indicates that CI users rely on more networks than NH controls when processing visual sentences, which involve areas such as STG, LIFG, and LIPL. In a prior fNIRS study, Fullerton et al. (2022) examined cross-modal functional connectivity between auditory and visual cortices in a sample of post-lingually deaf CI adults and age-matched NH controls. They demonstrated that CI users had greater cross-modal functional connectivity between left auditory and visual cortices for speech stimuli, irrespective of the type of sensory modality, compared to NH controls, and that cross-modal functional connectivity for visual speech was positively correlated with CI outcomes. They thus concluded that CI adults with post-lingual deafness may be able to engage a distributed, multimodal speech network to improve speech understanding. Our research revealed enhanced task-related connectivity in response to visual stimuli when compared to NH participants, corroborating Fullerton et al.'s (2022) findings. This provides further evidence that CI users may have improved multisensory integration and more extensive neural networks for speech or language processing. Finally, this multimodal interaction reinforces our previous cortical activation analyses that showed increased responses in fronto-temporal–parietal regions, particularly superior cross-modal activation in temporal regions by visual speech among proficient CI children. Regrettably, the optode configuration of fNIRS did not include the visual cortex in our study, preventing us from analyzing different functional networks that involve visual brain regions. Perhaps there is no direct functional connection between auditory cortex and frontoparietal areas; instead, cortical activation and coherence values may reflect responses in another functional network, such as the connections between visual cortex and auditory regions or between visual cortex and the frontoparietal network In the future, it will be necessary to further explore the activity of different functional networks during speech processing in pre-lingually deaf CI children, which should include but are not limited to visual cortex, auditory cortex, and frontoparietal areas.

4.5. Potential applications in clinic

Restoring a deaf person's ability to recognize and distinguish auditory speech is the primary objective of the surgical implantation of CI. As indicated before, a number of variables, including age-at-onset, duration of deafness prior to implantation, age-at-implantation, and duration of CI use, can affect speech outcomes in CI users (Tomblin et al., 2005; Lin et al., 2008; Niparko et al., 2010; Tobey et al., 2013). However, in our study, only age-at-implantation was negatively correlated with CI outcomes. This result supports the previous theory that such known variables can explain only a small portion of the variance in CI speech outcomes, leaving a considerable portion unexplained (Niparko et al., 2010; Geers et al., 2011). It is worth noting that the relationship between age-at-implantation and speech performance with a CI is weak ($r = -0.346$); therefore, it may be inaccurate to rely solely on this variable to predict speech outcomes following implantation. Our current findings in a group of pre-lingually deaf CI users suggest a strong correlation ($r = 0.764$) between cortical activation of STG in response to visual speech and speech understanding ability with a CI, even after controlling the confounding variables. Additionally, cortical activation of the LIFG could serve as a potential cortical marker for effortful listening in CI children. In summary, fNIRS-based measurements of cortical activation, particularly the cross-modal responses of STG, may provide objective, additional value to help with a more precise prognosis of CI outcomes. Furthermore, using these neuromarkers in combination with behavioral speech understanding tests is also more beneficial and efficient to guide post-implant programming, modify rehabilitation training strategies, and assess speech performance, especially for infants and children.

4.6. Limitations

One limitation is that although comparable speech materials were used in both the behavioral speech understanding test phase and the neuroimaging phase to avoid training effects, our inference of trial accuracy in the neuroimaging phase based on the behavioral results is not accurate enough. In addition, our paradigm does not allow us to differentiate brain activation between correct trials and incorrect trials or to investigate the correlation between the levels of cortical activation and response time. Future studies should explore the speech recognition accuracy in the neuroimaging phase and its effects on cortical activation in the temporal, frontal, and parietal cortex of individuals with hearing loss, both with and without hearing devices. Another noteworthy limitation is that the optode configuration of fNIRS used in our study did not include the visual cortex, preventing us from examining the functional connection between visual regions and auditory regions or other brain regions. There are also some limitations to using fNIRS as a diagnostic tool, despite its positive attributes, as discussed in the previous paragraph. One major drawback is that fNIRS can only image superficial regions of cortex in humans due to its shallow imaging depth. Furthermore, scalp thickness may interfere with the ability of fNIRS to accurately image cortical activity. Additionally, not all participants are able to tolerate the discomfort or tightness caused by the fixation of optodes, making fNIRS imaging impossible in some cases.

5. Conclusion

In conclusion, the current fNIRS study revealed that: (1) compared to PCIs or NH controls, the temporal regions exhibited significantly greater activity to visual speech in GCI group; (2) an increase in activation of auditory brain regions to both auditory and visual speech in CI users were directly correlated to auditory speech understanding ability, with the strongest positive association between cross-modal brain plasticity and CI outcome; (3) beyond STG, brain activation of LIFG would be associated with a top-down modulatory mechanism to visual cross-modal reorganization and recovery of meaning from degraded speech; (4) the precise role of neural activity in inferior parietal regions was unclear, perhaps referring to both deactivation of the DMN and activation of the speech comprehension network. We suggest that cross-modal reorganization in auditory cortices may be at least one of the neural bases of highly variable CI performance due to its beneficial effects for speech understanding, thus supporting the ability to predict and assess CI prognosis, and that cortical activation of the LIFG may be a cortical marker for effortful listening. According to our research, fNIRS can identify functional brain differences between CI users and NH listeners that are associated with their auditory speech understanding following implantation. As a result, fNIRS may have the potential to be used in the clinical management of CI candidates and users, either in evaluating speech intelligibility objectively at the cortical level or in directing rehabilitation strategies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethical Committee of Chongqing General Hospital. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

X-QZ: experimental design, fNIRS paradigm writing, data collection, data processing, and manuscript writing. Q-LZ: neuroimaging data collection. XX: fNIRS test materials provision and fNIRS stimuli editing. M-RL, HL, SL, and TZ: behavioral data collection. WY: experimental design, project implementation management, and manuscript review. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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A review of auditory processing and cognitive change during normal ageing, and the implications for setting hearing aids for older adults

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Throughout our adult lives there is a decline in peripheral hearing, auditory processing and elements of cognition that support listening ability. Audiometry provides no information about the status of auditory processing and cognition, and older adults often struggle with complex listening situations, such as speech in noise perception, even if their peripheral hearing appears normal. Hearing aids can address some aspects of peripheral hearing impairment and improve signal-to-noise ratios. However, they cannot directly enhance central processes and may introduce distortion to sound that might act to undermine listening ability. This review paper highlights the need to consider the distortion introduced by hearing aids, specifically when considering normally-ageing older adults. We focus on patients with age-related hearing loss because they represent the vast majority of the population attending audiology clinics. We believe that it is important to recognize that the combination of peripheral and central, auditory and cognitive decline make older adults some of the most complex patients seen in audiology services, so they should not be treated as "standard" despite the high prevalence of age-related hearing loss. We argue that a primary concern should be to avoid hearing aid settings that introduce distortion to speech envelope cues, which is not a new concept. The primary cause of distortion is the speed and range of change to hearing aid amplification (i.e., compression). We argue that slow-acting compression should be considered as a default for some users and that other advanced features should be reconsidered as they may also introduce distortion that some users may not be able to tolerate. We discuss how this can be incorporated into a pragmatic approach to hearing aid fitting that does not require increased loading on audiology services.

KEYWORDS

ageing, cognitive performance, hearing aids, auditory processing, compression speed, compression ratio, noise reduction

1. Introduction

In this review paper, we highlight the importance of recognizing the effects of normal ageing on hearing aid fitting because it has a considerable impact on an individual's understanding of speech and ability to benefit from hearing aids. Auditory processing and cognition decline throughout early, middle and late adult life and undermine our ability to hear in all types of listening situations. "Normal ageing" refers to non-pathological changes in cognition and auditory ability with age (1). We do not discuss pathological changes with age such as mild cognitive impairment or dementia. Whilst considerable research efforts continue to be deployed to understand the association between hearing loss and dementia, we believe it is particularly important to address normally-ageing older adults because they represent the vast majority of patients attending audiology clinics. In the UK National Health Service (NHS), older adults (over 55 years of age) represent 78% of adult audiology attendances and 87% of those fitted with hearing aids (2); and reported hearing problems appear more strongly associated with age than the degree of peripheral hearing loss, which suggests that processes other than peripheral hearing play a role (2, 3). For the purposes of this review we define "peripheral" changes as those restricted to the outer, middle and inner ear and auditory nerve. We define "central" changes as those within the central auditory nervous system, from the level of the cochlear nucleus up to the cortex, which includes elements of cognition. The aim of this review is to determine the relevant factors in auditory processing and cognition that might have implications for the way in which we set hearing aids, and to define the best approach to setting hearing aids for normally-ageing older adults based on the evidence in the literature. Whilst we do not discuss the relationship between hearing and dementia, it is likely that any recommendations regarding setting hearing aids for those with reduced degrees of cognition due to normal ageing will be particularly applicable to those with pathological cognitive decline.

We first provide a brief review of age-related change to central auditory processing and how this alters dependence on different elements of speech (Section 2). We then offer a short review of the basic concepts of cognitive change with age (Section 3), and how a decline in some elements of cognition also alters speech perception, particularly undermining listening in more challenging circumstances (Section 4). This understanding then enables us to determine how hearing aid parameters and fitting procedures might affect older adults' listening ability. In Section 5, we derive a set of evidence-based principles for fitting hearing aids to older adults, and assess specific hearing aid parameters against these principles. We review evidence for an association between some elements of cognition and the benefit, or increased impairment, that may be caused by hearing aid processing strategies. We particularly focus on evidence that addresses the benefit, or harm, caused by fast or slow-acting compression speeds for those with different degrees of cognition. We also assess why the evidence may not always appear consistent. We then offer a discussion of how one might determine practical fitting guidelines for audiologists who predominantly see older adults in clinic (Section 6). Finally, we discuss gaps in the current evidence-base and what further research might be needed (Section 7).

2. The effects of ageing on auditory processing

The central auditory nervous system (referred to simply as the "auditory system" in subsequent text) is a uniquely complex sensory network, engaging peripheral sensory organs, multiple processing layers in the brainstem, the auditory cortex and wider cortex, culminating in conscious perception and understanding, as well as extensive "top-down" control. The processing of different aspects of speech is distributed across the auditory system. For example, some neurons are tuned to overall amplitude modulation from lower to higher levels of the system (4) and others are phase-locked to periodic patterns in the acoustic detail of speech (5, 6). Segregating and grouping sounds depends on multiple binaural processes from the cochlear nucleus up to the cortex, dependent on effective neural synchrony (7). Multiple pathways in the cortex, largely between temporal and frontal lobes, support a hierarchical process of word recognition, integration into phrases and sentences, syntax (grammar) and semantics (meaning) (8–10). Higher-level processes also depend on the relevance of sounds and lower-level processes can be enhanced via top-down control, enabling selective processing (11).

Age-related changes to the underlying neural infrastructure cause progressive "central" auditory deficits with increasing age (1, 12–17). As "lower" and "higher" level processes are interrelated, the effects of peripheral and central decline can be difficult to dissociate. Age-related cochlear damage generates a degraded input to the auditory system. The degraded nature of the input is exacerbated by the loss of synapses and auditory nerve fibers, often referred to as "hidden hearing loss." This synaptic loss particularly affects fibers that are sensitive to louder sounds and may particularly impair speech-in-noise (SIN) perception (18–20). With increasing age there is a general reduction in the density of connections in the brainstem and cortical structures involved in auditory processing (14, 21). A deterioration in brainstem structures and the cortex impairs timing information, gap detection, localization, spectral processing and efferent control of the hair cells (22–25). These combined changes can undermine auditory scene analysis, impair an individual's ability to attend to a target speaker (26) and reduce the ability to distinguish elements of speech in quiet (SIQ), non-familiar accents and SIN (27, 28).

Temporal information in speech cues can be differentiated across a number of frequency bands (29): information about the speech envelope (ENV) is carried primarily in the frequency band below 50Hz; information about voicing and periodicity primarily in the frequency band between 50 and 500Hz; and information about temporal fine structure (TFS) in the frequency band above 500Hz. ENV and TFS are the most important cues forming the basis of speech perception, frequency perception and localization (30). However, for those with sufficient hearing, ENV and TFS provide redundant cues that support processing of the speech signal (31). A difference in the pitch of voicing helps differentiate individuals in multi-talker situations (32). Vocoder experiments that replaced TFS with a carrier signal or noise, which was modulated by ENV, demonstrated that only a small number of frequency bands are required for successful speech perception in quiet even when TFS was lacking (33). However, the same was not true when speech was presented in a noisy background. Adding back TFS to a signal progressively improved SIN performance (34, 35). The ability to make use of ENV with little TFS can also be evidenced by the success of cochlear implants, which provide a grossly reduced representation of spectral detail (29, 36). Besides supporting speech perception in noise (36–38), TFS also supports binaural localization and separation of competing sounds (39), perception of pitch and music (29, 30) and perception of motion (40). Individuals with peripheral hearing impairment cannot make good use of TFS which can lead to difficulties hearing in noisy situations (41).

Comparisons between young and old listeners with matched normal hearing, intelligence and education suggest that speech perception declines with age, demonstrating a greater effect than can be predicted by hearing thresholds (3, 42–44). Monaural TFS sensitivity declines constantly throughout early-to-late adulthood (45), whereas monaural processing of ENV is less affected (46, 47). Binaural processing of both TFS and ENV declines with age, although declining TFS sensitivity has some association with the degree of hearing loss whereas the association between ENV sensitivity and hearing loss is weak (46, 47). Besides TFS, cognitive performance has also been found to predict speech perception. Although both TFS sensitivity and some cognitive domains decline with age, they do not appear to be directly related to each other once the effect of age is removed (48). TFS sensitivity was found to be a stronger factor than cognitive ability and ENV sensitivity in predicting speech perception in quiet for normal hearing listeners, and cognition the stronger factor for predicting performance in noise (3). Reduced SIN perception with increasing age can be more generally associated with reduced cognitive abilities (49), reduced coding accuracy and TFS sensitivity (50, 51), poorer binaural processing (52) and sound segregation (26). Sensitivity to periodicity perception also declines with age, affecting the perception of intonation (53), discrimination of voicing (54) and the emotional content of speech (55, 56). Some elements of speech perception are therefore specific to auditory processing, whereas others are dependent on domains of cognition not specific to auditory processing.

3. Cognitive change during normal ageing

"Cognition" refers to the processes of acquiring, retaining and using knowledge (57) and has many constituent elements, including reasoning, memory, speed, knowledge, reading, writing, maths, sensory, and motor abilities (58). One can differentiate cognition from auditory processing because the latter is specific to the analysis of sound, whereas the former is not. Whilst the auditory system processes sound, cognitive processes develop meaning and understanding from the sound. However, it should be recognized that this is a simplistic description because of the inter-related nature of the systems which together deploy "bottom-up" and "top-down" processes. Some elements of cognition decline with age, but some remain stable or improve (59). Cognitive abilities can be separated into two basic domains (60, 61): "fluid intelligence," characterized as the speed and ability to resolve problems in novel situations; and "crystallized intelligence" that is an accumulation and use of skills, knowledge and experience. Fluid intelligence generally peaks at about 20 years of age and declines at a consistent rate throughout adult life, whereas crystallized intelligence increases with age. As a result, an individual's overall performance in psychometric tests of intelligence remains largely stable through most of adult life (60, 62). It should be noted that the range of ability between individuals also increases with age (21, 60, 63) so age alone is not a good measure of specific elements of cognitive function. Individuals of different ages may therefore perform equally well at a complex task, but may be using a different blend of cognitive abilities to complete the task based on the strength of different cognitive domains (64). Accordingly, an overall measure of "general cognition" is not a useful concept when considering a specific complex task, such as listening. Cognitive reserve, developed through education and other lifetime experiences, appears to provide some individuals with greater resilience against cognitive decline (65). This, and other genetic, environmental, health and lifestyle factors, will mediate any cognitive change with age (63) and an individual might further modify function via cognitive training and physical exercise (66). In short, it is important to determine the specific elements of cognition that relate to different tasks rather than make any assumption of homogeneity amongst an age group.

Several theories have been proposed to describe the process of decline in some cognitive abilities. The processing-speed theory (67) suggests that a decline in speed results in processes failing to complete in time to be useful, and that slower processes reduce the amount of available processing capacity. A reduction in processing capacity, caused either by a reduction in processing speed or by other processes of decline, could undermine episodic memory (recollection of personal experiences) and the initiation of more complex processes (68). Note that episodic memory declines more with age compared to semantic memory (recollection of facts) and procedural memory (unconscious performance of tasks) (59). A second theory suggests that there is a limit on the amount of processing resources (69). Based on this idea, Baddeley & Hitch (70) introduced the concept of "working memory" (WM) as a system that stores and processes information relevant to a current task. A third theory postulates that an age-related failure to filter out irrelevant information is the cause for WM to become "cluttered," thus reducing available capacity (71). Each of the individual theories cannot explain all of the features of cognitive decline and it is likely that there are multiple processes with cumulative effects (59).

One way to categorize the basic concepts of fluid and crystallized intelligence into further subtypes of cognition, particularly useful in relating specific processes to speech perception, is provided by the Cattell-Horn-Carroll model (72, 73) (Figure 1). The model describes a three-level hierarchy of cognitive abilities: general ability, broad domains and narrow domains. Broad domains are basic characteristics that manage a range of behaviors. Narrow domains are highly specialized and may be specific to certain types of task. Auditory processing (Ga) is included as a broad domain in the CHC model (Figure 1). Some elements of overall sound processing and perception are specific to Ga, whereas some elements rely on other narrow domains. Note that the generalized concept of fluid intelligence is not specifically shown in the model, but includes most of the broad domains of the model, i.e., those other than crystallized intelligence (Gc). Nevertheless, in general terms, abilities in the wide domain of fluid intelligence are those that tend to decline with increasing age.

Note that ongoing refinements to the model introduce further broad and narrow domains beyond those shown here (72). Episodic memory is contained within the definition of learning/encoding efficiency (Gl) in the CHC model (Figure 1) (73). Executive function is not commonly included in the Cattell-Horn-Carroll model and

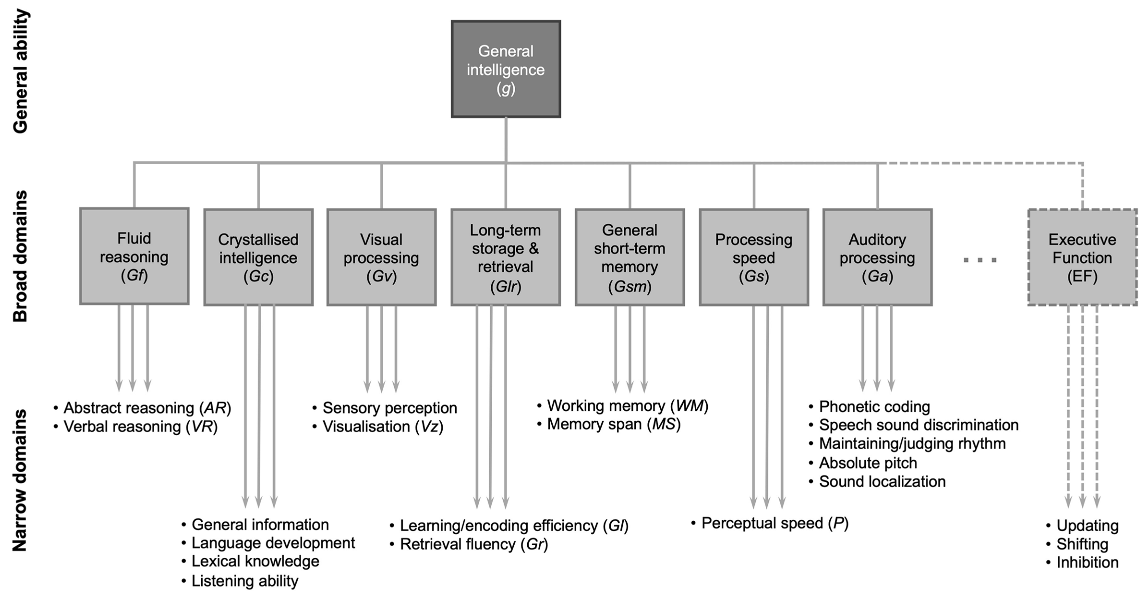

FIGURE 1
A partial representation of the Cattell-Horn-Carroll (CHC) theory of cognitive abilities showing general intelligence (*g*) consisting of broad domains of cognitive function, under which there are narrow domains that can be assessed with specific tests. Figure developed from (72, 73). Note that there are a greater number of broad domains and the narrow domains shown are only selected examples of those in each broad domain (24).

there is no clear consensus on its definition (73). It may be thought of as a cognitive "control" function that mediates narrow domain abilities, although its three core elements may be considered as separate domains that: enable "shifting" between tasks; monitoring tasks and "updating" WM as necessary; and "inhibiting" other tasks or automated responses in order to complete a task (74).

4. The effects of cognitive change on speech perception

In this section we focus on the elements of cognition that may underlie impaired listening ability. Not enough is currently known about how specific narrow domains of cognitive ability (Figure 1) relate to auditory performance in specific listening situations. However we do know that WM often plays a role and is frequently associated with SIN performance (75, 76), understanding fast speech (77) or with general auditory performance across a range of tasks (78, 79). WM is more predictive of SIN performance in older age groups compared to younger groups (80) or in more challenging conditions, such as a lower signal-to-noise ratio (81). Older adults with greater WM resources may be better able to adapt to difficult listening situations (78, 82). WM is often used as a broad term and encompasses both storage and processing-dependent WM tasks. These different types of tasks can have different associations to different types of listening situations (75, 83–85). Executive function is another cognitive factor that is often associated with listening and the degree of listening effort (86). Inhibition, which a sub-domain of executive function (Figure 1), and processing speed are also cognitive functions associated with reduced auditory performance (87–89). Different domains of cognition appear to be more strongly predictive of listening ability for more difficult listening tasks (90, 91). A meta-analysis (92) provided an overview over various cognitive functions and their association with different SIN tasks. It showed that SIN performance correlated with measures of processing speed ($r = 0.39$), inhibition ($r = 0.34$), WM ($r = 0.28$), and episodic memory ($r = 0.26$). These are all narrow cognitive domains that deteriorate throughout adulthood (62, 67, 68, 71, 93) and their effects may be, in part, additive.

One consequence of the changes to hearing and cognition may be an increase in effort when listening (94, 95). Listening effort is defined in the Framework for Understanding Effortful Listening (FUEL) (96) as an allocation of cognitive resources to overcome listening obstacles. It is a finite resource and its capacity will be expended at different rates dependent on the inherent difficulty of a task and an individual's motivation to overcome obstacles in listening. Listening effort likely engages multiple neurological systems (97) and is an important factor in speech perception. It should be considered in the context of age-related cognitive decline because it may also affect the motivation of individuals to comply with treatment or engage socially (98, 99). In addition, hearing aids have the potential to reduce, or increase, listening effort (100–104).

The relative importance of hearing loss, auditory processing and cognitive function for predicting overall auditory performance will depend on the specific listening situations encountered (76), which will vary in real-life (105). Different forms of SIN test engage different narrow cognitive domains (92). SIN tasks can be distinguished according to the target and masker signal, and both of these affect the type of processing needed for successful listening (92). The type of masking noise has a considerable effect; individuals perform better in steady-state noise compared to multi-talker babble and the latter yields stronger associations with cognitive function (85, 92, 106–108). An intelligible masking signal provides both energetic and informational masking, and is most likely to divide the attention of a listener, offering the greatest cognitive challenge (75), although other cues such as the different gender or fundamental frequency of the signal and noise source can overcome some effects (109).

A number of speech models have attempted to conceptualize the role of different cognitive functions within the pathway of speech understanding. Gordon-Salant et al. (21) adapted a theoretical model (110) to describe a bottom-up process of hierarchical signal processing. The "sensory system" undertakes spectral and temporal processing to discriminate between sound sources. This is further refined by the "perceptual system," employing inhibition to direct attention, and the "cognitive system" that analyses and identifies words, and develops meaning, feeding back to lower levels of the system, requiring processing speed, WM capacity and semantic knowledge, also engaging long-term memory (Glr). The model by Bronkhorst (11) is broadly similar in principle and highlights the role of attention control, an element of executive function, in which attention is triggered by certain signal characteristics, that then engenders selective processing at lower levels, or "pre-attentive" stages, of the auditory system. The Ease of Language Understanding (ELU) model (111, 112) largely focusses on situations in which there is conflict between an input signal and lexical information stored in memory, e.g., due to an unusual accent, which then requires engagement of a feedback loop to resolve it, particularly requiring WM, executive function and learning/encoding efficiency. Taken as a whole, these models highlight the critical dependence of listening on certain specific narrow cognitive domains. However, given that research studies cannot assess all real-life listening situations, one cannot conclude that these are the only cognitive domains of relevance, but that they represent those most commonly measured in the context of the limited listening tasks employed in studies, and there may well be other confounding factors such as alternative cognitive strategies that individuals use to compensate (64). The models also highlight that poor fidelity of the input signal (via hearing loss or inappropriate hearing aid processing) can cause greater conflict in resolving speech and, ultimately, a failure to do so. Overall, the models support the finding that speech intelligibility is associated with processing speed, inhibition, WM and long-term storage and retrieval (92) and will consequently decline with age as these narrow cognitive domains deteriorate. It should also be pointed out that a decline in some cognitive domains will not only undermine speech intelligibility, but may also impair the perception of speech quality (113), even where intelligibility is unaffected (114), and undermine an individual's perception of aided speech.

In summary, certain narrow cognitive domains (Figure 1) will be associated with different types of auditory task. A wide array of cognitive tasks are employed across different studies (92), so the presence and strength of associations between cognition and auditory performance will depend on the narrow cognition domains assessed and the task used to assess them, as well as the type of auditory task, its level of difficulty, the type of stimulus, noise and other cues used (64, 115), the degree of context, vocabulary and visual cues (116–118). Furthermore, there is an association between hearing loss and cognitive decline (119) that may act as a confound in studies. Sensory impairment can affect an individual's performance on cognitive tests, often requiring recall of spoken words or text-based tests, dependent on hearing and vision, so that it is possible that this causes falsely enhanced associations (61, 120, 121). It may therefore be considered unsurprising that the outcomes of research studies are not wholly consistent because they do not employ consistent paradigms.

5. Implications for hearing aid fitting

5.1. Principles

The preceding sections have summarized the effects of ageing on peripheral hearing, auditory processing and cognition. It is now important to determine which of these factors are relevant to hearing aid fitting and how some signal processing strategies may create benefit or impediment for individuals with differing degrees of cognition and auditory processing. The "optimum" hearing aid fitting should not solely consider peripheral hearing loss, but should aim to deliver maximum benefit over time, considering hearing loss, auditory processing, cognition and non-auditory factors that affect an individual, their perception of treatment and ability or intention to comply with it. For example, no amount of fine-tuning of a hearing aid's gain will deliver benefit if there is a perception of unacceptable distortion or if individuals feel unable or unwilling to use their hearing aids. As a result, too many hearing aids remain under-utilized or unused (122). Selection of hearing aid parameters must take all of these factors into account.

Hearing loss degrades the fidelity of the input to the auditory system, undermining its ability to take advantage of temporal and spectral cues and requiring additional effort to resolve mismatches. It is unreasonable to expect that hearing aids can fully restore this input (123). Hearing aids can only address some of the loss in peripheral sensitivity. They cannot directly improve elements of auditory processing or cognition, but they may enhance the signal-to-noise ratio or suppress noise that might distract from the signal or increase listening effort. However, some hearing aid settings may significantly degrade the input signal in ways that hamper auditory processing, undermine speech perception or listening comfort, and increase listening effort (124, 125). The primary role of audiologists should be to address the concerns of, and provide benefit to, the individual patient, so it is important that the patient is given the opportunity for input and that these signal enhancement principles are understood and alternative settings considered (126). In general, hearing aid users with greater cognitive ability appear to benefit more from hearing aids (127). It is therefore important to derive some clear evidence-based principles for hearing aid settings for older adults. Accordingly, for those older adults with reduced auditory processing and cognitive abilities in relevant narrow domains, we can state the following principles based on the preceding review:

1. Older adults will generally be more dependent than younger adults on ENV for speech perception, which is less impaired than TFS with increasing age for monaural listening (46, 47, 128). Older adults will therefore be more susceptible to ENV distortion (124, 129). A primary aim of hearing aid fitting should therefore be to ensure that speech is audible but with minimal distortion to ENV (130).
2. Given that a reduced temporal accuracy with age undermines gap detection (23, 131), quiet gaps between elements of speech should be maintained.

3. Binaural processing of TFS and ENV is degraded with age (46, 47, 52) and impairs interaural level difference (ILD) and interaural time difference (ITD) cues (23, 132). Use of bilateral hearing aids should not further disrupt theses cues, e.g., via fast gain changes that particularly diminish the aided level difference.
4. Reduced binaural processing makes older adults more susceptible to binaural interference (132, 133). There is evidence that some individuals may perform better in noisy situations with a unilateral aid (134) although this is not consistent across studies (135). Unilateral aiding should be considered where there is any indication of binaural interference (136). There should not be a presumption that bilateral aiding is best in every case.
5. General impairment of SIN performance with age (21, 27, 49) indicates a need to improve the signal-to-noise ratio through the use of directionality.
6. Introducing distortion to ENV may increase listening effort and diminish the capacity for listening (100–103). Hearing aid processing should aim to minimize cognitive load and listening effort (86, 96) by avoiding unnecessary distortion to the speech signal, loudness discomfort or other perceptual sound difficulties. Noise reduction settings should be considered (104).

These principles should not be regarded as novel in any way. Directionality has been employed for many years in analogue and digital hearing aids. However, since the inception of digital hearing aids it has been suggested that audiologists should pay greater attention to the distortional aspects of hearing aid processing, rather than solely considering the amplification needed to correct peripheral hearing loss (137, 138). This has also previously been applied specifically to hearing aid fittings for older adults (130). It has long been recognized that hearing aid settings, the associated aided speech recognition and overall satisfaction will be, in part, dependent on cognitive ability (139–141) and that different hearing aid processing strategies will have different advantages and disadvantages for individuals with varying degrees of cognitive function (96). The following sections will consider various hearing aid parameters, how they affect the principles above, and the effect of cognitive change on the fitting process.

Before doing so, it is worth considering more carefully what is meant by "distortion." In simple terms, distortion can be defined as any non-linear change from the original signal, although the inherent purpose of hearing aids is to modify sound. Multiple signal processing strategies alter speech signals in many ways and it is not a straightforward exercise to measure distortion across its different forms (142), and even less so to equate any measure of disruptive distortion to the perception of a hearing aid user. For example, if one were to measure the distortion introduced by compression, one is immediately faced with the issue of how to combine a measure of change to ENV and a measure of change to TFS, and whether these have detrimental effects after processing in the auditory system. Korhonen et al. (143) suggested a method of assessing modulation in frequency bands, but this only evaluates changes to ENV. Hearing aids introduce multiple sources of distortion and widely-available test box measures, such as total harmonic distortion, are unrepresentative of the overall distorting effects of a hearing aid on the speech signal. The loss of differentiation between the modulation of the speech signal and that of a competing talker or background noise when they are compressed together in a hearing aid is known as "cross-modulation." This undermines the auditory system's ability to separate sounds because shared modulation will be interpreted as originating from a single source (144), and can be considered as a loss of information from the original signal. There is more recent evidence that, for complex speech signals, the auditory system uses the interaction between modulations in the frequency and time domains, known as "spectrotemporal modulation," which is an important determinant in speech intelligibility. Spectrotemporal modulation is undermined by a combination of reduced frequency-tuning and TFS sensitivity (145, 146), although it is unclear how it is distorted by hearing aid processing (147).

There have been numerous initiatives that have attempted to quantify overall distortion and relate it to speech intelligibility and perceived quality; see Kates and Arehart (148) for a summary. Perhaps most promising are the Hearing Aid Speech Perception Index (HASPI) and the Hearing Aid Speech Quality Index (HASQI) (148). These are neural-network models incorporating assumptions of peripheral and central auditory processes, then fit to measurement data for hearing impaired and normal-hearing listeners. The models offer clear differentiation in quality and intelligibility between hearing aids from different manufacturers and between different hearing aid settings (149). It is therefore possible that HASPI and HASQI could become clinical tools that can be used to evaluate distortion. However, to be most useful they would need to be validated against different patient groups because optimal settings are likely dependent on an individual's cognition or other factors. Moreover, even after validation, there may remain considerable variation between individual preferences. Likewise, it is unclear what trade-off there should be between intelligibility and quality scores, or how this would be determined on an individual basis.

5.2. Compression speed

Reducing the dynamic range of sound to match that of a hearing-impaired person, i.e., compression, is a fundamental feature of digital hearing aids. Hearing aids filter sound into frequency bands, or frequency channels, such that different degrees of compression, and other types of processing, can be differently applied within each channel. Wide-dynamic range compression (WDRC) with short time constants, or fast-acting compression (FAC), was employed to enable exaggeration of quieter syllables or phonemes within words by quickly applying greater gain, so is often referred to as "syllabic compression." This type of compression is based on the fact that some elements of speech may be inaccessible to a hearing-impaired listener, typically high-pitched fricatives for those with a high-frequency hearing loss. FAC aims to restore normal loudness perception across the frequency range (150). Hearing aids with slow-acting compression (SAC) enhance high-frequency sounds solely via the application of different amounts of gain in each frequency channel. In practice, most systems employ similar attack times (1–10 ms), which was to protect patients from sudden loud sounds (150), so "fast" and "slow" hearing aids are largely differentiated by the release times (151). FAC is usually characterized by attack times of 0.5–20 ms and release times of 5–200 ms, whereas the release times for SAC are typically between 500 ms and 2 s (150). The instantaneous gain for any input level and frequency will accordingly be determined by both the gain settings for quiet and loud input levels (i.e., that which should be applied for a long-duration sound) and the compression speed (i.e., whether the aid reacts fast enough to reach the gain setting). It should be recognized that simply comparing fast and slow compression speeds is a simplification. There are various approaches to the implementation of compression speeds in hearing aids that may be applied differently by frequency channel, by direction of change in sound intensity (150), or adaptive systems that change compression speed by acoustic situation (152–157). Furthermore, fast-acting impulse noise protection may be employed as a separate system to WDRC, although the details of these approaches are usually proprietary (158).

FAC can be interpreted as contravening many of the principles suggested above for individuals with reduced degrees of cognitive function. In general terms, FAC has the effect of "flattening" ENV, whereas ENV is preserved by SAC (Figure 2) (150, 159). FAC may therefore impair speech perception by changing the speech signal in a number of ways: distorting speech envelope cues; amplifying the noise in gaps, undermining gap detection; and reducing modulation detection that enables separation of individual speakers (150, 160–166). FAC might also impair sound localization based on interaural differences, although the evidence for this is weak (167). FAC also impairs localization of sounds in reverberant conditions (168). Even in quiet situations, increasing the number of frequency channels, as is typically deployed in almost all hearing aids, reduces the spectral contrast of vowels and associated speech intelligibility with FAC (159, 169). Proponents of FAC contended that listeners cannot be aware of contrasts in amplitude if a signal is presented below the threshold of the cochlea at a particular frequency (170). However, this argument was largely based on evidence from two-channel systems. In modern multi-channel hearing aids, increasing the number of channels increases the amount of distortion when using FAC (159). Hearing aid users prefer fewer channels when FAC is used, whereas the number of channels does not make a difference with SAC (159). In principle, FAC should only be employed to make weak phonemes audible in quiet conditions for those with mild-to-moderate degrees of hearing loss (171) and does not offer benefit in noisy situations (151, 172). Overall, those with greater degrees of hearing loss tend to benefit less from FAC (173). In truth, to make a proper comparison between FAC and SAC, one should consider the speech signal as presented to the auditory system after processing via the cochlea. As we are unable to do this in humans, we must seek to determine objective or subjective measures of performance from the patient population, such as performance in speech intelligibility tests or self-reported benefit and satisfaction. Other evidence can be sought from animal models in which neural responses can be measured with hearing aid-processed sound (174), suggesting that FAC acts to undermine spectral and temporal contrasts, leading to a failure to restore consonant identification in quiet. Computational models of the auditory system might also be used to assess the effects of different hearing aid processing strategies. These suggest that slow compression leads to a greater restoration of the neural representation of speech than fast compression (175). The HASPI-HASQI model, discussed above, can be employed to compare intelligibility and quality in different

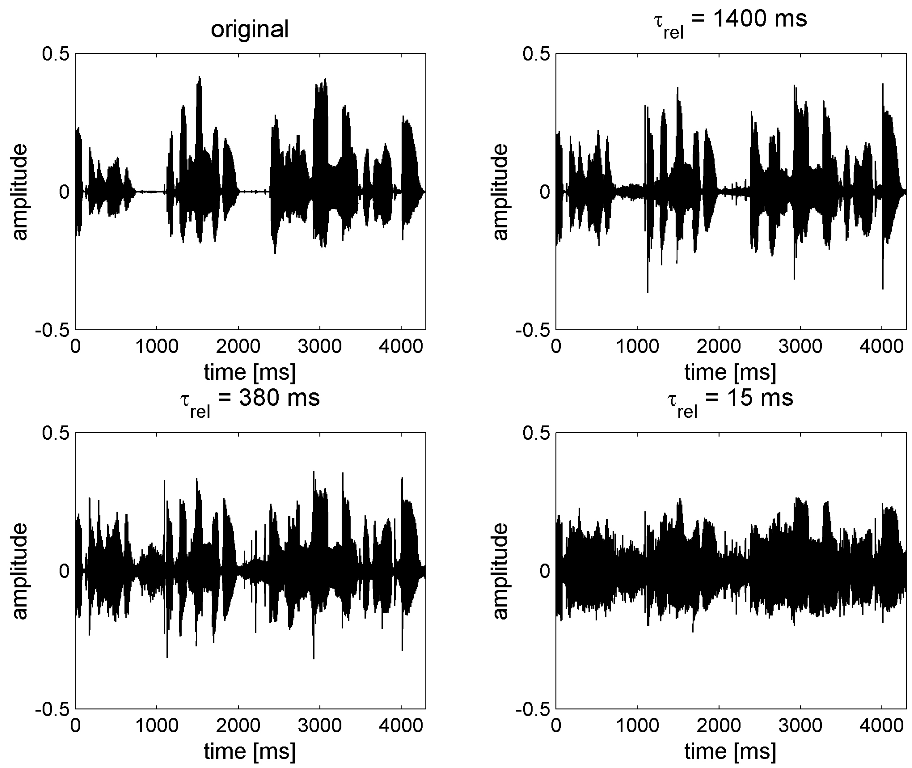

FIGURE 2
The effect of compression speed on speech envelope cues, reproduced with permission from Holube et al. (159). The original speech signal (top left) is processed through a 16-channel system with an exaggerated compression ratio of 8:1 using various release times (τ_{rel}) from long (1,400ms, slow-acting compression) to short (15ms, fast-acting compression).

scenarios, although it has not been specifically used to compare compression speeds. However, it does suggest that increased processing complexity does not inherently provide better performance (149).

There are a considerable number of studies that compare the outcomes of using hearing aids with FAC and SAC and relate it to individuals' cognitive scores. A seminal set of studies by Gatehouse et al. (141, 172, 176) compared five linear and non-linear fitting strategies using FAC and SAC, with a crossover design, for older adults with mild-to-moderate sensorineural hearing loss. Three non-linear strategies were employed: slow-slow, using slow-acting release times across low and high frequency bands respectively; fast-slow, a hybrid strategy using fast release times for low frequencies (<1,500 Hz) and slow times for high frequencies; fast-fast, using fast release times in both bands. Speech intelligibility was measured in several conditions, altering the speech presentation level and signal-to-noise ratio. Non-linear hearing aid strategies provided better aided speech recognition than linear approaches, with FAC offering greater benefit than SAC, but the degree of benefit declined with increasing speech presentation level or reduced signal-to-noise ratio. The slow-slow paradigm offered significantly greater listening comfort, and slow-slow and fast-slow were significantly preferred by users. Conversely, fast-fast and fast-slow paradigms had significantly better speech intelligibility, both user-reported and measured. However, whilst the level of a subject's cognition had no influence on speech tests scores when using SAC (slow-slow or fast-slow), fast-fast compression generated a significant negative correlation between cognition and speech perception, resulting in a wider range of benefit and impediment to patients. In summary, the benefits of FAC over SAC were only accessible to those with better cognitive scores, able to take advantage of increased audibility at the cost of reduced "temporal contrasts," whereas SAC offered greater benefit than FAC for those with lower cognitive scores. It is notable that these studies used hearing aids with only two channels so, based on the discussion above, one might speculate that the difference observed may have been greater with multichannel hearing aids. The study was replicated with much the same result, further demonstrating that the association between SIN performance and cognitive test scores was stronger when more demanding listening tasks were used (106). Hearing loss was the stronger predictor of SIN performance, relative to WM, when SAC was employed; whereas WM was a stronger predictor than hearing loss when using FAC. Other studies have found WM to predict SIN performance in difficult situations when FAC was applied (177–179), concluding that FAC created a disadvantage relative to SAC for those with lower WM (125). Likewise, stronger preference for SAC relative to FAC, when listening to speech and music, can be associated with individuals with lower TFS sensitivity (180). Hearing aid users with poor TFS sensitivity are also affected more by ENV distortion (129). There is also some interaction between different elements of hearing aid processing. For example, adults may prefer SAC when mild noise reduction is employed, but FAC when strong noise reduction was applied, although the effect sizes were small (181). Conversely, a number of similar studies have found that the relationship between compression speed and SIN performance was not affected by the variation in cognitive scores (177, 182–188). One study suggested that FAC offers greater benefit than SAC in quiet and noisy situations for all users (189), irrespective of cognitive scores, although this showed linear amplification to be better than FAC or SAC, and significant differences were only seen at lower presentation levels. In any case, the researchers went on to suggest adaptive compression speeds that utilized SAC in noisy environments (155).

It is difficult to compare studies because of the different paradigms used for testing speech and cognition, as discussed in Section 4. This is further confounded by variable application of algorithms, the number of channels employed in commercial and research hearing aids, and situations that may not be representative of a user's daily experience (190). Studies also vary widely in the amount of acclimatization allowed for research participants, if any, and results vary between new and experienced hearing aid users (107, 191). Complete consistency can therefore hardly be expected between studies and a systematic review found it difficult to draw clear lessons (192). On balance, the studies suggest that individuals with lower degrees of cognition will fare worse with FAC, compared to SAC, in some listening situations that are challenging. Those with high cognitive scores will derive benefit from FAC, compared to SAC, in quiet situations. Audiologists must consider audibility, distortion to ENV and listening comfort when setting a hearing aid, amongst other things. Furthermore, the preceding discussion largely addressed only objective benefit, i.e., aided speech intelligibility, in various situations, but not the perceptions of users that will affect outcomes, not least in mediating compliance with treatment. A number of studies show that users generally prefer SAC in noisy, or all, situations (107, 141, 184, 193) or that different individuals have different preferences, with a greater average preference towards SAC (180).

5.3. Compression ratio

The compression ratio defines the range of gain applied within a hearing aid channel. A higher compression ratio increases the range of input levels that, after amplification, are audible without being uncomfortably loud and should improve speech intelligibility in quiet, but will reduce intelligibility in background noise (151, 171). The effective compression ratio is dependent on the compression speed. In simple terms, SAC reacts too slowly to reach the highest levels of gain determined by the compression ratio within a short timeframe, such as a word, so the distorting effect on ENV for that word is smaller than FAC (Figure 2), where gain may change within the full range determined by the compression ratio during each word spoken. Consequently, the same compression ratio cannot be set for FAC and SAC systems. A compression ratio of 3.0 or less will have little effect on speech envelope cues for SAC (194). However, the amount of distortion introduced by FAC will be broadly proportional to the compression ratio and it is generally recommended that it is not set greater than 3.0 (195) or 5.0 (151, 152). Distortion will be further exaggerated by increasing the number of frequency channels (159). Increasing the compression ratio can reduce consonant recognition (196) and overall speech recognition (197). When asked to subjectively rate the quality of speech, listeners tend to prefer lower compression ratios in quiet and even more so ($CR \leq 2.0$) in noise (159, 197, 198). It should also be noted that that the compression ratio is measured with steady-state signals and the effective compression for a fluctuating signal like speech is lower (199); hence, the longer the release time, the lower the effective compression ratio (151, 152). A greater compression ratio can therefore be set for SAC without noticeable distortion, and the additional comfort availed can be interpreted as a benefit of SAC

(150). In order to avoid distortion to ENV for older adults, compression ratio must be reduced significantly if FAC is used.

5.4. Noise reduction

Noise reduction algorithms aim to reduce the level of non-speech sounds and increase comfort. A meta-analysis found that noise reduction does not consistently improve speech intelligibility, but is moderately beneficial for sound quality and comfort (200). Noise reduction can be fast or slow-acting and can cause disruption to the speech signal by alterations to gain in specific frequency channels, and this may be differently tolerated by those with different degrees of cognition. As noted above, the strength of noise reduction employed interacts with the preference for FAC or SAC (181). Nevertheless, those with relatively good cognitive scores benefit from stronger noise reduction, whereas it may be detrimental to those with lower scores (125). Background noise impairs WM function, making it harder to recall words, especially for more complex listening challenges. Noise reduction may overcome this problem by reducing the demands on WM, but may mainly apply to those with higher degrees of WM in more challenging tasks (201). Some studies suggest that it may apply to those with lower degrees of WM only in less challenging tasks (202, 203). Strong noise reduction likely impairs speech intelligibility for those with low WM or executive function (204, 205), although moderate noise reduction is preferred in most situations and some users prefer strong noise reduction despite the loss in intelligibility (206). Overall, moderate noise reduction likely improves listening comfort without undermining speech intelligibility in most cases, although there is some variability in individual preference.

5.5. Other hearing aid parameters

Hearing aids, by their nature, alter a sound signal and inherently introduce some form of distortion relative to the original. Other features manipulate the sound, including frequency-dependent gain, directional microphones, feedback management, frequency lowering, expansion and wind-noise reduction. Any hearing aid processing that distorts ENV may impair speech perception and this may be especially detrimental to those with lower degrees of cognition (207). However, there is less evidence relating the benefits or drawbacks of these features in relation to cognition.

There is some evidence that frequency-lowering, or frequency compression, can benefit those with higher WM scores but it might act to undermine intelligibility in those with lower WM scores (124). A meta-analysis of frequency-lowering suggested that it has a small benefit in quiet situations, although results were inconsistent and situation-dependent (208), and it may impair speech perception in noise (209). However, frequency lowering might be beneficial in noise for younger adults or those with steeply-sloping hearing loss (103). Frequency-lowering might be trialed as an option, but may impair listening for those with lower cognitive scores.

One dimension of hearing aid setting that has well-established benefits and consistently positive outcomes is the use of directionality to improve signal-to-noise ratio (206) so it is not considered in any detail here. Whilst directionality applies gain preferentially to sounds based on direction, it does not inherently distort the sound in the same way as non-linear processing schemes. There is a similar benefit from directionality for any compression speed irrespective of the degree of WM function (210).

5.6. Non-auditory factors

This review is focused on hearing aid parameters and their effect on aided outcomes for older adults with cognitive change related to normal ageing. Whilst not a subject of this review, we should be cognizant of the fact that hearing care for older adults must include a wider appreciation of their needs including physical and listening comfort, psychological, social, behavioral and environmental considerations, and these have implications on hearing aid settings, acceptance and outcomes (211). For example, despite a declining ability to make use of multi-sensory inputs (212), older adults still benefit from visual inputs for speech perception (118) so visual deficits should be corrected. Education of families and careers should incorporate some understanding of auditory decline and enable them to make adjustments, e.g., via avoidance of fast speech (212), use of clear speech, providing cues before speaking (109), maximizing context (213), familiarity (214) and environmental adjustments to reduce background noise. Other non-auditory factors associated with the comorbidities of age and reduced cognition that can inhibit successful use of hearing aids include dexterity, self-efficacy, attitude, motivation, family support and self-image (98, 99, 215, 216) as well as the "simple" or "complex" manner in which a hearing aid is configured (e.g., with or without programs or control buttons). The cognitive status of individuals will also affect clinical interactions because higher degrees of fluid intelligence enable them to engage more with life (217), handle problems such as acclimatizing to a hearing aid, and to be more proactive in taking action to address their health (218). In short, a hearing aid fitting must provide the patient with a solution that they find manageable and acceptable and, as seen in much of the research discussed above, patients' preferences are not always aligned with the solution that gives maximum speech intelligibility. In summary, whilst we attempt to determine the best approach to setting hearing aid parameters in this review, we recognize that these recommendations should be interpreted within the broader scope of an individual's needs.

6. Discussion: a pragmatic approach to setting hearing aids for older adults

The preceding sections of this paper have reviewed the literature to determine how age-related changes to cognitive domains and auditory processing alter speech perception and, in particular, an individual's relative dependence on different speech cues that might be disrupted by different approaches to hearing aid processing. In this section, we aim to apply the evidence to the clinical hearing aid fitting process in order to provide pragmatic guidance to clinicians.

As part of a patient-centered care model (219) the audiologist's primary role is to offer support and provide benefit to each individual, where the total benefit can be considered as a combination of objective and perceived benefit, preference, and ability to comply with treatment. This perspective means that the "optimal hearing aid fitting" must therefore address all of these aspects of care. In consequence, audiologists require a broad skill set that includes counselling (219) and some level of technical understanding. However, some relevant technical factors, not least compression speed, are rarely provided by hearing aid manufacturers in specification sheets, nor is it easy in our experience for audiologists to acquire such information. This is a fundamental concern because compression speed and compression ratio are primary determinants for the amount of distortion introduced to ENV. Given that audiologists are, in part, dealing with the hearing aid as a "black box," and that research findings are not always consistent, it is perhaps unsurprising that there are no clear technical guidelines for fitting hearing aids to older adults (220).

However, the research is broadly consistent in a number of ways. First, older adults are more likely dependent on ENV for understanding speech. FAC causes distortion to ENV that can undermine speech perception, whilst emphasizing elements of TFS that cannot be utilized by many older hearing aid users, and might disrupt binaural inputs. Second, hearing aid users tend to prefer SAC on average, although individuals have different preferences. FAC is likely better in quiet for those with good cognitive processes related to hearing, but likely degrades speech intelligibility and the acceptability of hearing aids for those with lower degrees of cognition. Third, the variation in cognitive processes between individuals increases with age, so we cannot know which specific settings offer the most benefit for an individual, nor whether objective benefit will be aligned with their preference.

The combination of peripheral and central auditory decline therefore means that older adults represent some of the most complex patients, as well as the most numerous. Consequently, age-related hearing loss should never be treated as "standard care" simply because of its high prevalence. Determining the correct hearing aid strategy for an individual hearing aid user is therefore a major challenge. One might think that it would be useful to undertake tests of cognition or TFS sensitivity in clinic. However, it is uncertain that a test score could usefully indicate a specific course of action, nor which cognitive tests should be used. Verbally-delivered cognitive tests are affected by hearing loss and there is no well-established test that has been shown to be unaffected by sensory impairment (61, 120, 221). It is unclear whether audiologists are able to conduct cognitive tests sufficiently well and their utility in clinical situations needs evidencing (222). Speech testing might give some indication of overall ability and it has been suggested that it be more widely used (223) because standard audiometry provides no useful evidence regarding auditory processing and cognition. However, it is equally unlikely that a speech test score could equate directly to a specific hearing aid setting and user preference. It is also unclear whether clinical speech-testing is sufficiently sensitive to determine any benefit derived from alternative hearing aid settings. Consequently, in addition to the current lack of applicable tools, it is debatable whether the additional loading on clinical time would yield sufficient benefit to be justified. In any case, many audiology services face demand and resource pressures, particularly in public sector systems with universal treatment, so extending the test battery significantly may not be implementable.

We therefore propose a pragmatic approach to hearing aid setting that could be implemented within typical current fitting appointments. The principles above can be employed to ensure that relevant factors are considered for older adults, which we define nominally as those over 55 years of age in line with the English NHS definition of age-related hearing loss. We believe the following statements concerning hearing aid settings for older adults follow directly from the evidence:

1. All factors that introduce distortion to ENV should be explicitly considered in hearing aid fittings. This should primarily include compression speed and compression ratio, but also noise reduction, frequency lowering and other advanced features.
2. Compression speed and compression ratio are primary determinants of the degree of distortion introduced to ENV. This indicates a need for hearing aid manufacturers to publish compression speeds as part of their standard product information, and provide products that allow clinicians to change compression speed, or offer adaptive compression speed algorithms that can be selected appropriately for each individual.
3. SAC should be considered as the default setting for older adults and should be employed in noisy environments for all hearing aid users. However, recognizing the variation in preference between individuals, both SAC and FAC approaches can be provided in separate hearing aid programs and the audiologist can employ validation techniques to assess which is best set as the default program. There is no good reason that hearing aids should default to FAC for older adults.
4. If FAC is used, the compression ratio should be reduced to levels that avoid ENV distortion. There is no clear evidence that suggests a specific value, so it is difficult to provide robust guidance. Our own clinical experience and discussions with hearing aid manufacturers suggests a value as low as 1.5. This is, admittedly, anecdotal but there is some evidence to suggest that linear aids are preferred over WDRC aids with FAC and a compression ratio of 2.0 when subjectively rating the quality of aided speech (159). Users also prefer CR $\leq$ 2.0 in noise (197, 198).
5. Directionality is always beneficial to improve the signal-to-noise ratio. This might also include a consideration of ear-molds in place of open-fittings, because the latter reduces directional benefit (224, 225). Alternatively, other assistive devices and accessories may be considered to improve directionality or enhance the signal-to-noise ratio.
6. Noise reduction is likely best set to moderate, although this depends on each hearing aid manufacturer's approach and the evidence base is not strong. Strong noise reduction may well impair speech perception, especially for those with lower degrees of cognition. However, the user may be offered options or multiple programs because some may prefer stronger noise reduction in some situations.
7. Other advanced hearing aid features, such as frequency lowering, may also distort the signal in ways that further impair speech intelligibility for those with reduced abilities in some cognitive domains. The evidence is generally weak, so these should be considered as options for each individual.
8. Unilateral aiding should be considered where binaural interference is suspected. This is easily achieved in clinic by comparisons of speech intelligibility and listening comfort with bilateral hearing aids versus the left and right hearing aid working unilaterally. In some cases, clinicians may find that the

individual's speech intelligibility is significantly better when aiding only one of the ears, and intelligibility may be impaired or the sound distorted whenever gain is applied to the other ear.

One should recognize that any recommendation regarding hearing aid parameters cannot be prescriptive given the current state of knowledge and considering the wide variability in individual needs. This implies that there must be some process of ensuring that hearing aid settings are optimal, or at least acceptable, for each individual. Overall, we believe that a full consideration of hearing aid parameters needs to be combined with the over-riding principles of patient centered care. This engenders a need to balance the key elements of the hearing aid fitting process, including verification, validation and counselling. "Verification" is the process of matching hearing aid gain to a prescribed target using real ear measurements (REMs). "Validation" should aim to provide evidence that all hearing aid settings are suitable for an individual. This may include simple tests of loudness discomfort and speech intelligibility, more advanced techniques such as speech mapping, paired comparison approaches (226), or questionnaires and self-reporting tools (227). Finally, "counselling" addresses non-audiometric factors such as the patient's expectations, self-image and self-efficacy (228). This approach will likely improve the rate of treatment compliance (229, 230). The following statements are not novel, but we believe they are worth re-stating in light of the principles discussed above for setting hearing aids for older adults:

9. Conducting verification and matching gain to a prescription target does not, in itself, make a good hearing aid fitting. The verification process is solely aimed at setting individualized hearing aid gain and does not encourage a consideration of the other parameters highlighted in this review. For example, setting the gain to a prescription target for 50, 65, and 80 dB input levels may lead to high compression ratios where FAC is used, causing inappropriate ENV distortion. Verification is an important step that may offer a large (231) or small (232) benefit, but the resulting gain settings must be considered in the light of the other parameters discussed above and adjusted appropriately.
10. The only clinical process that can evaluate overall hearing aid settings and their suitability for an individual is validation (233). Accordingly, we believe that it is important that verification is always followed by proper validation in clinic (234) and that clinicians should consider the balance of time given to each process during fitting appointments. The hearing aid user should not perceive distortion and loudness discomfort, and sufficient speech intelligibility and sound acceptability should be demonstrated. In short, clinicians should consider both the intelligibility and quality of speech (235). However, it is recognized that current validation techniques, e.g., using live voice or speech mapping, are subjective and more objective methods of assessing the likely perception of overall distortion would be helpful. Appropriate objective methods are currently lacking in clinical practice.
11. Hearing aids cannot overcome all of the peripheral and central auditory deficits discussed in this review, so wider considerations should be addressed to achieve the optimum outcome in the perception of the individual user. Audiologists must, of course, consider other non-auditory factors. Informational counselling regarding central auditory decline should aim to set reasonable expectations for the hearing aid user and their families or careers (236, 237) and can promote modification of the environment and behaviors related to the elements of decline in central auditory processing discussed above. This may include use of clear speech, visibility of mouth movements and reducing background noise.

7. Implications for further research

Research studies use a wide array of both cognitive and listening tasks, so the associations observed between them are variable. Although WM tasks predominate in many studies, it is not the only domain of cognition that is relevant (92) and we are yet to fully understand which elements of cognition might relate to every listening condition (64). It would seem prudent to consolidate a range of cognitive tests in research studies. There is also a lack of validated cognitive tests for those with a sensory impairment, because many tasks are delivered verbally or visually, so hearing loss may be a confounding factor (61, 120, 121) and must be considered as part of research design. In large part, studies relate cognitive status to performance in listening tasks, although some studies relate it to user preference. It should be clear that individual preferences are not always aligned to objective performance and may be based more on listening comfort, effort or some other perception of quality, so it would seem sensible to measure both objective performance and subjective benefit in research studies.

Whilst there is variation in the evidence, it appears to us that the balance of evidence suggests that slow-acting compression may be the best default position for most older adults along with other cautious settings for compression ratios and noise reduction, although accepting there will be individual variations. However, further research should seek to confirm the size of the effect. Furthermore, most research on the effect of hearing aid settings considers one parameter in isolation whilst other parameters are held constant. This is unlikely to reflect the overall function of commercial hearing aids and assess the interaction between different hearing aid features. Recent work has demonstrated the interactions between compression speed and other settings, such as noise reduction and directionality (181, 210), so further research should establish whether combinations of hearing aid processing strategies negate the overall effect of individual settings in the user's perception. It is also important to be able to evaluate balanced measures of speech intelligibility and quality, and relate them to the overall perception of distortion. This indicates a need to further develop clinical tools, such as HASQI and HASPI (148, 149), to determine an objective measure of distortion appropriate for individuals with varying degrees of hearing loss and cognitive ability, that also aligns with user perception. This further begs the question of whether some test of cognitive ability is useful or implementable within clinical practice.

In this paper we have proposed an approach to setting hearing aids for older adults. Whilst this may be derived from the balance of evidence, it is not specifically validated. We have therefore designed a randomized control trial based on the principles discussed in this paper, pre-registered on the Center for Open Science's Open Science

Framework (OSF), at https://osf.io/fdzeh. The SHAOA (Setting Hearing Aids for Older Adults) study has been approved by the UK Health Research Authority and National Health Service (NHS) Research Ethics Committee (IRAS ID 313159), and it has been adopted onto the NHS National Institute for Health Research (NIHR) portfolio. Finally, in suggesting this approach, we make an implicit assumption that audiologists may not consider all of the factors that have been highlighted here, which we have not evidenced. Accordingly, we will also complete an online survey of UK clinicians to evaluate this, under University of Manchester ethics approval.

Author contributions

RW conducted an initial long-form literature review which was reviewed with comments and changes from HD and AH. RW wrote the draft of this paper with comments and revisions from HD and AH. RW is Principal Investigator for ongoing research with HD and AH as academic supervisors. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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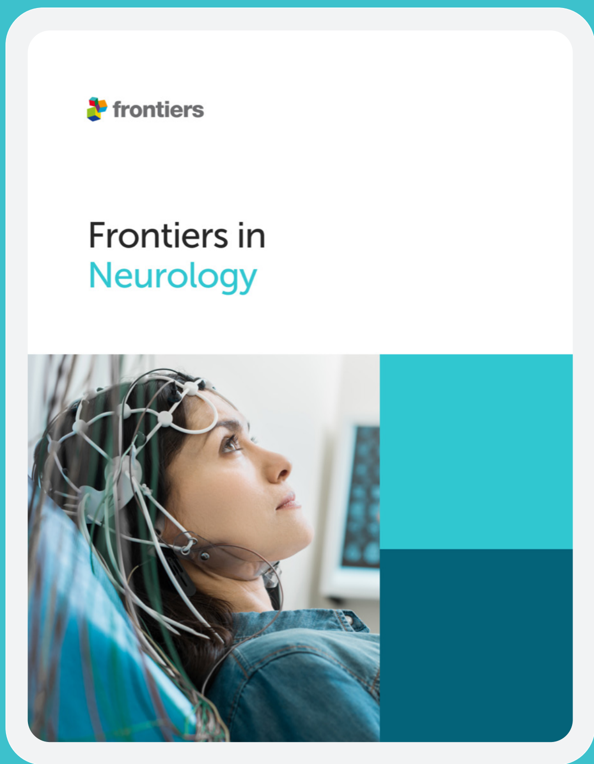

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