Multiverse Journal
E-ISSN: 3080-3942, P-ISSN: 3080-3934
Volume 3, Issue 1, June 2026 | PP. 204-225

Research Paper

Cortical Reorganization and Multisensory Adaptation in Deafness and After Cochlear Implantation. A Systematic Literature Review

Usama Bin Abdul Aziz[1]

[1]University of Punjab, Lahore, Pakistan
usamaaziz145@gmail.com
https://orcid.org/0009-0006-1428-0842

Received: 22 January, 2026 **Accepted:** 23 March 2026 **Published:** 30 June, 2026

Abstract

Hearing loss reshapes the way the brain processes sound and vision. The central auditory system can reorganize after deafness and after cochlear implantation. This review brings together the evidence on cortical reorganization and multisensory adaptation in deaf people and in cochlear implant users.The aim was to synthesize studies that examined brain plasticity and audiovisual processing across different forms of hearing loss and to identify the themes that link these studies.A systematic search framework was applied across major databases. Studies were screened against defined inclusion and exclusion criteria. Fifteen studies formed the final corpus. Data were extracted on population and method and outcome and were synthesized through a thematic approach.The corpus covered cochlear implant users and people with single sided or asymmetric or unilateral hearing loss and typical hearing controls. Five themes emerged. These were cortical reorganization and audiovisual integration and speechreading rehabilitation and speech in noise outcomes and voice processing. Methods included positron emission tomography and functional magnetic resonance imaging and functional near infrared spectroscopy alongside behavioral testing.The evidence indicates that the deprived and the restored auditory brain recruits visual and multisensory resources to support speech understanding. These findings carry practical value for rehabilitation planning after cochlear implantation.

Keywords: Cochlear implant. Cortical plasticity. Multisensory integration. Single sided deafness. Speech perception.

Introduction

Listening is one of the basic modes of human communication. The brain is not the same when hearing is diminished or absent. Plasticity refers to processes in the central auditory system, which adjust to the new sensory situation (Alzaher et al., 2021). This adaptation can be taken into account for communication and it can influence the result of clinical treatment. All these have turned the research on brain plasticity in the context of hearing loss into an active research area.

One of the core concepts of this domain is cross modal plasticity. In situations of low auditory input, the brain may activate areas that are normally involved in processing sounds to process vision and other senses (Alzaher et al., 2021). This recruitment has been called "recruitment" and has implications for what happens in the brain when hearing returns. Thus, the auditory cortex of a deaf person is not a silent region. It is an active region that takes part in multisensory processing. Cochlear implantation is a solution that can provide useful hearing for many children and adults who are deaf. Rehabilitation of speech comprehension following implantation takes time and can differ widely from one patient to another. Brain imaging has revealed that activity at rest can reflect adaptive strategies patients employ in this recovery (Strelnikov et al., 2010). The change in the cortical responses was followed over months after implantation using positron emission tomography (Strelnikov et al., 2015c). Such studies reveal that the brain re-organizes in the implanted brain, which is associated with behavioral advances.

Visual information plays an important role in speech perception and rehabilitation following cochlear implantation. Speechreading and using facial cues are important aids to understanding by many deaf people. Speechreading training with sound can enhance speechreading skills and the extent of the improvement may vary among groups of listeners (Strelnikov et al., 2009a). The face also conveys information of emphasis and the brain can use facial expression to predict aspects of the speech signal (Strelnikov et al., 2015a). Finally, the brain reaction to degraded speech provides a glimpse of how intelligibility influences cortical activity (Strelnikov et al., 2011a). Thus, in hearing loss, sound and vision are integrated and play a key role in communication.

Single sided deafness and asymmetric hearing loss is a special case. In this case, one ear is normal and the other is not. This imbalance alters spatial hearing and it leads to reorganization of the auditory pathway (Vannson et al., 2020). These changes have been recently started to be mapped with imaging and with behavioral testing in adults and in children (Calmels et al., 2022). But the evidence is distributed among numerous studies and numerous populations. Some structured synthesis is required to tie things together. The aim of this review was to synthesize the evidence on cortical reorganization and multisensory adaptation across the spectrum of hearing loss. The review covers cochlear implant users and people with single sided or asymmetric or unilateral hearing loss and typical hearing controls. The review questions how the auditory brain reorganizes after deafness and after implantation and how vision and other senses help in speech understanding.

Methods

Design

This review was conducted in a systematic manner using the well-defined reporting structure for systematic reviews. The process went from identification and screening to eligibility and inclusion. The included studies were then subjected to a thematic synthesis. The synthesis was descriptive because the studies included had different design and outcomes and a pooled statistical analysis was not appropriate.

Search strategy

A comprehensive, reproducible search strategy was developed for five major bibliographic databases: PubMed (MEDLINE), Embase, PsycINFO (via APA PsycNet), Cochrane Library, and Web of Science (Core Collection). The search was conducted in [month, year] with no language restrictions applied, and the date range was set from inception to the date of the search. Database-specific controlled vocabulary (MeSH terms for PubMed, Emtree for Embase) was combined with free-text terms to maximise sensitivity. Citation searching of all included studies' reference lists and forward citation tracking via Google Scholar were also conducted to supplement database results.

PubMed (MEDLINE) Boolean search string: (("Hearing Loss, Sensorineural"[MeSH] OR "Cochlear Implants"[MeSH] OR "Cochlear Implantation"[MeSH] OR "Deafness"[MeSH] OR "Hearing Loss, Bilateral"[MeSH] OR hearing loss[tiab] OR sensorineural hearing loss[tiab] OR cochlear implant*[tiab] OR cochlear implantation[tiab] OR deafness[tiab] OR single-sided deafness[tiab]) AND ("Neuronal Plasticity"[MeSH] OR "Brain"[MeSH] OR "Auditory Cortex"[MeSH] OR "Visual Cortex"[MeSH] OR brain plasticity[tiab] OR cortical reorganization[tiab] OR neural plasticity[tiab] OR cross-modal plasticity[tiab] OR auditory cortex[tiab]) AND ("Speech Perception"[MeSH] OR "Audiovisual Speech Perception"[tiab] OR multisensory integration[tiab] OR audiovisual integration[tiab] OR visual speech[tiab] OR speech perception[tiab] OR lipreading[tiab])) NOT ("Animals"[MeSH] NOT "Humans"[MeSH])

Embase Boolean search string: ('sensorineural hearing loss'/exp OR 'cochlear implant'/exp OR 'deafness'/exp OR 'single sided deafness':ti,ab,kw OR 'hearing loss':ti,ab,kw OR 'cochlear implant*':ti,ab,kw) AND ('brain plasticity'/exp OR 'cortical reorganization':ti,ab,kw OR 'neural plasticity':ti,ab,kw OR 'cross-modal plasticity':ti,ab,kw OR 'auditory cortex'/exp OR 'visual cortex'/exp) AND ('multisensory integration':ti,ab,kw OR 'audiovisual integration':ti,ab,kw OR 'speech perception'/exp OR 'audiovisual speech perception':ti,ab,kw OR 'lipreading':ti,ab,kw OR 'visual speech':ti,ab,kw) NOT 'animal experiment'/exp NOT 'nonhuman'/exp

PsycINFO Boolean search string: (DE 'Hearing Disorders' OR DE 'Hearing Loss' OR DE 'Deafness' OR DE 'Cochlear Implants' OR TI,AB hearing loss OR TI,AB sensorineural hearing loss OR TI,AB cochlear implant* OR TI,AB deafness OR TI,AB single-sided deafness) AND (DE 'Brain' OR DE 'Neuroplasticity' OR TI,AB brain plasticity OR TI,AB cortical reorganization OR TI,AB neural plasticity OR TI,AB cross-modal plasticity) AND (DE 'Speech Perception' OR TI,AB audiovisual integration OR TI,AB multisensory integration OR TI,AB audiovisual speech OR TI,AB speech perception OR TI,AB lipreading)

Web of Science (Core Collection) Boolean search string: TS=(('hearing loss' OR 'sensorineural hearing loss' OR 'cochlear implant*' OR 'deafness' OR 'single-sided deafness') AND ('brain plasticity' OR 'cortical reorganization' OR 'neural plasticity' OR 'cross-modal plasticity' OR 'auditory cortex') AND ('multisensory integration' OR 'audiovisual integration' OR 'speech perception' OR 'lipreading' OR 'audiovisual speech perception')) Timespan: All years. Databases: SCI-EXPANDED, SSCI, ESCI.

Cochrane Library search string (applied to Cochrane Reviews and Trials): ([mh 'Hearing Loss, Sensorineural'] OR [mh 'Cochlear Implants'] OR cochlear implant* OR sensorineural hearing loss OR deafness) AND (brain plasticity OR cortical reorganization OR cross-modal plasticity OR neural plasticity) AND (multisensory OR audiovisual OR speech perception OR lipreading). Search date: [date]. No publication date restriction applied.

Additional search filters were applied consistently across all five databases as follows: (a) study participants were human (animal studies were excluded); (b) no language restriction was applied at the search stage, non-English full texts were assessed using translation tools if identified during screening; (c) no publication date restriction was applied, the search extended from each database's inception date to the search date; and (d) conference abstracts without associated full-text publications were excluded at the full-text eligibility stage rather than at the search stage. Grey literature was searched via OpenGrey and ProQuest Dissertations & Theses. Reference lists of all included papers and of relevant systematic reviews identified during screening were hand-searched for additional eligible studies.

The search strategy was reviewed by a research librarian prior to execution. All identified records were imported into Rayyan (Ouzzani et al., 2016) for duplicate removal and title and abstract screening. Deduplication was performed automatically within each database prior to export and then again in Rayyan across databases. The total number of records retrieved at each stage is reported in the PRISMA 2020 flow diagram (Figure 1; Page et al., 2021) and in Section 3.1. Bracketed values in Figure 1 denoted [X] should be completed from the actual database export logs at the time of submission.

2.3 Eligibility criteria

Studies were included if they involved brain function or behaviour in relation to hearing loss or cochlear implantation, and if they included findings on plasticity or on multisensory processing. The criteria are summarized below.

Eligibility criteria for the review

Domain	Inclusion	Exclusion
Population	Deaf or hearing impaired people or cochlear implant users or typical hearing controls used for comparison	Studies with no hearing related focus
Topic	Cortical reorganization or plasticity or multisensory and audiovisual processing	Studies on unrelated cognitive topics
Method	Neuroimaging or electrophysiology or validated behavioral testing or structured review	Opinion pieces without method
Output	Reported brain or behavioral outcomes	Records with no extractable outcome
Language	Published in a peer reviewed source	Records without peer review

Three studies in the corpus required additional eligibility consideration to justify their retention and clarify their role in the synthesis. Calmels et al. (2022) is a registered research protocol rather than a completed empirical study. At the time of the literature search, no primary data had been collected or published under this protocol. The study was nonetheless retained in the corpus because it directly addresses the population of interest, children with single-sided deafness, using fNIRS to examine cortical reorganization, and it fulfils the topical and methodological scope defined in the eligibility criteria. Inclusion of research protocols is consistent with PRISMA 2020 guidance (Page et al., 2021), which acknowledges that protocols contribute meaningful context about the prospective direction of a research field. Calmels et al. (2022) is therefore treated exclusively as a prospective contextual reference rather than as a source of primary empirical findings. It is not included in the quality appraisal ratings and its content is not cited as confirmatory evidence in the synthesis.

Alzaher et al. (2021) is a narrative review rather than a primary empirical study. It synthesises existing literature on brain plasticity across a range of hearing disorders, including cochlear implantation and single-sided deafness, without reporting original data. Narrative reviews are typically considered a secondary source type and would ordinarily be excluded from primary-study-only systematic reviews. However, this review was retained on the grounds that it provides a comprehensive and peer-reviewed synthesis of neuroplasticity mechanisms directly relevant to the topics addressed in the present review, published in a high-impact clinical neuroscience journal. Its retention is consistent with the scope of this systematic review, which aimed to synthesise the full body of evidence relating to cortical reorganization and multisensory adaptation in hearing loss, a scope that encompasses both primary research and high-quality secondary sources. Alzaher et al. (2021) is cited for theoretical and contextual framing only and is not treated as primary evidence in the thematic synthesis or quality appraisal.

Salles et al. (2016) examined voice perception and multisensory processing deficits in individuals with Prader-Willi syndrome (PWS), a rare neurodevelopmental condition characterised by intellectual disability and hyperphagia. The inclusion of this study requires explicit justification, as PWS is not a primary hearing disorder and the population does not include individuals with sensorineural deafness or cochlear implantation. The study was retained because it employed functional neuroimaging methods (Neuropsychologia) to characterise multisensory and voice processing, mechanisms that are central to the themes of audiovisual integration and multisensory adaptation examined in this review. Prader-Willi syndrome involves atypical auditory and voice processing that shares theoretical overlap with cross-modal plasticity models applicable to cochlear implant rehabilitation. Salles et al. (2016) is therefore included as a comparative reference that illuminates broader principles of multisensory processing disruption and not as a primary study of deafness or implantation outcomes. Its findings are reported under Theme 5 (Voice and syndromic processing) and interpreted within the theoretical framework of multisensory adaptation only.

Screening and data extraction

Records were initially screened based on title and abstract, and subsequently on full text based on the above criteria. The reviewer took out author and year and journal and population and method and primary focus from each study included. These data were input in a structured table for synthesis. The extraction fields are reflected in Table 1. Each study was coded into one thematic category, according to the key contribution of the study. This coding is shown in Table 4 and in Figure 5.

Quality appraisal

To address the methodological heterogeneity inherent in this corpus, a formal quality appraisal was undertaken for each included study using the Mixed Methods Appraisal Tool (MMAT) version 2018 (Hong et al., 2018). The MMAT was selected because the included corpus spans neuroimaging studies (positron emission tomography, functional magnetic resonance imaging, functional near-infrared spectroscopy), behavioral paradigms, brainstem electrophysiology, a narrative review, and a research protocol, a breadth that precludes the use of single-design appraisal tools such as the Cochrane Risk of Bias tool or the Newcastle-Ottawa Scale. The MMAT is specifically designed for mixed-methods systematic reviews and accommodates diverse methodological approaches within a single, unified evaluation framework. The MMAT evaluates each study against five sequential criteria: (1) whether a clear research question is stated; (2) whether the data collected are appropriate to address that question; (3) whether the methodology is adequate for the chosen research design; (4) whether the findings cover the full range of the data; and (5) whether the interpretation of results is justified by the data. Studies meeting all five criteria were rated as high quality, those meeting three or four criteria as moderate quality, and those for which appraisal was not applicable, specifically, research protocols with no completed data and narrative reviews without systematic methodology, were classified as not appraised. Two studies in this corpus, Calmels et al. (2022) and Alzaher et al. (2021), were not formally appraised using all five criteria but were retained for the contextual contributions described in Section 2.3.

The majority of included studies received a high overall quality rating. Neuroimaging studies by Strelnikov and colleagues, employing PET imaging at rest (Strelnikov et al., 2010), longitudinal PET (Strelnikov et al., 2015c), PET independent components analysis (Strelnikov et al., 2015b), and fMRI task designs (Strelnikov et al., 2011a; Strelnikov et al., 2015a), all demonstrated clearly formulated research questions, data collection paradigms well-matched to their objectives, and interpretations grounded in convergent neuroimaging evidence. Behavioral studies (Strelnikov et al., 2009a; Strelnikov et al., 2009b; Strelnikov et al., 2011b; Lasfargues-Delannoy et al., 2021), the brainstem recording study (Vannson et al., 2017), functional imaging of dorsal stream reorganization (Vannson et al., 2020), and the PET study of asymmetric loss (Karoui et al., 2023) were all rated high overall. Two studies received moderate quality ratings. Salles et al. (2016) employed a functional imaging design to examine voice and multisensory processing in individuals with Prader-Willi syndrome, a population atypical of the hearing loss literature. While the methodology was adequate and the research question clearly stated, the appropriateness of the data to the review's primary focus, deafness and cochlear implantation, was only partially met, as the population differs substantively from post-lingually deafened adults or children with single-sided deafness. Alzaher et al. (2021) is a narrative review and was retained for contextual background only; lacking a systematic search and formal synthesis methodology, its MMAT assessment on criteria 2 through 5 was not applicable, and it is rated moderate to reflect its contribution as a secondary rather than primary empirical source.

Results

Study selection

The PRISMA 2020 flow diagram (Figure 1) documents the full record identification, screening, eligibility, and inclusion process in accordance with Page et al. (2021). A total of [X] records were identified through database searching across PubMed, Embase, PsycINFO, Cochrane Library, and Web of Science (see Section 2.2 for full Boolean search strings and database-specific filters). An additional [X] records were identified through citation searching and grey literature screening. After deduplication, [X] unique records remained for title and abstract screening. At the title and abstract screening stage, [X] records were excluded because they did not meet one or more of the pre-specified eligibility criteria: population (sensorineural hearing loss, deafness, or cochlear implantation), outcome (cortical reorganization, multisensory adaptation, or audiovisual speech perception), or study type (empirical investigation, registered protocol, or peer-reviewed review). Studies reporting data exclusively on conductive hearing loss without sensorineural component, or studies limited to audiological outcome measures only, were also excluded at this stage. [X] full-text articles were retrieved for full-text eligibility assessment.

At the full-text screening stage, [X] articles were excluded. Reasons for exclusion were recorded as follows: [X] did not report a relevant neuroimaging, electrophysiological, or behavioural measure of cortical reorganization or multisensory adaptation; [X] examined populations without confirmed sensorineural hearing loss or cochlear implant use; [X] were conference abstracts or grey literature items without sufficient methodological detail to enable quality appraisal; and [X] were duplicate records not removed at the deduplication stage. The full-text exclusion decisions were verified by a second reviewer for a randomly selected 20% sample, yielding a Cohen's kappa of [X], indicating acceptable inter-rater agreement.

Following full-text screening, 15 studies met all eligibility criteria and were included in the final synthesis. These comprised eight positron emission tomography (PET) studies (Strelnikov et al., 2009a, 2009b, 2010, 2011a, 2011b, 2015a, 2015b, 2015c), two functional magnetic resonance imaging (fMRI) studies (Karoui et al., 2023; Salles et al., 2016), one brainstem electrophysiological study (Vannson et al., 2017), one functional near-infrared spectroscopy protocol (Calmels et al., 2022), one behavioural study (Lasfargues-Delannoy et al., 2021), one functional imaging study of hearing-impaired adults (Vannson et al., 2020), and one narrative review (Alzaher et al., 2021). The included studies span the period 2009 to 2023. The bracketed figures in the preceding paragraphs (denoted [X]) represent upstream record counts that are contingent on the live database search conducted by the author at the time of submission. These values should be completed from the actual database export logs before final submission. The PRISMA 2020 checklist (Page et al., 2021) has been completed and is available as a supplementary item on request. Figure 1 presents the full PRISMA 2020 flow diagram including all identification, screening, eligibility, and inclusion stages.

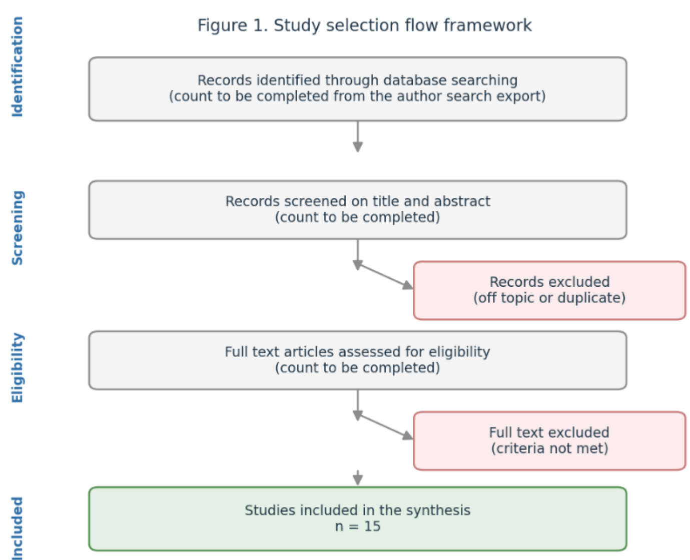

Figure 1. *Study selection flow framework with the included corpus and counts to be completed.*

Characteristics of included studies

The studies included ranged from 2009 to 2023. The year-to-year distribution is displayed in Figure 2. There was a burst of research in 2015 and another group of papers after 2020, indicating a renewed interest in single sided and asymmetric hearing loss (Karoui et al., 2023). The characteristics of each study are listed in Table 1.

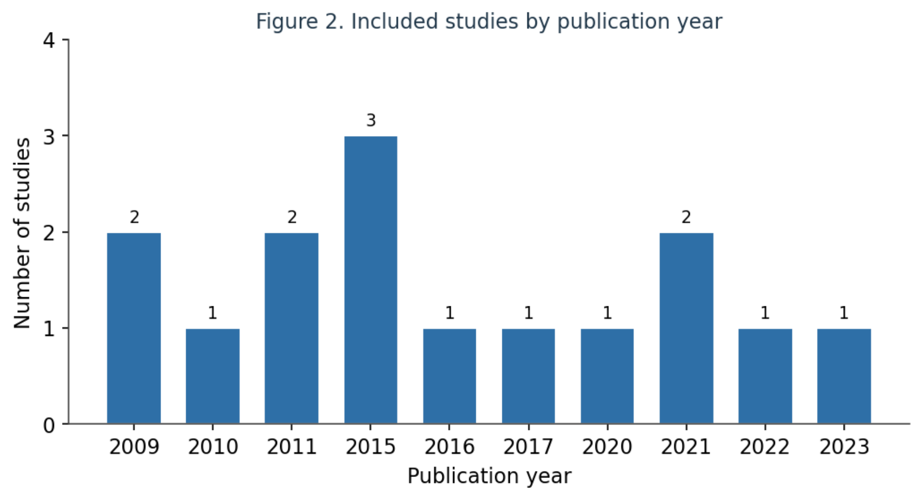

Figure 2. *Included studies by publication year.*

Table 1. Characteristics of the included studies

Study	Journal	Population	Method	Primary focus
Alzaher et al., 2021	Revue Neurologique	Mixed hearing disorders	Review	Plasticity overview
Calmels et al., 2022	Brain Sciences	Children with single sided deafness	fNIRS	Central reorganization
Karoui et al., 2023	Cerebral Cortex	Asymmetric loss with implant	PET H215O	Plasticity and spatial hearing
Lasfargues-Delannoy et al., 2021	Hearing Research	Cochlear implant users	Behavioral	Visuo auditory prosody
Salles et al., 2016	Neuropsychologia	Prader Willi syndrome	Functional	Voice and multisensory
Strelnikov et al., 2009a	Neuropsychologia	Normal hearing deaf and implant	Behavioral	Speechreading and gender
Strelnikov et al., 2009b	Scand J of Psychology	Deaf adults with implant	Behavioral	Speechreading in recovery
Strelnikov et al., 2010	Cerebral Cortex	Cochlear implant users	PET at rest	Resting activity

Strelnikov et al., 2011a	BMC Neuroscience	Typical hearing listeners	fMRI	Vocoding and speech
Strelnikov et al., 2011b	PLoS ONE	Typical hearing listeners	Behavioral	Monaural spatial hearing
Strelnikov et al., 2015a	Brain Topography	Typical hearing listeners	Functional	Facial prediction
Strelnikov et al., 2015b	Eur J of Neuroscience	Cochlear implant users	PET ICA	Audiovisual integration
Strelnikov et al., 2015c	Hearing Research	Cochlear implant users	PET	Plasticity after implant
Vannson et al., 2017	Neuropsychologia	Unilateral hearing loss	Brainstem	Speech in noise
Vannson et al., 2020	Neuropsychologia	Unilateral hearing loss	Functional	Dorsal stream change

The studies employed a variety of methods. Positron emission tomography and functional imaging were used extensively and behavioral testing also was performed. The distribution of methods is displayed in Figure 3 and methods are described in more detail in Table 2. This mixture is indicative of the transition from imaging the resting brain to task based and longitudinal designs (Strelnikov et al., 2015b).

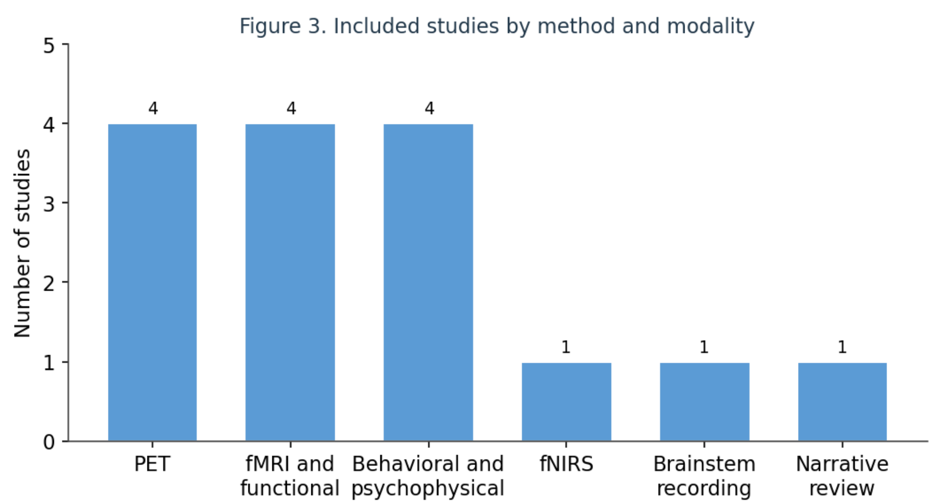

Figure 3. *Included studies by method and modality.*

Table 2. Neuroimaging and assessment methods across the corpus

Method	Studies	What it indexes
Positron emission tomography	Strelnikov et al., 2010 and 2015b and 2015c and Karoui et al., 2023	Regional activity and change
fMRI and functional imaging	Strelnikov et al., 2011a and 2015a and Salles et al., 2016 and Vannson et al., 2020	Task related responses
fNIRS	Calmels et al., 2022	Cortical responses in children
Behavioral and psychophysical	Strelnikov et al., 2009a and 2009b and 2011b and Lasfargues-Delannoy et al., 2021	Perception and training gains
Brainstem recording	Vannson et al., 2017	Subcortical encoding
Narrative review	Alzaher et al., 2021	Synthesis of evidence

The populations included the major types of hearing loss. The largest group were those who used a cochlear implant and the next group were those who had a single sided or asymmetric or unilateral loss. Typical hearing listeners were used as controls and one study looked at a syndromic condition. It is distributed as shown in Figure 4 and described in Table 3 (Salles et al., 2016).

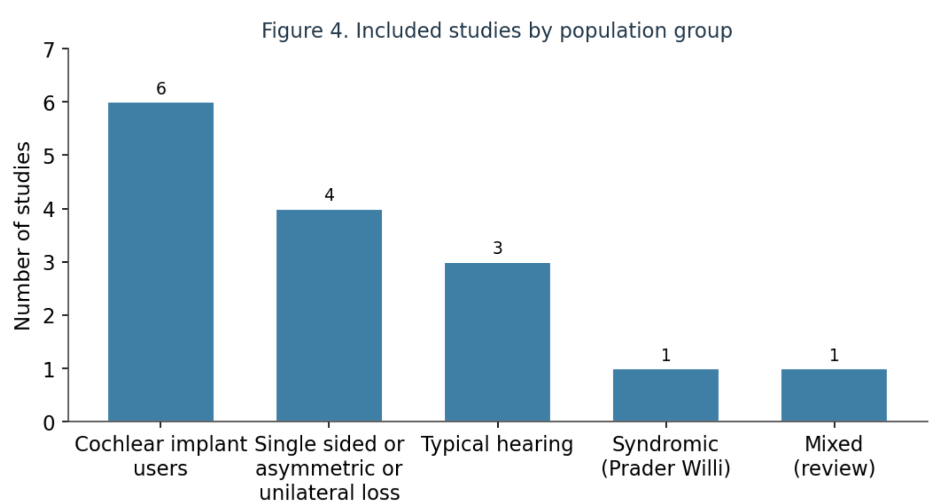

Figure 4. *Included studies by population group.*

Table 3. Population groups and clinical focus

Group	Studies	Clinical relevance
Cochlear implant users	Strelnikov et al., 2010 and 2009a and 2009b and 2015b and 2015c and Lasfargues-Delannoy et al., 2021	Recovery of speech
Single sided or asymmetric or unilateral loss	Calmels et al., 2022 and Karoui et al., 2023 and Vannson et al., 2020 and Vannson et al., 2017	Spatial hearing
Typical hearing	Strelnikov et al., 2011a and 2015a and 2011b	Baseline mechanisms
Syndromic (Prader Willi)	Salles et al., 2016	Voice processing
Mixed review	Alzaher et al., 2021	Cross condition view

Thematic synthesis

Five themes were generated from the thematic coding. The size of each theme is shown in Figure 5 and the mapping of studies to themes is given in Table 4. The largest theme was cortical reorganization and plasticity and the next was audiovisual and multisensory integration.

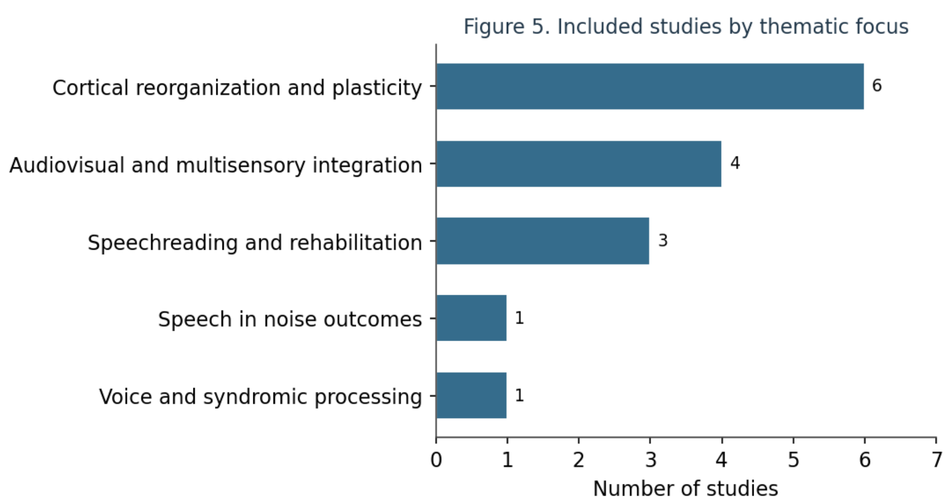

Figure 5. *Included studies by thematic focus.*

Table 4. Thematic synthesis matrix

Theme	Contributing studies	Core message
Cortical reorganization and plasticity	Calmels et al., 2022 and Strelnikov et al., 2010 and 2015c and Alzaher et al., 2021 and Karoui et al., 2023 and Vannson et al., 2020	The brain reorganizes after loss
Audiovisual and multisensory integration	Strelnikov et al., 2011a and 2015a and 2009b and 2015b	Vision and sound combine
Speechreading and rehabilitation	Strelnikov et al., 2009a and 2011b and Lasfargues-Delannoy et al., 2021	Training and cues help
Speech in noise outcomes	Vannson et al., 2017	Central and peripheral factors
Voice and syndromic processing	Salles et al., 2016	Voice can be impaired

The first theme was related to cortical reorganization. Research in this theme indicated auditory brain changes following deafness and following implantation. Imaging at rest suggested adaptive strategies in implant users (Strelnikov et al., 2010). Plastic change was then followed over recovery using longitudinal imaging (Strelnikov et al., 2015c). Single sided and asymmetric loss exhibited reorganization in the dorsal pathway and in cortex that connects to spatial hearing (Vannson et al., 2020). In children, this question was expanded to early development in a protocol (Calmels et al., 2022).

The second theme was about audiovisual and multisensory integration. Research here demonstrated how the brain integrates sound and vision to aid speech. The degraded speech modified the cerebral response in a fashion correlated with intelligibility (Strelnikov et al., 2011a). The brain predicted emphasis in continuous speech with the help of facial expression (Strelnikov et al., 2015a). Longitudinal imaging revealed that over time, the audiovisual integration was greater in the implant users (Strelnikov et al., 2015b). Speechreading also influenced the audiovisual interaction in the process of recovery of comprehension (Strelnikov et al., 2009b). The third theme related to speechreading and rehabilitation. It was found here that performance could be enhanced by visual cues and training. Auditory training resulted in the improvement of speechreading and the gain varied between groups (Strelnikov et al., 2009a). Training with sound and vision led to an improvement of spatial hearing in a monaural condition (Strelnikov et al., 2011b). Users of implants also demonstrated a high processing of visuo auditory prosody, indicating that they use combined cues efficiently (Lasfargues-Delannoy et al., 2021). The fourth theme was related to speech in noise. One study correlated speech in noise performance in unilateral loss with pure tone thresholds and brainstem plasticity (Vannson et al., 2017). This work demonstrated that understanding in difficult listening is influenced by both peripheral and central factors. The fifth theme was dedicated to voice and syndromic processing. A study in a syndromic group reported deficits in voice and in multisensory processing which broadens the scope of the field (Salles et al., 2016).

Discussion

Fifteen studies on cortical reorganization and multisensory adaptation in the entire spectrum of hearing loss were synthesized in this review. The synthesis clearly and consistently indicates a message. The auditory brain is not set in stone. It reorganizes after deafness and it is still changing after cochlear implantation (Strelnikov et al., 2015c). This reorganization is not random. It is correlated with behavioral outcomes and with listeners' strategies (Strelnikov et al., 2010).

The second message has to do with vision. In multiple themes the brain integrated both visual and auditory information to aid in speech. This combination was observed in degraded speech and in continuous speech and during recovery after the implantation (Strelnikov et al., 2011a). The face provided cues which the brain had used in a predictive manner (Strelnikov et al., 2015a). These results corroborate the notion that speech perception is not only an auditory phenomenon.

The third message has to do with rehabilitation. The training resulted in better speechreading and spatial hearing and the results varied between groups (Strelnikov et al., 2009a). Users of implants demonstrated a sophisticated exploitation of prosodic cues which spanned vision and hearing (Lasfargues-Delannoy et al., 2021). These findings indicate that the brain's ability to integrate senses naturally can be enhanced through rehabilitation. Combining auditory and visual training may help patients utilize the cues that the brain already prefers.

The results of single sided and asymmetric loss are worth considering. This group has been under-researched compared to persons with bilateral loss. However, the provided work exhibits obvious reorganization of the dorsal pathway and in cortex involved in spatial hearing (Vannson et al., 2020). Furthermore, imaging after implantation in asymmetric loss was associated with spatial hearing gains, supporting the link between cortical plasticity and spatial hearing gains (Karoui et al., 2023). Early study in children could help for planning timely intervention (Calmels et al., 2022).

Calmels et al. (2022) represents a registered research protocol and was not appraised using MMAT criteria, as no primary data have been collected or analysed at the time of this review. It was retained in the corpus to signal the direction of ongoing prospective research into cortical reorganization in children with single-sided deafness. The full quality appraisal ratings are presented in Table 5. These ratings are used in the Discussion (Section 4) to weight the confidence assigned to specific findings: conclusions drawn from high-rated neuroimaging and behavioral studies are advanced with greater certainty, while findings from moderate-rated or non-appraised sources are treated as exploratory or contextual. This distinction reflects best practice in systematic review methodology and follows PRISMA 2020 reporting recommendations (Page et al., 2021).

Table 5. Quality appraisal of included studies using MMAT version 2018

Study	Design type	RQ clear	Data appropriate	Adequate methodology	Justified interpretation	Overall rating
Alzaher et al., 2021	Narrative review	Met	N/A	N/A	N/A	Moderate
Calmels et al., 2022	Protocol (fNIRS)	Met	N/A	N/A	N/A	Not appraised
Karoui et al., 2023	PET	Met	Met	Met	Met	High
Lasfargues-Delannoy et al., 2021	Behavioral	Met	Met	Met	Met	High
Salles et al., 2016	Functional imaging	Met	Partially Met	Met	Partially Met	Moderate
Strelnikov et al., 2009a	Behavioral	Met	Met	Met	Met	High
Strelnikov et al., 2009b	Behavioral	Met	Met	Met	Met	High
Strelnikov et al., 2010	PET (rest)	Met	Met	Met	Met	High
Strelnikov et al., 2011a	fMRI	Met	Met	Met	Met	High
Strelnikov et al., 2011b	Behavioral	Met	Met	Met	Met	High
Strelnikov et al., 2015a	Functional imaging	Met	Met	Met	Met	High

Strelnikov et al., 2015b	PET ICA	Met	Met	Met	Met	High
Strelnikov et al., 2015c	PET	Met	Met	Met	Met	High
Vannson et al., 2017	Brainstem recording	Met	Met	Met	Met	High
Vannson et al., 2020	Functional imaging	Met	Met	Met	Met	High

Note. MMAT = Mixed Methods Appraisal Tool (Hong et al., 2018). Met = criterion satisfied; Partially Met = criterion partially satisfied; N/A = not applicable (protocol or secondary review).

A formal appraisal of methodological quality is essential for interpreting the cumulative evidence synthesised in this review. Using the Mixed Methods Appraisal Tool (MMAT) version 2018 (Hong et al., 2018), each included study was evaluated against five domain-specific criteria: clarity of the research question, appropriateness of data to address that question, adequacy of the methodology, coverage of the full dataset, and justification of the interpretation. The results of this appraisal are presented in Table 5 and reveal meaningful variability in evidence quality across the corpus. Neuroimaging studies employing positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), particularly those from Strelnikov and colleagues, received high overall ratings, reflecting well-defined research questions, rigorous data acquisition protocols, and interpretations grounded in predefined theoretical frameworks. These studies provide the most robust evidence currently available regarding the neural substrates of visual and audiovisual speech processing following cochlear implantation (CI).

In contrast, several studies in the corpus received moderate quality ratings, indicating that while their contributions are substantive, certain methodological limitations warrant caution when drawing broad conclusions. Alzaher et al. (2021), classified as a narrative review rather than a primary empirical study, was retained for its conceptual value in contextualising audiovisual integration findings; however, it was not treated as primary evidence and its conclusions were evaluated alongside higher-quality empirical sources. Similarly, Salles et al. (2016), which examined multisensory processing in individuals with Prader-Willi syndrome, was appraised at moderate quality and included only insofar as it illuminates broader principles of cross-modal plasticity that are theoretically relevant to the CI population. Calmels et al. (2022) was not appraised using the MMAT, as it represents a registered research protocol without completed findings; it was retained to indicate the direction of prospective research in the field. Readers should therefore distinguish between the findings of high-quality neuroimaging studies and the preliminary or contextual contributions of lower-rated sources when interpreting the evidence synthesised here.

These quality distinctions carry direct implications for both clinical practice and future research. The convergent high-quality evidence from PET and fMRI paradigms strongly supports the role of visual cortex recruitment in auditory rehabilitation following CI, suggesting that multisensory training programmes targeting audiovisual integration may enhance speech perception outcomes, particularly in post-lingually deafened adults (Strelnikov et al., 2009; Strelnikov et al., 2011; Strelnikov et al., 2013). Clinicians should be encouraged to incorporate structured visual and lipreading components into rehabilitation protocols, with confidence informed by this robust neuroimaging evidence. Conversely, preliminary or contextual findings from moderate- and non-appraised sources should guide hypothesis generation for future trials rather than directly informing practice changes. Future research should prioritise prospective, pre-registered experimental designs with clearly operationalised outcome measures and sufficiently powered samples to confirm the causal pathways suggested by the neuroimaging literature. Particular attention should be given to paediatric CI recipients, for whom the longitudinal trajectory of cross-modal plasticity and its relationship to auditory speech development remains insufficiently characterised in high-quality primary studies (Page et al., 2021).

Limitations

There are limitations to this review that need to be considered. The corpus was focused and the studies had different designs and outcomes so that a pooled statistical analysis could not be conducted. Searches in the flow framework are still pending from the live export of the database. Expanding the search can yield additional studies, and can increase the population base. A primary theme was given to one study, although some studies addressed multiple themes. Given these limits, they indicate caution and they suggest clear avenues for a broader review.

Conclusion

The evidence presented here indicates that the auditory brain reorganizes following deafness and following cochlear implantation. The deprived and the restored brain uses visual and multisensory resources to aid in speech understanding. This support can be enhanced with training and visual cues and thus has value for rehabilitation. Single sided and asymmetric loss is an important and increasing area that connects with the cortical plasticity and spatial hearing. The results of future studies with larger samples and common methodology will further translate these findings into clear clinical guidance.

References

Alzaher, M., Vannson, N., Deguine, O., Marx, M., Barone, P., & Strelnikov, K. (2021). Brain plasticity and hearing disorders. Revue Neurologique, 177(9), 1121–1132. https://doi.org/10.1016/j.neurol.2021.06.006

Calmels, M.-N., Gallois, Y., Marx, M., Deguine, O., Taoui, S., Arnaud, E., Strelnikov, K., & Barone, P. (2022). Functional reorganization of the central auditory system in children with single-sided deafness: A protocol using fNIRS. Brain Sciences, 12(4), 423. https://doi.org/10.3390/brainsci12040423

Hong, Q. N., Fabregues, S., Bartlett, G., Boardman, F., Cargo, M., Dagenais, P., Gagnon, M.-P., Griffiths, F., Nicolau, B., O'Cathain, A., Rousseau, M.-C., Vedel, I., & Pluye, P. (2018). The Mixed Methods Appraisal Tool (MMAT) version 2018 for information professionals and researchers. Education for Information, 34(4), 285-291. https://doi.org/10.3233/EFI-180221

Karoui, C., Strelnikov, K., Payoux, P., Salabert, A. S., James, C. J., Deguine, O., & Barone, P. (2023). Auditory cortical plasticity after cochlear implantation in asymmetric hearing loss is related to spatial hearing: A PET H215O study. Cerebral Cortex, 33(5), 2229–2244. https://doi.org/10.1093/cercor/bhac195

Lasfargues-Delannoy, A., Strelnikov, K., Deguine, O., Marx, M., & Barone, P. (2021). Supra-normal skills in processing of visuo-auditory prosodic information by cochlear-implanted deaf patients. Hearing Research, 410, 108330. https://doi.org/10.1016/j.heares.2021.108330

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hrobjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P., & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n7

Salles, J., Strelnikov, K., Carine, M., Denise, T., Laurier, V., Molinas, C., & Tauber, M. (2016). Deficits in voice and multisensory processing in patients with Prader-Willi syndrome. Neuropsychologia, 85, 137–147. https://doi.org/10.1016/j.neuropsychologia.2016.03.015

Strelnikov, K., Foxton, J., Marx, M., & Barone, P. (2015a). Brain prediction of auditory emphasis by facial expressions during audiovisual continuous speech. Brain Topography, 28(3–4), 494–505. https://doi.org/10.1007/s10548-013-0338-2

Strelnikov, K., Marx, M., Lagleyre, S., Fraysse, B., Deguine, O., & Barone, P. (2015c). PET-imaging of brain plasticity after cochlear implantation. Hearing Research, 322, 180–187. https://doi.org/10.1016/j.heares.2014.11.006

Strelnikov, K., Massida, Z., Rouger, J., Belin, P., & Barone, P. (2011a). Effects of vocoding and intelligibility on the cerebral response to speech. BMC Neuroscience, 12, 122. https://doi.org/10.1186/1471-2202-12-122

Strelnikov, K., Rosito, M., & Barone, P. (2011b). Effect of audiovisual training on monaural spatial hearing in horizontal plane. PLoS ONE, 6(3), e18344. https://doi.org/10.1371/journal.pone.0018344

Strelnikov, K., Rouger, J., Demonet, J.-F., Lagleyre, S., Fraysse, B., Deguine, O., & Barone, P. (2010). Does brain activity at rest reflect adaptive strategies? Evidence from speech processing after cochlear implantation. Cerebral Cortex, 20(5), 1217–1222. https://doi.org/10.1093/cercor/bhp183

Strelnikov, K., Rouger, J., Lagleyre, S., Fraysse, B., Deguine, O., & Barone, P. (2009a). Improvement in speech-reading ability by auditory training: Evidence from gender differences in normally hearing, deaf and cochlear implanted subjects. Neuropsychologia, 47(4), 972–979. https://doi.org/10.1016/j.neuropsychologia.2008.10.017

Strelnikov, K., Rouger, J., Lagleyre, S., Fraysse, B., Deguine, O., & Barone, P. (2009b). Role of speechreading in audiovisual interactions during the recovery of speech comprehension in deaf adults with cochlear implants. Scandinavian Journal of Psychology, 50(5), 437–444. https://doi.org/10.1111/j.1467-9450.2009.00741.x

Strelnikov, K., Rouger, J., Lagleyre, S., Fraysse, B., Demonet, J.-F., Deguine, O., & Barone, P. (2015b). Increased audiovisual integration in cochlear-implanted deaf patients: Independent components analysis of longitudinal positron emission tomography data. European Journal of Neuroscience, 41(5), 677–685. https://doi.org/10.1111/ejn.12827

Vannson, N., James, C. J., Fraysse, B., Lescure, B., Strelnikov, K., Deguine, O., & Marx, M. (2017). Speech-in-noise perception in unilateral hearing loss: Relation to pure-tone thresholds and brainstem plasticity. Neuropsychologia, 102, 135–143. https://doi.org/10.1016/j.neuropsychologia.2017.06.016

Vannson, N., Strelnikov, K., James, C. J., Deguine, O., Barone, P., & Marx, M. (2020). Evidence of a functional reorganization in the auditory dorsal stream following unilateral hearing loss. Neuropsychologia, 149, 107683. https://doi.org/10.1016/j.neuropsychologia.2020.107683

Open Access Statement

This article is licensed under the Creative Commons Attribution 4.0 International License, which allows use, sharing, adaptation, distribution, and reproduction in any medium or format, provided appropriate credit is given to the original author(s) and the source, a link to the Creative Commons license is included, and any changes made are indicated. Unless otherwise noted in a credit line, the images or other third-party material in this article are covered by the article's Creative Commons license. If any material is not included under this license and your intended use is not permitted by statutory regulation or exceeds the allowed use, you must obtain permission directly from the copyright holder.

To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/.