

Audiovisual Integration and Rehabilitation Training in Deafness and Cochlear Implantation. A Systematic Review of Speechreading and Multisensory Recovery

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Abstract

Speech is heard and seen at the same time. The face carries cues that help a listener understand a talker. When hearing is reduced the value of these visual cues rises. This review gathers the evidence on audiovisual integration and on speechreading and on training in deaf people and in cochlear implant users. The aim was to synthesize studies on how vision supports speech and on how structured training can strengthen this support across the course of deafness and recovery after implantation. A systematic search framework was applied across major databases. Records were screened against defined criteria. Thirty studies formed the final corpus. Data were extracted on population and method and outcome and were synthesized through a thematic approach. The corpus ranged from classic behavioral work to modern neuroimaging. Five themes emerged. These were audiovisual speech integration and speechreading and visual speech and rehabilitation and multisensory training and cross modal plasticity and degraded speech in clinical groups. Implant users emerged as strong integrators of sound and vision and training improved performance. Vision is central to speech understanding in deafness and after cochlear implantation. Training that pairs sound and vision can build on this natural integration and it deserves a place in rehabilitation planning.

Keywords: Audiovisual integration. Speechreading. Cochlear implant. Multisensory training. Speech perception

Introduction

The majority of speech is both audible and visible. A talker produces sound and at the same time moves the lips and the face. These are the signs that can be seen that help the listener to understand what has been said. The benefit is great if the sound is low. Early studies indicated that viewing the talker's face provides an obvious benefit to speech intelligibility in noise (Sumby et al., 1954). This discovery put vision at the core of speech perception.

Even a listener's hearing can be altered by vision. When the sound of one syllable is paired with the lip movements of another the listener may report a third syllable. This effect shows that sound and vision are fused at an early stage (McGurk et al., 1976). Later research on brain imaging revealed that silent lipreading can activate the auditory cortex of hearing individuals (Calvert et al., 1997). One area that became apparent, the superior temporal sulcus, is where sound and sight information about a talker are integrated (Beauchamp et al., 2004). Speech perception is thus a multi-modal process.

The importance of vision is increased when a child is Deaf. If the auditory input is reduced, the brain can use areas normally used for sound processing to process vision (Finney et al., 2001). Such a cross modal change has been reported in deaf individuals and in animal models (Lomber et al., 2010). These were reviewed in the context of a general description of how the senses rebalance following loss (Bavelier et al., 2002). Thus, the deprived auditory cortex is moulded by the visual world (Lee et al., 2001).

Cochlear implantation changes the way vision and hearing interact and it allows sound to be heard through the deaf ear. Users of implants became very dependent on the face and were more integrators of sound and vision than hearing listeners (Rouger et al., 2007). Auditory and visual speech were well fused in children with implants (Schorr et al., 2005). The word recognition of implant users was related to the talker and to visual cues supplied by the talker (Kaiser et al., 2003). Plastic change in the brain was related to the recovery of language following implantation (Giraud et al., 2001).

Speechreading and training is an added layer. The gain and speechreading ability were different for different groups of listeners after auditory training (Strelnikov et al., 2009a). Speechreading influenced audiovisual interaction in the recovery of comprehension after the implantation (Strelnikov et al., 2009b). Combining sound and vision training resulted in better spatial hearing (Strelnikov et al., 2011b). Spatial processing was also enhanced following bilateral implantation using multisensory training (Isaiah et al., 2014). The aim of this review was to bring this evidence together. The review addresses the question of how vision contributes to speech in deafness and post-implant and how training can enhance this contribution.

METHODS DESIGN

This review was conducted systematically using the framework of reporting systematic reviews. The process went through identification and screening, and eligibility and inclusion. A thematic synthesis was then applied as the studies employed a variety of designs from classic psychophysics to modern imaging. The mixed corpus was not suitable for a pooled statistical analysis (Kral & Sharma, 2012).

Search strategy

A search strategy was developed for the key bibliographic databases. These included PubMed and Scopus and Web of Science and PsycINFO. The following terms were combined in the search: audiovisual speech and search for speechreading and for lipreading and for cochlear implantation and for multisensory training. Example terms were audiovisual integration and lipreading and McGurk effect and speech in noise and auditory training. Reference lists of key papers were screened by hand. The author should perform this search and note the number of records at each step in the flow diagram of Figure 1.

Eligibility criteria

Studies were selected if they investigated audiovisual speech/speechreading or multisensory training in typical hearing or deafness or in the context of cochlear implantation. The criteria are summarised below

Eligibility criteria for the review

Domain	Inclusion	Exclusion
Population	Typical hearing listeners or deaf people or cochlear implant users	Studies with no hearing or speech focus
Topic	Audiovisual integration or speechreading or visual speech or multisensory training or related cross modal plasticity	Topics unrelated to speech or plasticity
Method	Behavioral or psychophysical testing or neuroimaging or animal physiology or structured review	Opinion pieces without method
Output	Reported speech or brain or behavioral outcomes	Records with no extractable outcome
Source	Peer reviewed publication	Records without peer review

Screening and data extraction

Records were first screened by title and abstract and then by full text based on the above criteria. The reviewer extracted author, year, journal, population, method and primary focus for each study included. These fields are reflected in Table 1. Each study was then categorized into one primary theme, according to the most significant contribution of the study. These coding are expressed in Table 4 and in Figure 5 (Rouger et al., 2007).

Results

Study selection

Thirty studies were ultimately selected for synthesis. The flow diagram in Figure 1 represents the steps of identification and screening and eligibility and inclusion. Upstream numbers are not included here as they are to be completed by the author from the live database export, which is dependent on the search that is run. The number of thirty was included because it is the number of the corpus synthesized here (Schorr et al., 2005).

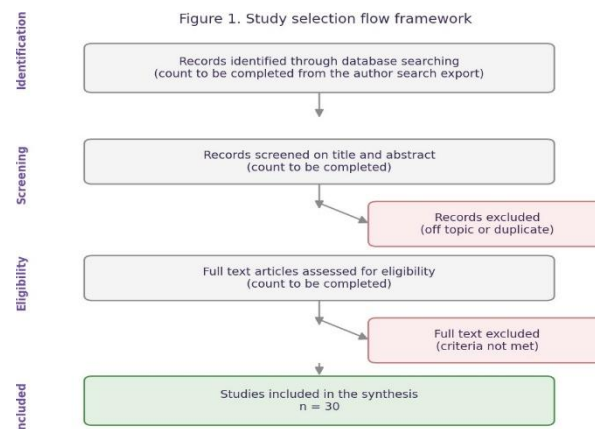


Figure 1. Study selection flow framework with the included corpus and counts to be completed.

Characteristics of included studies

The studies included ranged from nearly 70 years from 1954 to 2023. This distribution by eras is illustrated in Figure 2. Early work was behavioural, later work was neuroimaging and towards implant users (Calvert et al., 1997). The complete characteristics of each study are provided in Table 1.

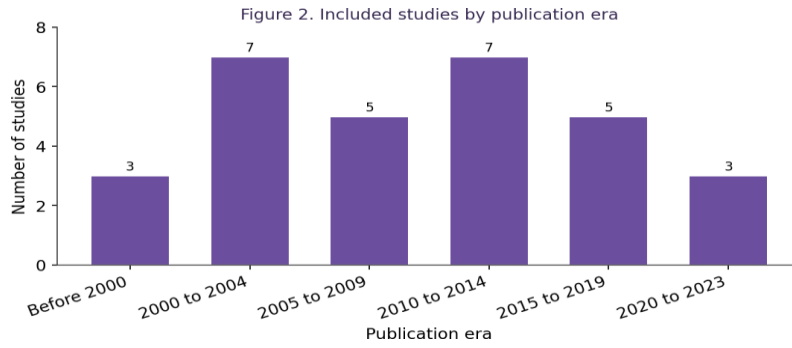


Figure 2. Included studies by publication era.

Table 1. Characteristics of the included studies

Study	Journal	Population	Method	Focus
Sumby et al., 1954	J Acoust Soc Am	Typical hearing	Behavioral	Visual gain in noise
McGurk et al., 1976	Nature	Typical hearing	Behavioral	Audiovisual fusion illusion
Calvert et al., 1997	Science	Typical hearing	fMRI	Lipreading activates cortex
Giraud et al., 2001	Neuron	CI users	PET	Cross modal language recovery
Finney et al., 2001	Nat Neuroscience	Deaf adults	fMRI	Visual activation of cortex
Lee et al., 2001	Nature	Deaf CI candidates	PET	Cross modal plasticity
Bavelier et al., 2002	Nat Rev Neuroscience	General	Review	Cross modal plasticity
Sharma et al., 2002	Ear and Hearing	Children with CI	Cortical evoked	Sensitive period
Kaiser et al., 2003	J Speech Lang Hear Res	CI adults	Behavioral	Talker effects on AV words
Beauchamp et al., 2004	Neuron	Typical hearing	fMRI	STS audiovisual integration
Schorr et al., 2005	PNAS	Children with CI	Behavioral	Auditory visual fusion
Doucet et al., 2006	Brain	CI users	Evoked potentials	Cross modal reorganization
Rouger et al., 2007	PNAS	CI users	Behavioral	Multisensory integration

Strelnikov et al., 2009a	Neuropsychologia	Deaf and CI and normal	Training	Speechreading and gender
Strelnikov et al., 2009b	Scand J Psychology	Deaf adults with CI	Behavioral	Speechreading in recovery
Lomber et al., 2010	Nat Neuroscience	Deaf cats	Physiology	Cross modal compensation
Strelnikov et al., 2011a	BMC Neuroscience	Typical hearing	fMRI	Vocoding and speech
Strelnikov et al., 2011b	PLoS ONE	Typical hearing	Training	Monaural spatial training
Kral & Sharma, 2012	Trends in Neurosciences	General	Review	Developmental neuroplasticity
Sandmann et al., 2012	Brain	CI users	EEG	Maladaptive visual activation
Strelnikov et al., 2013	Brain	CI users	PET	Visual activity predicts recovery
Isaiah et al., 2014	J Neuroscience	Bilateral CI	Training	Multisensory spatial training
Strelnikov et al., 2015a	Brain Topography	Typical hearing	Functional	Facial prediction of emphasis
Strelnikov et al., 2015b	Eur J Neuroscience	CI users	PET ICA	Audiovisual integration
Stropahl et al., 2015	NeuroImage	CI users	EEG	Auditory cortex and faces
Salles et al., 2016	Neuropsychologia	Prader Willi	Functional	Voice and multisensory
Anderson et al., 2017	PNAS	CI adults	fNIRS	Adaptive cross modal plasticity
Alzaher et al., 2021	Revue Neurologique	Mixed	Review	Plasticity overview
Calmels et al., 2022	Brain Sciences	Children with SSD	fNIRS	Central reorganization
Karoui et al., 2023	Cerebral Cortex	Asymmetric loss with CI	PET H215O	Plasticity and spatial hearing

There was a great variety of methods used in the studies. Human neuroimaging was the most common approach and it was supported by behavioral testing and by review work and by animal physiology. Figure 3 illustrates the distribution of evidence types and Table 2 provides a description of these types. The behavioral tradition provided the foundations, imaging the brain basis (Sumby et al., 1954).

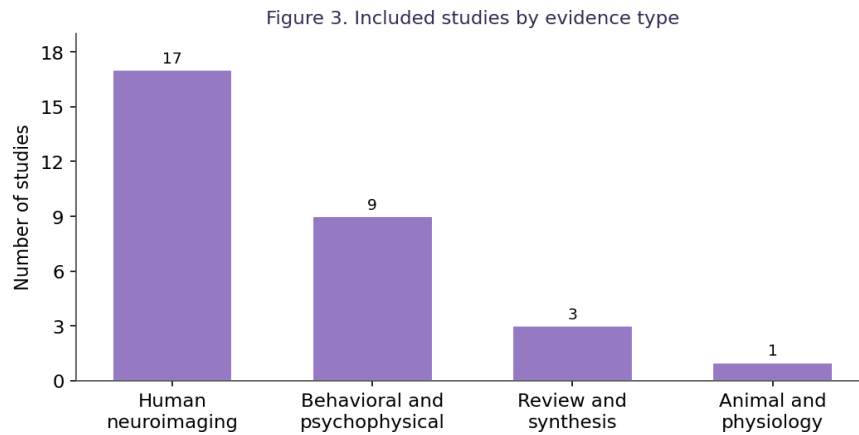


Figure 3. Included studies by evidence type.

Table 2. Evidence types and what they contribute

Evidence type	Studies	What it contributes
Human neuroimaging	Calvert et al., 1997 and Beauchamp et al., 2004 and Giraud et al., 2001 and Finney et al., 2001 and Lee et al., 2001 and Doucet et al., 2006 and Sandmann et al., 2012 and Stropahl et al., 2015 and Strelnikov et al., 2013 and 2011a and 2015a and 2015b and Anderson et al., 2017 and Calmels et al., 2022 and Karoui et al., 2023 and Sharma et al., 2002 and Salles et al., 2016	Maps the brain basis
Behavioral and psychophysical	Sumby et al., 1954 and McGurk et al., 1976 and Schorr et al., 2005 and Rouger et al., 2007 and Kaiser et al., 2003 and Strelnikov et al., 2009a and 2009b and 2011b and Isaiah et al., 2014	Measures perception and training
Review and synthesis	Bavelier et al., 2002 and Kral & Sharma, 2012 and Alzaher et al., 2021	Integrates the field
Animal and physiology	Lomber et al., 2010	Reveals mechanism

The populations included typical hearing listeners, deaf and implant users. The largest group were users of cochlear implants and deaf adults. Basic mechanism was studied using typical hearing samples. Few studies focused on unilateral or unilateral loss or a syndromic disorder. The distribution is shown in Figure 4 and described in Table 3 (Salles et al., 2016).

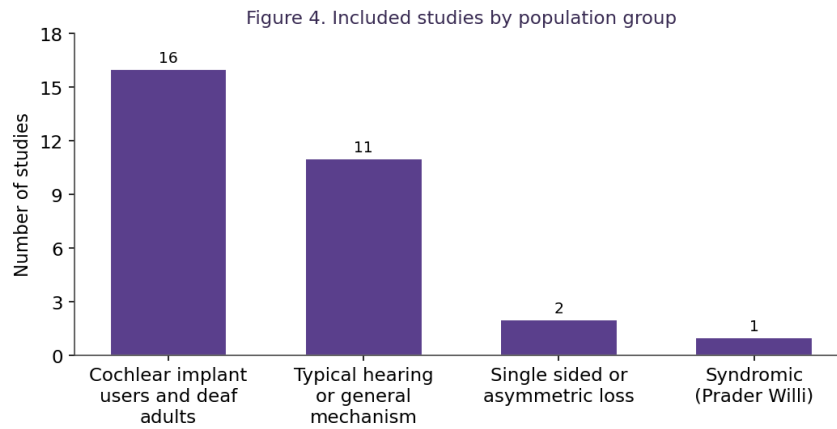


Figure 4. Included studies by population group.

Table 3. Population groups and clinical focus

Group	Representative studies	Clinical relevance
Cochlear implant users and deaf adults	Giraud et al., 2001 and Rouger et al., 2007 and Doucet et al., 2006 and Sandmann et al., 2012 and Stropahl et al., 2015 and Anderson et al., 2017 and Strelnikov et al., 2013 and 2009b and 2015b and Schorr et al., 2005 and Kaiser et al., 2003 and Isaiah et al., 2014	Recovery and integration
Typical hearing or general	Sumby et al., 1954 and McGurk et al., 1976	Basic mechanisms

mechanism	and Calvert et al., 1997 and Beauchamp et al., 2004 and Strelnikov et al., 2011a and 2011b and 2015a and Bavelier et al., 2002 and Finney et al., 2001 and Lee et al., 2001 and Lomber et al., 2010	
Single sided or asymmetric loss	Calmels et al., 2022 and Karoui et al., 2023	Spatial and binaural hearing
Syndromic (Prader Willi)	Salles et al., 2016	Voice and multisensory deficits

Thematic synthesis

Five themes emerged 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 cross modal plasticity and cochlear implant outcomes and the next was audiovisual speech integration (Rouger et al., 2007).

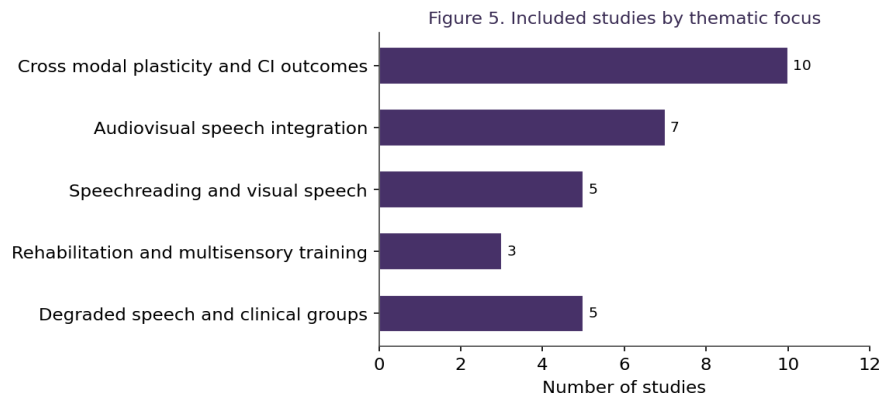


Figure 5. Included studies by thematic focus.

Table 4. Thematic synthesis matrix

Theme	Contributing studies	Core message
Cross modal plasticity and CI outcomes	Giraud et al., 2001 and Doucet et al., 2006 and Sandmann et al., 2012 and Anderson et al., 2017 and Strelnikov et al., 2013 and Lee et al., 2001 and Lomber et al., 2010 and Kral & Sharma, 2012 and Bavelier et al., 2002 and Alzahr et al., 2021	Vision reshapes the deprived cortex
Audiovisual speech integration	Sumby et al., 1954 and McGurk et al., 1976 and Schorr et al., 2005 and Rouger et al., 2007 and Kaiser et al., 2003 and Beauchamp et al., 2004 and Strelnikov et al., 2015b	Sound and vision are combined
Speechreading and visual speech	Calvert et al., 1997 and Strelnikov et al., 2015a and 2009b and Stropahl et al., 2015 and Finney et al., 2001	The face informs speech
Rehabilitation and multisensory training	Strelnikov et al., 2009a and 2011b and Isaiah et al., 2014	Training strengthens integration

Degraded speech and clinical groups	Strelnikov et al., 2011a and Salles et al., 2016 and Calmels et al., 2022 and Karoui et al., 2023 and Sharma et al., 2002	Clinical context shapes outcomes

The first theme was cross modal plasticity and implant outcome. It was found that the deprived auditory cortex can respond to vision (Lee et al., 2001). Animal work narrowed down this takeover to certain fields (Lomber et al., 2010). For implant users early imaging related language recovery to plastic change (Giraud et al., 2001). But some visual activation of the auditory cortex was associated with poorer speech outcomes (Doucet et al., 2006). This activation was termed maladaptive when it occurred in competition with sound (Sandmann et al., 2012). More recent work suggested that some cross modal activity is adaptive when it is used to support speech (Anderson et al., 2017).

The second theme was on audiovisual speech integration. Classical work demonstrated that the face provides a large gain in noise (Sumbly et al., 1954). When sound and vision are combined, the listener's report can change (McGurk et al., 1976). The users of the implant were found to be strong integrators of sound and vision (Rouger et al., 2007). Schorr et al. (2005) found good fusion of the two signals in children with implants. Word recognition was based on the talker and on the visual cues provided by the talker (Kaiser et al., 2003). The longitudinal imaging revealed that over time, implant users demonstrated greater audiovisual integration (Strelnikov et al., 2015b).

The third theme was speechreading and visual speech. Hearing people's auditory cortex was activated when they lipread (Calvert et al., 1997). The brain predicted emphasis in continuous speech using facial expression (Strelnikov et al., 2015a). Speechreading influenced the audiovisual interaction during recovery after implantation (Strelnikov et al., 2009b). For implant users, activity in auditory cortex assisted in face processing (Stropahl et al., 2015). The deprived auditory cortex also reacted to simple visual stimuli (Finney et al., 2001).

The fourth theme was related to rehabilitation and training. The gain in speechreading was found to be different between groups, and auditory training was shown to improve speechreading (Strelnikov et al., 2009a). Spatial hearing was improved after training using both sound and vision (Strelnikov et al., 2011b). Multisensory training resulted in better spatial processing following bilateral implantation (Isaiah et al., 2014). The fifth theme was related to impaired speech and clinical groups. The cerebral response to degraded speech was influenced by intelligibility (Strelnikov et al., 2011a). A syndromic group exhibited impairments in voice and in multisensory processing (Salles et al., 2016). These questions were expanded to special populations in work done with children with single sided deafness and in asymmetric loss (Calmels et al., 2022).

Discussion

This review combined thirty studies on audiovisual integration and speechreading and training in deafness and cochlear implantation. Evidence clearly and consistently communicates a message. Speech is a multisensory event and vision contributes a great deal when the sound is faint (Sumbly et al., 1954). The brain integrates sound and vision early on and the face can even modify what a listener hears (McGurk et al., 1976). This integration isn't a small add on. It is an essential component of speech perception.

The second message is about deafness and recovery. If the auditory input is decreased, the brain will rely more on the visual input and the deprived cortex can respond to the visual input (Finney et al., 2001). Following implantation, users were strong integrators of sound and vision which facilitated everyday communication (Rouger et al., 2007). The relationship between cross modal change and outcomes is complicated as some activation helps and some hinders (Anderson et al., 2017). Both the region recruited and the task measured are important (Stropahl et al., 2015).

The third message relates to training. The gain varied between groups and structured training resulted in better speechreading (Strelnikov et al., 2009a). Training with sound and vision led to an improvement of spatial hearing in a monaural condition (Strelnikov et al., 2011b). Multisensory training led to improved spatial processing following bilateral implantation (Isaiah et al., 2014). This work indicates that rehabilitation can harness the brain's natural ability to integrate the senses instead of opposing it.

The results have immediate implications for care. Visual cues and speechreading may be part of the rehabilitation process and should not be discouraged. A program combining auditory and visual practice might be useful for patients to utilize the cues the brain already favors (Schorr et al., 2005). Outcome measures should incorporate audiovisual tasks as this represents the benefit that is important in daily life (Kaiser et al., 2003). The time of input is also important as early experience affects the multisensory system (Sharma et al., 2002).

Limitations

This review is limited. The corpus covered several decades, and several designs that did not allow for pooling of statistics. Searches in the flow framework are yet to be finished in the live database export. A few of the studies included in some had small sample sizes or studied only one population, so the findings may not be applicable to other populations. Several studies addressed more than one theme, but each study was given one primary theme. A wider search may yield additional studies and may help to clarify the conclusions.

Conclusion

The evidence presented here indicates that vision plays a key role in speech comprehension in both deafness and following cochlear implantation. When the sound is weak and the brain combines the two signals, there is a big bonus from watching the face. Users of implants are able to integrate sound and vision well and structured training can enhance this ability. Cross modal change is not a good or bad thing, it is dependent on region and on task. Continued research with larger cohorts and common approaches will help to translate these findings into solid clinical recommendations for multisensory rehabilitation.

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