Hearing Research 461 (2025) 109272

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Research Paper

Preoperative MRI, audiovisual speech perception, and mood are associated with cochlear implant outcomes in adults with postlingual deafness

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ARTICLE INFO

Keywords:
Plasticity
Deafness
MRI
Surface-based analysis
Brainnetome Atlas
Cognition
audiovisual speech perception
Cortical thickness

ABSTRACT

Acquired severe to profound hearing loss is an increasingly challenging problem of our aging population. Cochlear implantation (CI) is the gold standard treatment for this advanced form of sensory deprivation. Despite the overall satisfactory results of CI, a substantial number of patients show unsatisfactory outcomes. This study aims to improve current predictive models of CI outcome by integrating preoperative MRI with behavioral data. We acquired a 3D T1 MRI to measure cortical thickness (CT) and volume using surface-based analysis and parcellation from the Brainnetome atlas. CI success at 6 months post-implant, as measured by audiovisual speech perception, was correlated with preoperative speech and audiovisual perception with hearing aids, and residual hearing, especially at the side of the non-implanted ear. In addition, CI outcome correlated positively with CT of the left superior temporal gyrus and sulcus, left inferior frontal region, and bilateral superior frontal regions. The volume of the left middle frontal gyrus and regions of the parietal lobe, especially at the left side, also correlated with CI outcome. Linear regression models revealed that CI outcome was best predicted by the combination of preoperative measures of audiovisual speech perception, residual hearing, depression and CT. Our results highlight the importance of preserved brain areas implicated in hearing, language, audiovisual integration, and cognitive functions for CI success. Furthermore, brain MRI in conjunction with other predictors can help to identify patients who may need more time to adjust to the CI, allowing a more tailored rehabilitation, and potentially greater efficacy.

Abbreviations

AVs	Audiovisual speech comprehension score
CI	cochlear implant
CT	cortical thickness
dB HL	decibel hearing level
dB SPL	decibel sound pressure level
HA(s)	hearing aid(s)
HADS	Hospital Anxiety and Depression Scale
HL	hearing loss
HT	hearing threshold(s)
PTA	pure tone audiometry
w/, w/o HA	with, without hearing aid(s)
WRS	average Word Recognition Score

1. Introduction

Acquired deafness is a significant and growing healthcare challenge in our ageing societies (Geneva: World Health Organization 2021). While the global population suffering from disabling hearing loss was estimated to be around 430 million in 2019, this figure could rise to 711 million by 2050 due to expected population growth and increased longevity (Geneva: World Health Organization 2021). Cochlear implantation is the standard treatment for severe to profound hearing loss when hearing aids (HA) are no longer sufficient. Despite global speech perception enhancement with a cochlear implant (CI), some patients present poor results (Moberly et al., 2016). For example, a review conducted by Boisvert et al. concluded that approximately 18 % of CI recipients with postlingual hearing loss show a speech perception

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https://doi.org/10.1016/j.heares.2025.109272
Received 11 February 2025; Received in revised form 25 March 2025; Accepted 5 April 2025
Available online 9 April 2025

improvement of <15 % (Boisvert et al., 2020). Previous studies have highlighted the impact of various factors in CI success rate in postlingual deafness. More specifically, clinical characteristics that influence the outcome include age at onset of severe to profound hearing loss, duration of hearing loss, use of HA and percentage of electrodes that are effective within the cochlea (Lazard et al., 2012; Bernhard et al., 2021; Kim et al., 2018). Furthermore, residual hearing levels in the better ear, regardless of which ear is implanted, significantly impact CI success, highlighting the importance of having a minimum level of hearing to maintain the language network.

However, when all these clinical factors are combined in a linear model, they only explain 22 % of the variance of CI outcome (Lazard et al., 2012). Many studies have therefore focused on the potential role of top-down processes in the success of CI therapy. These studies have highlighted the importance of cognitive skills such as working memory, attention and inhibition-concentration (AC Moberly et al., 2018; Zhan et al., 2020; Skidmore et al., 2020; Zucca et al., 2022). Furthermore, stress related to health, work/finance, social, and traumatic events, presence of depressive disorder or personality traits such as neuroticism, also impact CI outcome (Lailach et al., 2024; Muigg et al., 2019). Other studies have investigated whether results of CI therapy can be predicted by structural or functional changes in the brain. A recent study by Sun et al., performed in a large cohort of 94 postlingually deaf adults, addressed the role of clinical features and brain grey matter (GM) volumes (Sun et al., 2021). The results showed that GM volume of the thalamus and the left superior and middle temporal cortices best predicted success rate of CI therapy. In addition, GM volumes of these brain areas correlated strongly with the duration of deafness, which may negatively influence CI success. Unfortunately, this study did not take into account the possible role of psychological factors, nor that of speechreading abilities, factors which do contribute to CI outcome (Anderson et al., 2017). Indeed, speechreading and audiovisual speech integration are crucial for deaf patients as they support speech comprehension and preserve the linguistic representation of speech (Lazard and Giraud, 2017; Grégoire et al., 2022; Layer et al., 2022). Even after CI therapy, speechreading remains important to help decipher the altered auditory message transmitted through the device (Rouger et al., 2007).

The objective of this study was to identify the most accurate predictive factors of CI outcome in postlingually deaf subjects who underwent implantation in adulthood. In addition to preoperative clinical data, the study sought to ascertain whether GM measures from preoperative brain MRI could enhance CI success prediction. The preoperative clinical data evaluated included residual hearing with and without hearing aids (HAs), auditory and audiovisual speech perception, age at onset of hearing loss and age at implantation, and psychosocial factors such as anxiety and depression, which have been described as important predictive factors that are often underestimated (Lailach et al., 2024). Additionally, we explored the potential correlations between cortical thickness (CT) and GM volume with subsequent CI success, and its potential contribution to prediction accuracy. GM volume is a composite measure, influenced by thickness and surface (Dumitru, 2023). CT and cortical surface are genetically independent and are differently sensitive to clinical conditions (Storsve et al., 2014). Research that simultaneously examined multiple cortical features reveals that these features do not consistently exhibit uniform patterns of variation (Dumitru, 2023; Storsve et al., 2014; Li et al., 2012; Mills et al., 2020), highlighting the importance of studying both. Morphometric measures were derived from a routine clinical brain T1 MRI sequence prior to cochlear implantation. The exploration of predictive factors of speech comprehension with a CI in adults with acquired deafness is of paramount importance, given the significant individual and societal impact of deafness (Grégoire et al., 2022). This study makes a substantial contribution to the field of CI research, offering insights into the factors that influence adaptation to this technology.

2. Methods

2.1. Patients

A total of 71 adults with postlingual bilateral severe to profound hearing loss (hearing thresholds average superior to 70 dB HL), who were candidates for a CI, were identified at our tertiary academic hospital between 2018 and 2022 (Fig. 1). Patients who were not native French speakers with fluency in French language, as well as those with psychiatric or neurological disorders or other disabling sensory deficits, were excluded from the study. Thus, 63 patients that received a CI were included, of whom 7 did not complete the study. Ultimately, the results of 56 patients were analyzed. Written informed consent was obtained from each patient, and the study was approved by the local ethics committee of the hospital and faculty (2017/02AOU/384).

2.2. Behavioral data

Extensive audiometry testing was performed prior to surgery (Fig. 2). For hearing without any HA, we calculated the pure tone average (PTA) in dB HL for both ears at 0.5, 1, 2 and 4 kHz. Speech audiometry was performed using the monosyllabic phonemic cochlear lists of Lafon (Lafon, 1972) in the free field, i.e. via a speaker located in front of the patient or two speakers on either side. The words were presented at 40, 55 and 70 dB SPL, corresponding to soft, medium and loud voice, respectively. We then calculated the average Word Recognition Score (WRS) from these three intensities. To evaluate speech perception in the best aided condition, we used the WRS as described above, while patients were asked to use their HAs as usual. To estimate audiovisual speech comprehension, we used an in-house developed test coined DEWA (Deggouj and Wathour, 2022), hereafter referred to as AVs (AudioVisual score). For the preoperative assessment, the AVs was performed in the best aided condition, i.e. with HAs. In this test, patients listen and look to an audiovisual recording with a female speaker pronouncing monosyllabic French words from 2 balanced and validated lists of ten words. Patients must repeat as many words as possible, one after the other. The test was performed with the video of the speaker's face (audiovisual condition allowing speechreading) and without it (auditory alone condition). The difference between the scores in these two conditions gives an appreciation of the gain in speech comprehension related to speechreading. AVs was measured at 70 dB SPL (loud voice) and results are reported in percentage.

Information's about the etiology of deafness and the use of HA were also collected. The duration of HA use was used as an estimate of the duration of hearing loss. The onset age of hearing loss was calculated by subtracting the duration of HA use from the age. Anxiety and depression were measured using the Hospital Anxiety and Depression Scale (HADS) questionnaire (Zigmond and Snaith, 1983), which is a self-reported rating scale consisting of 14-items. Seven items relate to anxiety, and the others to depression. HADS subscores from 0 to 21, with scores between 0 and 7 considered as normal, scores between 8 and 10 as borderline with mild symptoms, and scores from 11 and up as abnormal with moderate to severe symptoms.

Genetic testing was not systematically carried out, except in cases where there was a family history of deafness or association with other suggestive disorders, such as a significant vestibular deficit suggesting a COCH gene mutation.

2.3. Postoperative outcomes with the cochlear implant

The outcome of CI therapy was evaluated at 6 months post-activation (i.e. 7 months after surgery). WRS and AVs were measured with the CI in the free field. If patients used an additional contralateral HA, they did not wear it during the test. In contrast to other studies, these measures were preferred over the classification by the Categories of Auditory Performance (CAP) (Archbold et al., 1995). Information on the type of

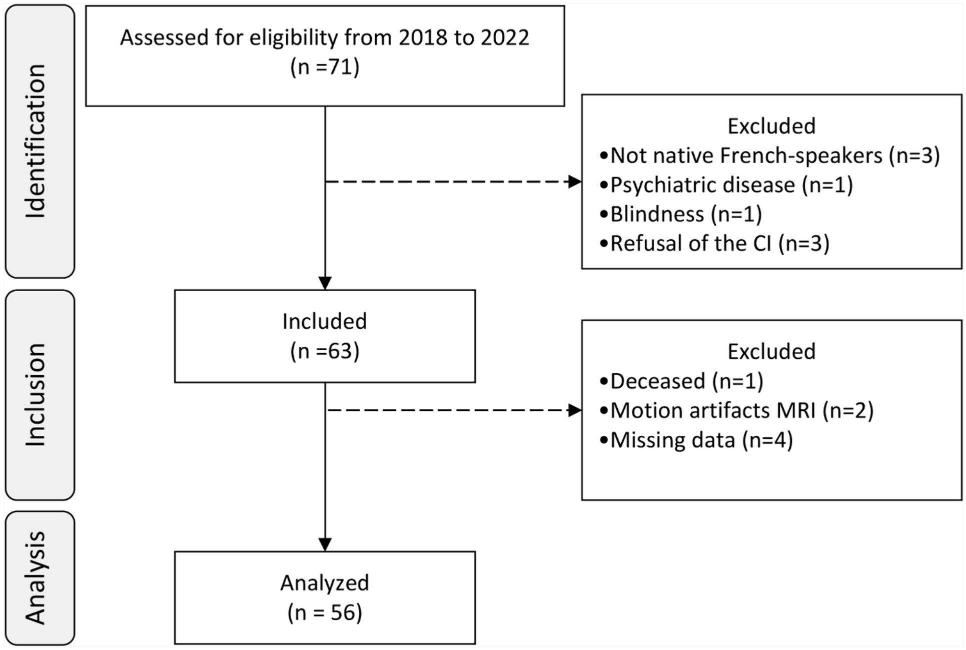

Fig. 1. Study flowchart. Of the 71 patients initially contacted for participation in the study, eight were excluded, and data from seven others had to be discarded, resulting in a final analysis of 56 patients.

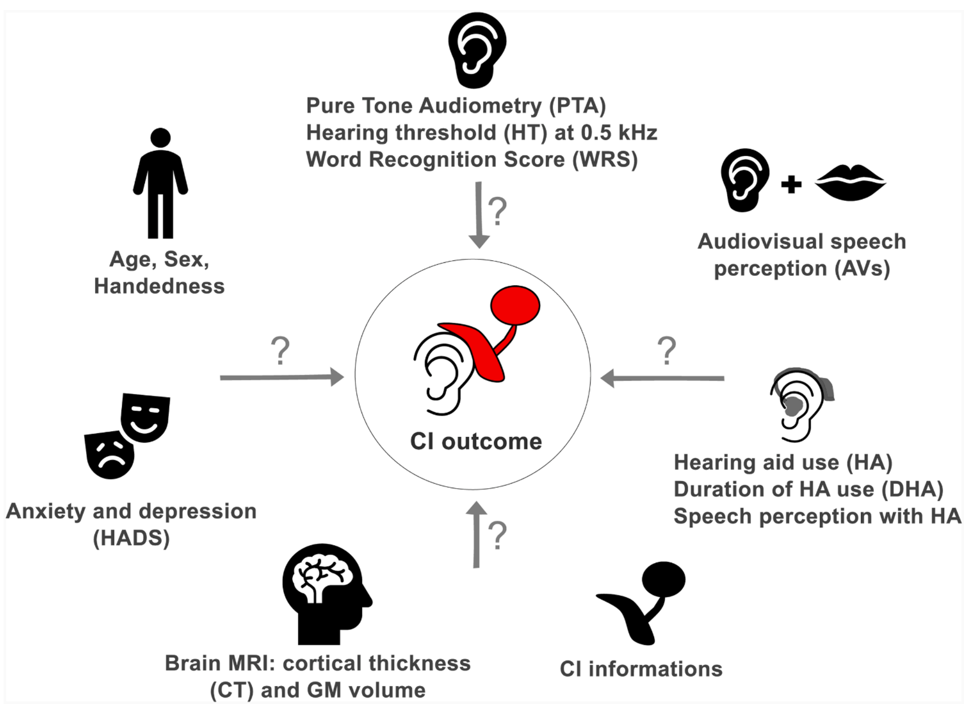

Fig. 2. Graphical summary of the study protocol. The objective of this study was to identify predictors of CI outcome. Traditional demographic data and information about hearing were collected, including age, duration of hearing aid use (DHA) and speech perception measured by the average word recognition score (WRS). Additionally, anxiety and depression scores, audiovisual speech perception (AVs), and cortical thickness and grey matter volume from MRI were considered.

electrodes used (straight versus perimodiolar) and the side that was implanted (right or left) was also recorded.

2.4. Preoperative brain magnetic resonance imaging

3D T1-weighted MRI data were recorded with a 3 T Skyra (Siemens Health Care, Erlangen, Germany), equipped with a 20-channel phased array HeadNeck coil, using the following acquisition parameters: TR=21 ms, TE=4.9 ms, slice thickness=1 mm, flip angle=25°, field of view=256×256 mm^2, and matrix=256×256, leading to 1 × 1 × 1 mm^3 isotropic voxels. The whole brain was analyzed and volumetrically segmented by employing the FreeSurfer analysis pipeline (http://surfer.nmr.mgh.harvard.edu/, version 7.1) using an array of automated sequences. Following the execution of the suite, each segmentation was carefully examined visually, and any detected inaccuracies in geometry were corrected by the same trained person. In addition to the aseg atlas that was used for subcortical volumetry and global cortical measures (i.e. mean thickness of each hemisphere), the Brainnetome Atlas (Fan et al., 2016) was used to extract CT and GM volume of specific regions. This atlas divides the brain into 246 regions (123 per hemisphere) according to their connectional architecture. The extracted GM measures were adjusted for age, sex and intracranial volume using a regression model, in order to account for their potential confounding effects on brain GM. Correlation analyses were performed using the residuals of this regression model. Furthermore, we conducted vertex-by-vertex surface-based analyses to explore localized patterns of GM variation that may not be captured by the atlas-based approach which relies on predefined regions. Age was added as a nuisance factor when examining CT and GM volume, as well as intracranial volume when examining GM volume. A smoothing with a FWHM (Full Width at Half Maximum) of 10 mm was applied.

2.5. Statistics

Comparisons of pre- and postoperative speech comprehension were realized using paired *t*-test, or a Wilcoxon signed-rank in case of deviation from normality (assessed by Shapiro-Wilk test). In case of independent groups, independent sample *t*-test or Mann-Whitney test was used (i.e. for the comparisons of the CI results according to the implanted ear). The equality of variances was assessed by Levene's test.

Correlations were performed to test for associations between pre- and postoperative continuous or ordinal data from behavioral measurements and GM measures extracted from anatomical MRI. The Shapiro-Wilk test was employed to assess bivariate normality. In cases of deviation from normality, Spearman's correlation was applied. To address the issue of multiple hypothesis testing and to control the false discovery rate, we used the Benjamini-Hochberg procedure with $P < 0.050$. To maximize the clinical applicability of our findings to the whole deaf population, regardless of handedness, we did not exclude left-handed and ambidextrous patients. To ensure that the overall results were also applicable to the non-right-handed group, additional analyses were conducted within this subpopulation.

We conducted different multiple linear regressions with the various preoperative variables to test their prediction power on AVs with the CI. The first model tested included all clinical preoperative variables. The least significant predictors were then removed from the model. Finally, we added the CT of the region that correlated the strongest with CI outcome to the linear model. The rationale for using CT instead of GM volume is that CT is largely unaffected by total intracranial volume, avoiding the need for a complex correction (Schwarz et al., 2016). Linear regression was performed on CT values without age-correction, since age was also introduced in the model. The adjusted coefficients of determination (adjusted R^2) were used to compare the models. Multicollinearity was checked using the tolerance and the Variance Inflation Factor (VIF), and redundant factors were suppressed. Statistical analyses were performed using SPSS version 25 whereas JASP (JASP Team 2024) was used for some figures.

3. Results

3.1. Patients' characteristics

Table 1 shows the patients' demographic characteristics. Fifty-seven percent of the patients were women, and 84 % were right-handed (11 % left-handed and 5 % ambidextrous). Most patients (96.4 %) wore HAs before CI, at both ears for 70 % of them. Twenty-three percent of the patients did not wear an HA anymore on the ear that was subsequently implanted, due to an absence of therapeutic gain. Five of the patients had suffered from a progressive HL since early childhood and were wearing HAs for mild to moderate uni- or bilateral HL before the age of 7. Preoperative speech comprehension, conducted with and without HA and speechreading, showed significant correlations with each other, as well as with residual hearing at 0.5 kHz ($p < 0.050$) (Supplementary Table S1). The results of the HADS questionnaires indicated that 20 % of the patients had a mild form of anxiety and 27 % presented moderate to severe symptoms. Depression was less present, with 13 % presenting mild symptoms and 7 % moderate to severe symptoms.

Table 1
demographic characteristics and behavioral results.

		Mean ± SD	Median	Range	Frequency
Age (years)		58.2 ± 17.5	62	18 - 85	
Sex					57 % female
Handedness					47 (84 %) right-handed, 6 (11 %) left-handed, 3 (5 %) ambidextrous
DHA (years)		16.5 ± 12	14.5	1 - 63	
Onset HL (years)		41.9 ± 19.2	42.5	5 - 77	
Anxiety subscore		7.6 ± 3.9	7	1 - 16	53 % normal, 20 % borderline, 27 % abnormal
Depression subscore		4.9 ± 3.4	4	0 - 15	80 % normal, 13 % borderline, 7 % abnormal
PTA (dB HL)	CI side	99.1 ± 14.1	99.4	70 - 120	
	Non-CI side	91.1 ± 16.3	90	65 - 120	
HT 0.5 kHz (dB HL)	CI side	88.8 ± 25.4	90	25 - 120	
	Non-CI side	78.1 ± 24.4	75	25 - 120	
WRS (%)	w/o HA	2.1 ± 6.8	0	0 - 40	
	w/ HA	16.3 ± 19.6	10	0 - 90	
AVs (%)		47.7 ± 21.9	50	0 - 90	
Etiology of HL	unknown				29 (52 %)
	genetic				16 (29 %)
	of whom COCH gene mutation (DFNA9)				*6 (11 %)*
	advanced otosclerosis				4 (7 %)
	idiopathic sudden HL				2 (4 %)
	Menière's disease				2 (4 %)
	chronic otitis				2 (4 %)
	congenital CMV				1 (2 %)

Anxiety and Depression subscores refer to HADS scoring (0–7: normal, 8–10: borderline, 11–21: abnormal). Abbreviations: AVs: Audio-Visual score, DHA: duration of HA use, onset HL: age at onset of HL, PTA: pure tone audiometry, HT 0.5 kHz: hearing thresholds at 0.5 kHz, WRS: average word recognition score, HL: hearing loss.

3.2. CI outcome and correlations with preoperative behavioral data

A CI was placed on the right side in 30 patients (53.6 %). Twenty-six devices came from Cochlear®, 16 from Medel® and 14 from Advanced Bionics®, with 26 straight electrodes (46.4 %). Speech comprehension with the CI alone (WRS post-CI) reached 34.5 ± 25.3 %, which is significantly better than preoperatively, even with HA in the best aided condition (16.2 ± 19.6 %, $p < 0.010$) (Fig. 3). AVs with CI reached 54.1 ± 17.2 %, which is also significantly better than preoperatively in the best aided condition (47.6 ± 21.9 %, $p < 0.050$). As expected, post-operative speech perception in the auditory-alone (WRS post-CI) and in the audiovisual conditions (AVs post-CI) correlated significantly ($r = 0.628$, $p < 0.010$). AVs post-CI exhibited no significant differences according to the implanted ear. Table 2 and Fig. 4 show the correlations

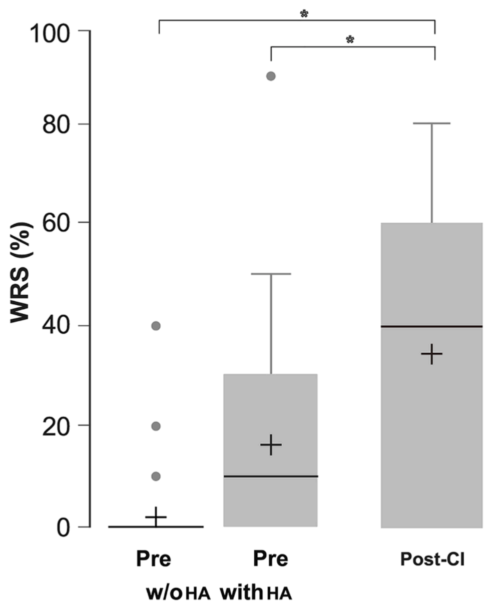

Fig. 3. Improvement in postoperative speech perception. Average Word Recognition Scores (WRS) were measured preoperatively with (w/) and without (w/o) hearing aids HA(s), and postoperatively with the CI. The crosses represent the mean, and the horizontal black lines the median. The inferior and superior borders of the grey box represent the first and third quartile respectively. WRS was significantly higher post-CI compared to the two pre-operative conditions (* $p < 0.010$).

Table 2
Correlations between preoperative clinical features and CI outcome.

	WRS post-CI	AVs post-CI
Age	−0.188	−0.201
Duration of HA use	−0.292	0.002
Age of onset of HL	−0.001	−0.208
Anxiety subscore	−0.184	−0.064
Depression subscore	−0.147	−0.117
HT 0.5 kHz at CI side	−0.246	−0.294
HT 0.5 kHz at non-CI side	−0.259	−0.408*
WRS without HA	0.192	0.267
WRS with HA	0.283	0.369*
AVs	0.421*	0.497*
Gain of speechreading	0.140	0.142

Significant results are marked with an asterisk ($p < 0.050$, FDR-corrected). Significant correlations were found between speech perception with CI and preoperative hearing, more specifically hearing threshold at 0.5 kHz in the non-implanted ear, speech perception with HAs (WRS with HA) and speech perception in the audiovisual condition (AVs). Gain of speechreading is the difference in speech perception with and without speechreading. Two outliers were removed respectively from the DHA (value of 63 years) and WRS w/ HA (value of 90 %), which allowed for the use of parametric tests. Abbreviations: HA: hearing aid(s), HL: hearing loss, HT: hearing thresholds, WRS: average word recognition score, AVs: audiovisual speech perception score.

between CI outcome and preoperative clinical data. AVs post-CI was significantly correlated with residual hearing at 0.5 kHz of the non-implanted ear ($r=-0.408$, $p < 0.050$, FDR-corrected, Fig. 4a): a lower hearing threshold at 0.5 kHz, indicative of better residual hearing, was associated with a more favorable result. Moreover, AVs post-CI was significantly correlated with preoperative speech perception with HA, both in the auditory alone (WRS w/ HA) ($r = 0.369$, $p < 0.050$, FDR-corrected, Fig. 4b) and audiovisual conditions (AVs) ($r = 0.497$, $p < 0.050$, FDR-corrected, Fig. 4c). We found no statistically significant correlation between CI outcome and age at implantation or age at onset of HL. However, there was a negative correlation between the WRS post-CI and the duration of hearing loss ($r=-0.292$, $p < 0.050$), but it did not survive correction for multiple comparisons. Preoperative levels of anxiety and depression were negatively associated with the duration of HL ($r=-0.315$ and -0.383 respectively, $p < 0.050$) (Fig. 5). However, no significant correlation was observed between these factors and age at onset of HL or at implantation.

3.3. Preoperative MRI and audiovisual speech perception with the CI

Globally, AVs with the CI correlated significantly with the mean CT of the left hemisphere ($r = 0.384$, $p < 0.050$, FDR-corrected), which was not correlated with any preoperative clinical data. Table 3 shows the correlations between CI outcome and CT and GM volumes of regions derived from the Brainnetome atlas. All regions are located within the left hemisphere and concern predominantly CT. None of the regions were correlated with any of the preoperative clinical data, especially preoperative AVs. The most significant correlation with CT was observed in the opercular part of the left A44 (BA 44), corresponding to the pars opercularis within the inferior frontal gyrus. This region also shows a strong correlation with post-CI AVs in the population of left-handed and ambidextrous patients (9 subjects, $r = 0.773$, $p < 0.050$). Fig. 6 illustrates the relationship between AVs post-CI and CT of the opercular part of left A44, using the residuals from the regression model, adjusted for age and sex. As highlighted, the correlation remains significant when separating non-right-handed individuals from the rest of the cohort. CT of the opercular part of the left A44 was not correlated with preoperative speech perception scores after correction for multiple comparisons (Supplementary Table S2). There were no significant correlations with the volume of any of the subcortical nuclei.

Fig. 7 and Table 4 show the results of the vertex-by-vertex surface-based analysis. These results largely confirmed the atlas-based analyses. AVs post-CI correlated positively with CT of four regions, centered on the left pars opercularis, left superior and middle temporal gyri, and bilateral superior frontal regions. In addition, AVs post-CI correlated positively with GM volume of the bilateral superior parietal area, left inferior parietal region and left rostral middle frontal region.

The clusters are numbered in accordance with the nomenclature employed in Fig. 7. The P-value of the correlation is reported (P), as well as the size and the MNI coordinates of the center of the clusters.

3.4. Linear regression models

We tested different linear regression models to predict AVs with CI at 6 months (Table 5 and Fig. 8). The first linear model included 9 preoperative clinical parameters and reached a R^2 adjusted of 0.273 ($p = 0.014$). By limiting the number of variables to the five most significant ones (Model 2), an R^2 adjusted of 0.333 ($p = 0.001$) was achieved. We constructed a third model that included CT of the opercular part of left A44, which emerged as the most strongly correlated CT measure with CI outcome. This model achieved an R^2 adjusted of 0.482 ($p < 0.001$) by including age, HADS depression score, residual hearing at 0.5 kHz of the non-implanted ear, WRS with HA, preoperative AVs and CT of the opercular part of the left Brodmann area 44. The accuracy of this model did not further improve by adding the CT or volume of other regions that correlated with CI outcome (Supplementary Table S3).

4. Discussion

The aim of this study was to estimate CI success by preoperative brain morphometry measures from 3D T1 MRI and clinical data. Our results show that CT and volume of regions within the left temporal and bilateral frontal and parietal lobes correlate with speech perception 6 months post-implant. Our analysis revealed strong correlations between audiovisual speech comprehension with the CI and CT of the left pars opercularis, left superior and middle temporal gyri, and bilateral superior frontal area. In addition, speech comprehension also correlated with GM volumes of the left rostral middle frontal, left inferior parietal, and

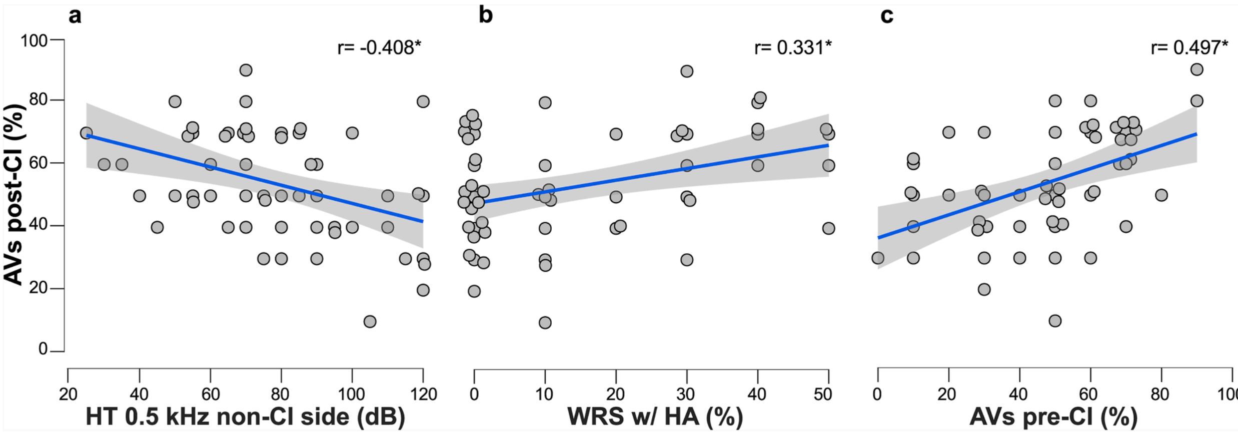

Fig. 4. Correlation between CI outcome and preoperative behavioral test scores. Each dot represents a patient. Linear regression lines with their 95 % confidence intervals are shown for each behavioral measure. Correlation coefficients (r) are presented, accompanied by their significance level (* $p < 0.050$, FDR-corrected). A significant negative correlation was found between AVs post-CI and the preoperative hearing threshold (HT) at 0.5 kHz at the non-implanted side (a). Positive correlations were found with preoperative speech perception with HAs (b) and preoperative AVs (c).

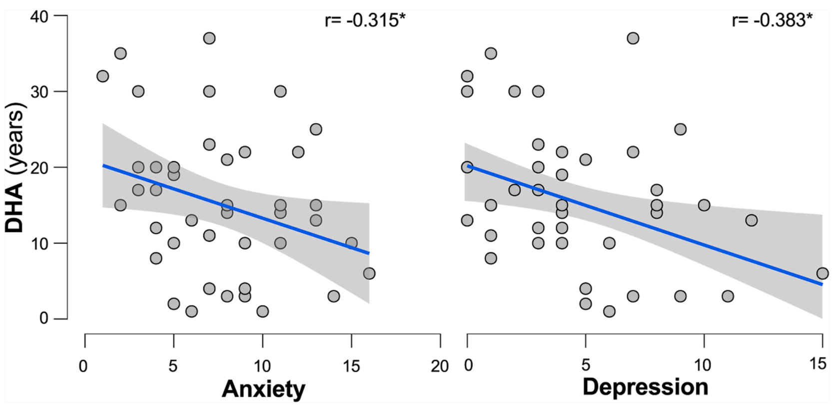

Fig. 5. Effect of duration of hearing loss on depression and anxiety. We found significant negative correlations between the duration of hearing loss (DHA) and depression and anxiety (* $p < 0.050$). One outlier with 63 years of hearing loss was removed from the statistical analysis.

bilateral superior parietal regions. A linear regression model including age, preoperative speech perception with HAs in both the auditory and the audiovisual conditions, HADS depression score, residual hearing at low frequency and CT of the left pars opercularis, explained up to 48.2 % of the variance of the results. When CT of the left pars opercularis was not included in the model, only 33 % of variability in outcome was explained, stressing the added value of brain morphometry data.

4.1. Relationship between preoperative clinical data and CI outcomes

Several studies (Lazard et al., 2012; Bernhard et al., 2021; Skidmore et al., 2020) have described that preoperative clinical characteristics may influence CI success. In our study, it was found that preoperative residual hearing at low frequency and speech perception, especially when measured with HA, impact CI outcome. The residual hearing threshold of the *non-implanted* ear was more strongly correlated with CI outcome than the threshold of the implanted ear. We explain this by the fact that the non-implanted ear is most of the time the least affected one and contributes to a larger extent to the stimulation of the auditory system. Our results are in line with those of a recent multicentric study in >2700 CI recipients (Goudey et al., 2021) showing that an *operational* auditory system is of utmost importance for a positive outcome of CI.

Also in line with earlier reports (Anderson et al., 2017; Moberly et al., 2023; Strelnikov et al., 2013; Stropahl et al., 2017), our data show that preoperative *audiovisual* speech perception is a better predictor of CI outcome than pure auditory speech perception. The inclusion of audiovisual speech perception in our linear regression model could be one of the reasons why we obtained a better predictive score of CI outcome than in previous studies, even when using only clinical data (Lee et al., 2021; Blamey et al., 2012). As previously mentioned, speechreading plays a crucial role in deaf individuals to decipher the altered auditory message, even for those wearing a CI (Grégoire et al., 2022, Rouger et al., 2007). Additionally, it helps maintain the linguistic representation of speech by engaging brain regions involved in oral language processing (Anderson et al., 2017).

Although numerous studies have shown a negative impact of duration of hearing loss on CI success rate (Lazard et al., 2012; Bernhard et al., 2021; Kim et al., 2018; Sun et al., 2021; Goudey et al., 2021; Zhao et al., 2020) (measured by pure auditory speech perception), our results show that *audiovisual* speech perception with CI is not affected by duration of HL. In other words, even if duration of HL negatively affects auditory rehabilitation with CI, good audiovisual integration skills can counteract this. The impact of age on CI outcome is still a matter of debate (Sun et al., 2021; Hiel et al., 2016). Our results show a slightly negative effect of age on CI outcome. This result is in line with recent papers showing a significant but mild effect of age on CI success (Boisvert et al., 2020; Goudey et al., 2021; Zhao et al., 2020). Another study did not find significant differences in outcome at 6 months between older and younger CI recipients, although outcome tended to degrade after 2 years of CI use in older adults (Lazard et al., 2023).

Table 3
Correlation between preoperative GM and audiovisual speech perception with the CI.

			Side	Brainnetome region	r
Thickness	*Whole left hemisphere*				0.384
	Parietal lobe	Precuneus	L	Medial part of A7	0.391
		Superior parietal lobule	L	Lateral part of A5	0.388
	Occipital lobe	Lateral occipital cortex	L	Lateral superior occipital gyrus	0.434
	Frontal Lobe	Inferior frontal gyrus	L	Opercular A44	0.477
		Middle frontal gyrus	L	Ventral area of A9/A46	0.368
		Superior frontal gyrus	L	Dorso-lateral A8	0.382
			L	Medial area of A8	0.384
			L	Lateral A9	0.371
		Orbital gyrus	L	Lateral area of A12/A47	0.369
		Precentral gyrus	L	A4 (tongue and larynx region)	0.362
	Temporal lobe	Superior temporal gyrus	L	T1.0 and T1.2	0.380
		Middle temporal gyrus	L	Anterior part of STS	0.394
		Posterior superior temporal sulcus (PSTS)	L	Rostral posterior part of STS	0.389
	Insular lobe		L	Dorsal dysgranular insula	0.438
Volume	*Parietal lobe*	Precuneus	L	Medial part of left A7	0.499
		Inferior parietal gyrus	L	Rostro-dorsal A40	0.443

The cortex is parcellated according to the Brainnetome Atlas. Reported Spearman's correlation coefficients (r) are significant at $P < 0.050$, FDR-corrected. All correlations are located in the left hemisphere.

Finaly, preoperative psychological factors such as anxiety and depression, can also negatively impact CI outcome, according to our results and those of others (Lailach et al., 2024). Deafness itself may augment prevalence of depressive symptoms (Powell et al., 2021; Powell et al., 2022; Reuter-Lorenz and Park, 2014). Interestingly, our results show that subjects with more recent deafness onset present higher depressive and anxiety scores, as confirmed in another study (Huang et al., 2024). This finding illustrates the remarkable resilience of late deaf subjects, who seem to have the capacity to progressively cope with their sensory impairment and accept it. It is worth adding that depression symptoms are partially reversible thanks to hearing loss restoration with HAs (Brewster et al., 2020).

4.2. Relationship between brain morphometric data from preoperative MRI and CI outcomes

Our results show that GM thickness and volume within the left temporal, bilateral frontal and parietal regions correlate positively with audiovisual speech perception with CI. However, these associations involve distinct regions for each structural characteristic. This pattern was previously observed in a study on prelingually deaf individuals, where CT was altered independently of volume. The authors hypothesized that concurrent changes in cortical surface area could explain the observed volume differences (Li et al., 2012).

One of the strongest correlations from our results was observed for CT of the left superior temporal gyrus and sulcus; their roles in hearing, and more specifically language processing, are well-known (Rauschecker, 2015; Hickok and Poeppel, 2007). Our results are in line with those of a recent study by Sun et al. (Sun et al., 2021), that showed a positive correlation between CI speech perception and GM volume in the left temporal sulcus. However, these authors also reported a *negative* correlation between CI outcome and an area in the superior temporal sulcus, and a positive correlation with thalamic volume. Several studies have reported a GM decrease and a WM alteration within bilateral temporal lobes both in patients with congenital and acquired auditory loss (Sun et al., 2021; Grégoire et al., 2022; Li et al., 2012). A recent study has highlighted that this GM volume decrease was mainly driven by a cortical thinning in age-related HL (Qiu et al., 2024). Besides its role in *auditory* language processing, the posterior part of the temporal region is also activated by lipreading, and this activation correlates with speech comprehension scores in CI users (Lazard and Giraud, 2017). Our results therefore confirm the suggestion by Sun et al. (Sun et al., 2021) that the preservation of this temporal region contributes to better CI success. Speechreading training and performance could contribute to the preservation of this cortical area, resulting in improved CI outcomes, as demonstrated by our findings and those of others (Anderson et al., 2017; Moberly et al., 2023; Strelnikov et al., 2013; Stropahl et al., 2017). Alternatively, the increase in CT of the posterior part of the temporal region could also be secondary to the use of HAs, as shown in subjects with age-related HL after one year of HA use (Pereira-Jorge et al., 2018).

In this study, CT of the left inferior frontal region correlated strongly with AVs post-CI. Moreover, our linear regression model improved significantly by the inclusion of CT measures of the opercular part of left BA44. In accordance with the present findings, earlier research demonstrated that the activation of the left inferior frontal gyrus, both during rest and in response to a speech task, serves as a predictor of CI outcome (Strelnikov et al., 2013; Mortensen et al., 2006). Furthermore, this region is activated in CI users in response to auditory only or incongruent audiovisual stimulations, likely reflecting the necessary cognitive engagement required to interpret the altered auditory message

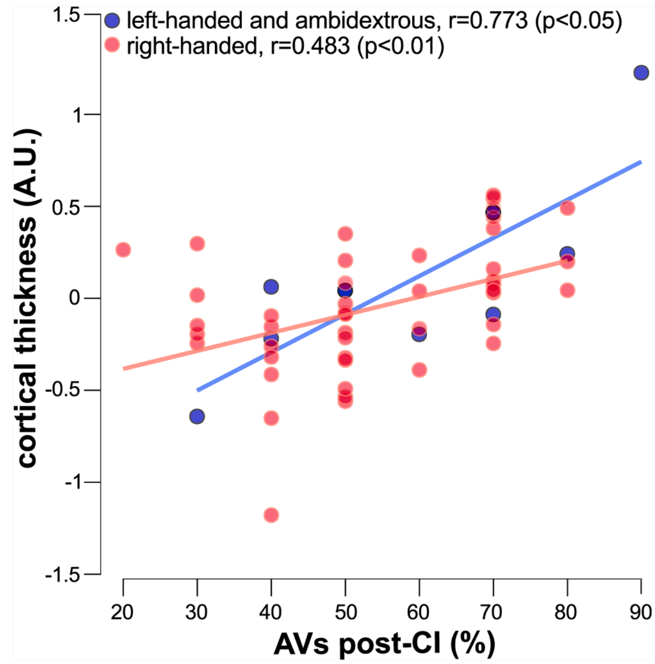

Fig. 6. Correlation between cortical thickness of the opercular part of the left A44 and AVs post-CI. Cortical thickness of the opercular part of the left A44 was introduced using the residuals from the regression model, adjusted for age and sex. The correlation remains significant when the cohort is divided into right-handed ($N = 47$) and non-right-handed (left-handed + ambidextrous, $N = 9$) patients. Abbreviation: A.U.: artificial unit.

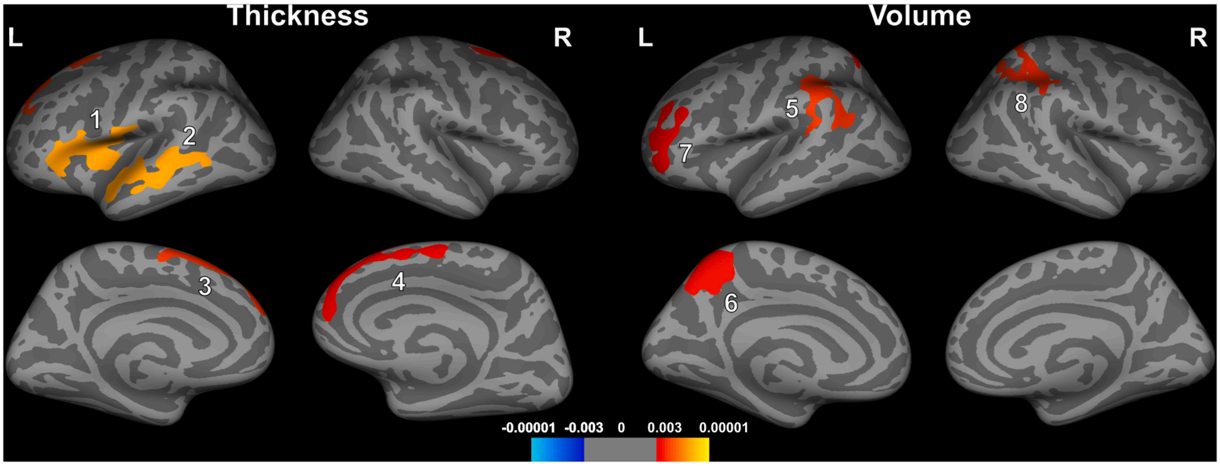

Fig. 7. Correlation between preoperative cortical thickness and volume and CI outcome. The vertex-by-vertex surface-based analysis shows significant positive correlations between AVs post-CI and preoperative cortical thickness (left panel) or cortical volume (right panel) ($p < 0.050$, after Monte Carlo simulation). Color bar indicates the uncorrected p-value. Six of the identified clusters were located in the left hemisphere. The clusters of CT were located in the left inferior frontal gyrus (cluster 1), left superior and middle temporal gyri (cluster 2), and bilateral superior frontal regions (clusters 3 and 4). Cortical volume clusters were located in the left inferior parietal area (cluster 5), left precuneus (medial superior parietal region, cluster 6), rostral part of the left middle frontal region (cluster 7), and right superior parietal region (cluster 8). The clusters are numbered in accordance with the nomenclature employed in Table 4.

Table 4
Characteristics of the clusters showing significant correlation with CI outcome from surface-based analysis.

				MNI coordinates			
	Cluster N°	P	Size (mm^2)	*X*	*Y*	*Z*	Brain area
Thickness	**1**	0.000	2499.32	−37.6	15.5	9.8	Left pars opercularis
	2	0.000	2425.34	−58.4	−56.3	−1.5	Left middle temporal
	3	0.000	1983.7	−6.6	33.8	49.8	Left superior frontal
	4	0.000	1830.85	22.5	0.6	63.9	Right superior frontal
Volume	**5**	0.000	1856.85	−43.6	−53.8	21.9	Left inferior parietal
	6	0.000	1661.28	−16.2	−66.7	59.2	Left superior parietal
	7	0.000	1619.79	−38.1	50	−3.4	Left rostral middle frontal
	8	0.000	1830.01	30.6	−47.5	44.4	Right superior parietal

(Song et al., 2015). The left inferior frontal cortex is broadly involved in speech processing, especially phonological processing (Papathanassiou et al., 2000; Hullett et al., 2024; MÁ et al., 2021), from perception to production (Hickok and Poeppel, 2007; Heim et al., 2008; Zatorre, 2002). It allows real-time auditory feedback, necessary for voice and articulatory control (Hullett et al., 2024). It is plausible that greater GM in the left inferior frontal region is partly due to the maintenance of some auditory feedback despite deafness, due to better residual hearing and functional use of hearing aids. Indeed, these behavioral factors are correlated with CI outcomes in our results (see Section 4.1). Higher language skills and cognitive functions may also preserve frontal GM and help patients to compensate for the loss of auditory feedback. In addition, higher cognitive resources, language skills and greater GM may be favored by continued social interactions despite hearing loss, allowing the maintenance of speech production.

In addition to the correlation with the left inferior frontal gyrus, CI outcome was also linked to GM of several other frontal and parietal subregions. Since these regions are largely involved in cognition, larger or thicker GM could be related to higher cognitive skills, leading to improved CI outcome. It is well known that the frontal lobe hosts various cognitive functions, in particular executive functions (working memory, inhibition-concentration, and planning and performance monitoring) (Dadario and Sughrue, 2023; Feng et al., 2022) and memory formation (Gilbert and Burgess, 2008). The precuneus and the inferior and superior parietal regions, which correlated with CI outcome in our study, also participate in cognitive skills, especially working memory, attention, spatial representation and visual motion perception (Breedlove and Watson, 2013; Culham and Kanwisher, 2001; Nickel and Seitz, 2005; Cavanna and Trimble, 2006). The latter skill has been shown to play a role in speechreading (Saalasti et al., 2023) and word retrieval (Schmidt et al., 2002). Interestingly, although AVs post-CI correlated with GM measures in frontal and parietal areas, no such strong correlation was found with preoperative AVs. Among various cognitive skills, working memory is thought to be particularly important in case of degraded hearing input (Rönnberg et al., 2013), which can be related to either hearing impairment or to the less refined auditory signal transmitted by the CI. CI outcome is also influenced by some general cognitive skills (Walia et al., 2022; Wazen et al., 2020). In addition, specific cognitive domains also seem to correlate with speech perception with CI, for instance processing speed (attentional domain) (Zucca et al., 2022), vocabulary and speed of lexical and phonological access (language domain) (Skidmore et al., 2020; Völter et al., 2022; Moberly et al., 2018), and non-verbal intelligence (Moberly et al., 2018; Beckers et al., 2023; Moberly et al., 2018). Conversely, CI itself improves some cognitive abilities, especially working memory, processing speed and attention (Knopke et al., 2021; Völter et al., 2018; Lin et al., 2023; Eickhoff et al., 2009; An et al., 2023). To summarize, we hypothesize that the increases in CT and volume of GM within frontal and parietal regions, which correlate with CI outcome, may be explained by better cognitive skills in CI recipients. This conjecture should be confirmed in future studies that combine neuroimaging and behavioral cognitive measures (Beckers et al., 2023).

From a more global perspective, our MRI data indicate that higher regional GM volume and thickness, compared to total intracranial

Table 5
Results of three linear regression models estimating AVs post-CI.

	Model Summary					Coefficients			
	Adj. R^2	SEE	ANOVA			B	SE B	t	P
			F	P					
Model 1	0.273	0.1465	2.794	0.014	(Constant)	0.685	0.253	2.668	0.012
					Age	−0.003	0.001	−2.001	0.053
					DHA	0.001	0.002	0.564	0.576
					Anxiety	0.006	0.009	0.665	0.510
					Depression	−0.013	0.011	−1.144	0.261
					HT CI side	0.000	0.001	0.251	0.803
					HT non-CI side	−0.002	0.002	−1.041	0.305
					WRS w/o HA	0.071	0.422	0.194	0.847
					WRS w/ HA	0.182	0.194	0.991	0.329
					AVs	0.242	0.136	1.818	0.078
Y = 0.685 + (−0.003 x age) + (0.001 x DHA) + (0.006 x anxiety) + (−0.013 x depression) + (0.000 x HT CI side) + (−0.002 x HT non-CI side) + (0.071 x WRS w/o HA) + (0.182 x WRS w/ HA) + (0.242 x AVs)									
Model 2	0.333	0.1388	5.400	0.001	(Constant)	0.752	0.219	3.434	0.001
					Age	−0.003	0.001	−1.977	0.055
					Depression	−0.009	0.008	−1.107	0.275
					HT non-CI side	−0.002	0.001	−1.331	0.191
					WRS w/ HA	0.193	0.168	1.145	0.259
					AVs	0.211	0.118	1.784	0.082
Y = 0.752 + (−0.003 x age) + (−0.009 x depression) + (−0.002 x HT non-CI side) + (0.193 x WRS w/ HA) + (0.211 x AVs)									
Model 3	0.482	0.1223	7.834	<0.001	(Constant)	0.421	0.215	1.961	0.057
					Age	0.000	0.001	0.218	0.829
					Depression	−0.007	0.007	−1.045	0.303
					HT non-CI side	−0.003	0.001	−2.345	0.024
					WRS w/ HA	0.102	0.151	0.677	0.502
					AVs	0.082	0.111	0.742	0.463
					CT left op A44	0.178	0.051	3.497	0.001
Y = 0.421 + (0.000 x age) + (−0.007 x depression) + (−0.003 x HT non-CI side) + (0.102 x WRS w/ HA) + (0.082 x AVs) + (0.178 x CT left op A44)									

Abbreviations: Adj. R^2: adjusted R^2; SEE: Standard Error of the Estimate; B: Unstandardized Coefficients; SE B: Standard Error of the Unstandardized Coefficients; DHA: duration of HA use, HT (non-)CI side: hearing thresholds at 0.5 kHz at (non-) CI side; CT left op A44: cortical thickness of the opercular part of left A44.

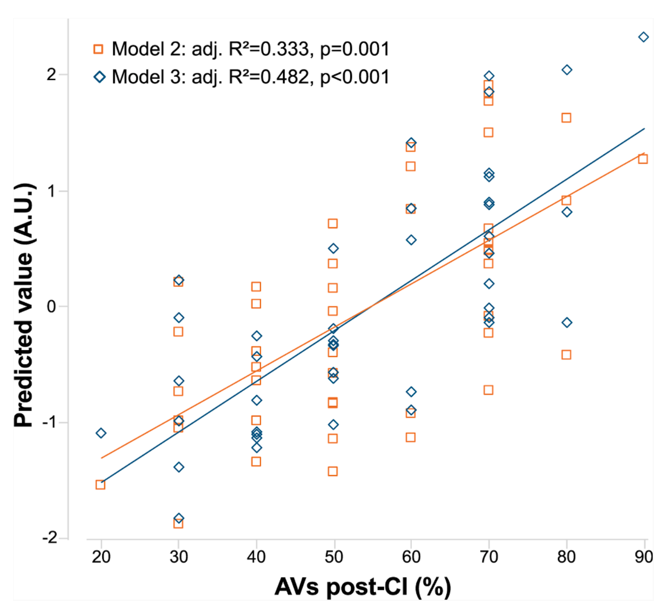

Fig. 8. Linear regression models of CI outcome prediction. Relationship between the actual audiovisual speech perception score (AVs post-CI) and its regression standardized predicted value. Results of linear regression models 2 and 3 are illustrated (see Table 5 for nomenclature). Model 3, which adds CT of the left pars opercularis in addition to the behavioral factors, has a higher predictive precision. Abbreviation: A.U.: artificial unit.

volume, are associated with better CI success. This relationship was not influenced by purported brain atrophy that is commonly observed in older individuals, as age was considered a nuisance factor in the statistical and surface-based analyses. Interestingly, hearing loss itself has been associated with accelerated whole brain atrophy (Manno et al., 2021; Lin et al., 2014) and faster cognitive decline (Powell et al., 2021; Lin et al., 2011; Hendriks et al., 2024), or at least poorer cognitive function (Croll et al., 2021), especially global cognitive and executive function, processing speed, and memory (Powell et al., 2021; Lin et al., 2011; Croll et al., 2021; Kramer et al., 2018). It has been hypothesized that both cognitive dysfunction and hearing loss are secondary to the same cause, which can be of genetic or general vascular origin (Baltes and Lindenberger, 1997). Furthermore, hearing loss itself may contribute to cognitive decline due to increased cognitive demands to decipher degraded auditory signals (Peelle, 2018), as well as through hearing loss-related social isolation (Lin et al., 2023; Hendriks et al., 2024; Livingston et al., 2020) and depression (Powell et al., 2021; Powell et al., 2022; Reuter-Lorenz and Park, 2014). In summary, the global GM atrophy that is correlated with worse CI outcome in our patients could be due to both hearing loss and cognitive decline. The deleterious effects of aging and hearing loss on brain structure and function can be partially delayed by various factors or interventions, such as higher IQ and education, cognitive and physical training, and social and intellectual engagements (Reuter-Lorenz and Park, 2014; Stern et al., 2020; Oosterhuis et al., 2023). Moreover, hearing loss rehabilitation itself enhances cognitive ability (Lin et al., 2023), delays dementia and reduces depression symptoms (Brewster et al., 2020) in addition to improve speech perception, and should therefore be strongly recommended.

4.3. Limitations and directions for future research

Our results reveal significant relationships between CI outcome and both preoperative behavioural and MRI data. Specifically, the linear regression models suggest that incorporating CT of the left inferior frontal gyrus into the model can enhance the accuracy of CI outcome prediction. Although we have a relatively robust sample size (N = 56), these results should be confirmed in an independent cohort.

Although we included only patients who received CI in adulthood, five had experienced HL before the age of 7 with progressive deterioration. Even if their HL was initially mild to moderate, and effectively compensated by HAs, it may still have influenced the normal development of the central auditory pathway and auditory cortex, and, consequently, brain imaging outcomes.

We did not take into account the potential effect of other factors that may influence CI success. For instance, the impact of rehabilitation interventions, such as the frequency and regularity of speech therapy, warrants further investigation. The etiology of deafness may also affect outcome, although a clear diagnostic of the cause of hearing loss is often lacking, both in this and other studies. One reason for this is that genetic analyses are not routinely performed due to their high cost.

We hypothesize that greater CT or GM volume, particularly within the frontal and parietal lobes, may contribute to better CI outcomes, potentially by supporting superior cognitive function. To test this hypothesis, systematic preoperative cognitive assessments should be conducted and correlated with CT and GM volume measurements obtained from preoperative brain MRI.

Future research should also focus on long-term outcomes (e.g., one year or more) to identify factors associated with slower CI adaptation or decline in speech perception over time.

Lastly, while this study focused on anatomical data with the objective of proposing predictive factors for CI outcomes based on anatomical MRI, which is readily applicable in clinical practice, it would also be valuable to explore how the cortical characteristics identified relate to functional reorganization in these regions. Functional MRI (fMRI) or metabolic (PET-FDG) data could be utilized for this purpose.

5. Conclusion

Our results suggest that preoperative structural MRI measures, audiovisual speech perception and mood are important predictors of CI success, explaining together 40 % of the variance. Preoperative audiovisual information integration emerged as a significant clinical predictor, likely due to its role in supporting the low-quality auditory signal provided by the CI. The preservation of GM in the left superior temporal gyrus and sulcus, as well as in the left inferior frontal gyrus and in parietal regions, was associated with higher CI success. This GM preservation may be linked to the preservation of functional language networks and higher cognitive resources that enable easier adaptation to the degraded auditory signal provided by the CI. Although these results warrant confirmation in a larger cohort, they underscore the significant influence of clinical and anatomical predictors, which could ultimately contribute to more precise and personalized treatment strategies for patients with hearing loss.

Funding source

This research was partly supported by a grant from the Rotary Club of Mechelen, Belgium.

Use of AI statement

During the preparation of this work, the authors used DeepL and ChatGPT in order to improve scientific writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Anaïs M. Grégoire: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Laurence Dricot:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation. **Caroline Huart:** Writing – review & editing, Conceptualization. **Monique Decat:** Writing – review & editing, Resources, Investigation. **Naïma Deggouj:** Writing – review & editing, Resources, Methodology, Conceptualization. **Ron Kupers:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.heares.2025.109272.

Data availability

The authors do not have permission to share data.

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