SPEECH PROCESSING IN COCHLEAR IMPLANT PATIENTS ACROSS DIFFERENT MODALITIES

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> *Wir sind nur so stark, wie wir vereint sind*
> *und so schwach, wie wir getrennt sind.*
>
> — **Albus Dumbledore**
> (**Harry Potter und der Feuerkelch**)

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ABSTRACT

Hearing loss is one of the leading causes of chronic disability (Vos et al., 2016) and it causes major problems in interpersonal communication. Cochlear implants (CIs) are the world's most successful neural prosthesis and they allow patients with severe to profound hearing loss to regain their hearing ability. However, hearing with a CI is very different from normal hearing (NH), as only limited auditory input is provided by the device. The capacity of the human cortex to adapt to this new auditory input, however, enables the patients to extract meaningful information within months after switch-on of the processor. During the period of deprived hearing, patients typically rely more strongly on visual cues like lip movement for communication. Hence it has been suggested that these individuals show a pronounced binding of the auditory and the visual system, allowing them to integrate auditory and visual speech information after cochlear implantation more efficiently. The included projects therefore investigate auditory, visual and audiovisual speech processing in hearing deprived individuals and different groups of CI users. They comprise three event-related potential (ERP) studies, split over four publications, each focusing on an individual perspective.

The main result of the first study shows a side-of-implantation effect in the auditory cortex of SSD CI users for auditory stimulation of both the CI ear and the NH ear. This is shown by an enhanced functional asymmetry for the left-ear implanted SSD CI users when compared to right-ear implanted SSD CI users. The second study reveals multisensory integration for NH listeners, SSD CI users and CI users with bilateral hearing loss, as depicted in shorter response times for audiovisual as compared to unimodal stimuli. Nevertheless, both CI user groups show delayed auditory-cortex responses and enhanced visual-cortex responses in comparison to the NH listeners. Different processing patterns are also evident in our prospective longitudinal study. Regarding the audiovisual speech stimuli, the CI group displays a more occipitally pronounced topography, especially in a visually attended condition, as well as a reduced auditory cortex response when compared to the NH listeners. Additionally, a condition difference between visually and auditory attended stimuli is present in the beta frequency range for the NH listeners only, which indicates an enhanced allocation of attention when processing the visually attended stimuli. Regarding the visual only speech stimuli, the CI group displays a reduced visual cortex activation, but a stronger functional connectivity between the visual and auditory cortex when compared to the NH listeners. All the results of the longitudinal study seem to be deprivation induced and remain unchanged after six months of CI use. Furthermore the altered visual processing relates to the CI outcome.

Taken together, the included projects contribute to a better understanding of speech processing in hearing deprived individuals and CI users in different modalities (auditory, visual and audiovisual). They reveal distinct processing strategies used to overcome the deprivation and the limited regained auditory input via a CI. The results could be used to improve the clinical rehabilitation process by including visual speech information into the currently purely auditory training and assessment. Moreover, first evidence for a relation between electrophysiological measures and the CI outcome pave the way for more precise prediction models.

ZUSAMMENFASSUNG

Schwerhörigkeit ist eine der Hauptursachen für chronische Behinderungen (Vos u. a., 2016) und verursacht große Probleme bei der zwischenmenschlichen Kommunikation. Cochlea-Implantate (CIs) sind die weltweit erfolgreichste neurale Prothese und ermöglichen es Patienten mit schwerem bis hochgradigem Hörverlust, ihr Hörvermögen wiederzuerlangen. Das Hören mit einem CI unterscheidet sich jedoch stark vom normalen Hören (NH), da das Gerät nur einen begrenzten auditiven Input liefert. Die Fähigkeit des menschlichen Kortex, sich an diesen neuen auditiven Input anzupassen, ermöglicht es den Patienten jedoch, innerhalb weniger Monate nach dem ersten Einschalten des Prozessors sinnvolle Informationen zu extrahieren. Während der Zeit des Hörverlusts verlassen sich die Patienten bei der Kommunikation in der Regel stärker auf visuelle Hinweise wie Lippenbewegungen. Es wird daher vermutet, dass diese Personen eine ausgeprägte Verbindung zwischen dem auditorischen und dem visuellen System aufweisen, die es ihnen ermöglicht, nach der Cochlea-Implantation auditive und visuelle Sprachinformationen effizienter zu integrieren. Die einbezogenen Projekte untersuchen daher die auditive, visuelle und audiovisuelle Sprachverarbeitung bei hörgeschädigten Personen und verschiedenen Gruppen von CI-Trägern. Sie umfassen drei Studien zu ereigniskorrelierten Potenzialen (ERP), die sich auf vier Veröffentlichungen verteilen, und jeweils eine individuelle Perspektive behandeln.

Das Hauptergebnis der ersten Studie zeigt einen Side-of-Implantation-Effekt im auditorischen Kortex von einseitig ertaubten CI-Nutzern bei auditorischer Stimulation, sowohl des CI-Ohrs als auch des NH-Ohrs. Dies zeigt sich in einer verstärkten funktionellen Asymmetrie bei einseitig links ertaubten CI-Trägern im Vergleich zu einseitig rechts ertaubten CI-Trägern. Die zweite Studie zeigt eine multisensorische Integration bei NH, SSD CI-Trägern und CI-Trägern mit beidseitigem Hörverlust, die sich in kürzeren Reaktionszeiten für audiovisuelle im Vergleich zu unimodalen Reizen zeigt. Dennoch zeigen beide CI-Trägergruppen im Vergleich zu den NH verzögerte Reaktionen des auditorischen Kortex und verstärkte Reaktionen des visuellen Kortex. Unterschiedliche Verarbeitungsmuster sind auch in unserer prospektiven Längsschnittstudie zu erkennen. In Bezug auf die audiovisuellen Sprachreize zeigt die CI-Gruppe eine stärker okzipital ausgeprägte Topographie, insbesondere in der visuell attendierten Bedingung, sowie eine reduzierte Reaktion des auditorische Kortex im Vergleich zu den NH. Darüber hinaus gibt es nur bei den NH einen Bedingungsunterschied zwischen visuell und auditiv attendierten Stimuli im Beta-Frequenzbereich, was auf eine erhöhte Aufmerksamkeitszuweisung bei der Verarbeitung der visuell attendierten Stimuli hinweist. Bei den rein visuellen Sprachreizen zeigt die CI-Gruppe im Vergleich zu den NH eine geringere Aktivierung des visuellen Kortex, aber eine stärkere funktionelle Konnektivität zwischen dem visuellen und dem auditorischen Kortex. Alle Ergebnisse der Längsschnittstudie scheinen deprivationsbedingt zu sein und bleiben auch nach sechsmonatiger CI-Nutzung unverändert. Außerdem steht die veränderte visuelle Verarbeitung in Zusammenhang mit dem CI-Ergebnis.

Insgesamt tragen die einbezogenen Projekte zu einem besseren Verständnis der Sprachverarbeitung bei hörgeschädigten Personen und CI-Trägern in verschiedenen Modalitäten (auditiv, visuell und audiovisuell) bei. Sie zeigen unterschiedliche Verarbeitungsstrategien auf, die eingesetzt werden, um die Deprivation und den begrenzten wiedergewonnenen auditiven Input durch ein CI zu überwinden. Die Ergebnisse könnten zur Verbesserung des klinischen Rehabilitationsprozesses genutzt werden, indem visuelle Sprachinformationen in das derzeit rein auditive Training und die Bewertung einbezogen werden. Darüber hinaus gibt es erste Hinweise auf einen Zusammenhang zwischen elektrophysiologischen Messungen und dem CI-Ergebnis, die den Weg für präzisere Vorhersagemodelle ebnen.

PUBLICATIONS

INCLUDED PUBLICATIONS

Weglage, A., Müller, V., Layer, N., Abdel-Latif, K. H., Lang-Roth, R., Walger, M., & Sandmann, P. (2022). Side of-implantation effect on functional asymmetry in the auditory cortex of single-sided deaf cochlear-implant users. Brain Topography, 35(4), 431-452.

Layer, N., **Weglage, A.**, Müller, V., Meister, H., Lang-Roth, R., Walger, M., Murray, M., & Sandmann, P. (2022). Electrophysiological differences and similarities in audiovisual speech processing in CI users with unilateral and bilateral hearing loss. Current Research in Neurobiology, 3, 100059.

Weglage, A., Layer, N., Meister, H., Müller, V., Lang-Roth, R., Walger, M., Sandmann, P. (2024). Changes in visually and auditory attended audiovisual speech processing in cochlear implant users: A longitudinal ERP study. Hearing Research, 109023.

Weglage, A., Layer, N., Müller, V., Meister, H., Lang-Roth, R., Walger, M. & Sandmann, P. (under review). Reduced visual-cortex reorganisation before and after cochlear implantation relates to better speech recognition ability. Journal of Neuroscience research. Sumitted on 18 July 2024

ADDITIONAL PUBLICATIONS

Layer, N., **Weglage, A.**, Müller, V., Meister, H., Lang-Roth, R., Walger, M., Murray, M., & Sandmann, P. (2022). The timecourse of multisensory speech processing in unilaterally stimulated cochlear implant users revealed by ERPs. NeuroImage: Clinical, 34, 102982.

Burkhardt, P., Müller, V., Meister, H., **Weglage, A.**, Lang-Roth, R., Walger, M., & Sandmann, P. (2022). Age effects on cognitive functions and speech-in-noise processing: An event-related potential study with cochlear-implant users and normal-hearing listeners. Frontiers in Neuroscience, 16, 1005859.

Layer, N., Abdel-Latif, K. H., Radecke, J. O., Müller, V., **Weglage, A.**, Lang-Roth, R., Walger, M., & Sandmann, P. (2023). Effects of noise and noise reduction on audiovisual speech perception in cochlear implant users: An ERP study. Clinical Neurophysiology, 154, 141-156.

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Part I

INTRODUCTION

This part provides an overview of all the necessary background information. Especially about hearing, from normal healthy hearing to deafness, as well as the basics and the functioning of the cochlear implant. The methods used in the included publications are also described in more detail.

1

INTRODUCTION

> *Nicht sehen trennt den Menschen von den Dingen.*
> *Nicht hören trennt den Menschen von den Menschen.*
>
> **— Emmanuel Kant**

1.1 HEARING AND HEARING LOSS

Hearing is the most important sense for the communication with other individuals. Therefore, any decline in the hearing capacity, regardless of the time point in the life course, affects day-to-day functioning in a negative manner. The recent world report of hearing (WHO, 2021) states that more than 1.5 billion people experience a degree of hearing loss, with approximately 430 million individuals suffering from moderate or higher severity of hearing loss. Unaddressed hearing loss can have a negative impact on the affected individuals daily life, especially for children, who are still developing language and cognition. In adults it often lowers the self-esteem and also influences their families, society and countries. Factors influencing the hearing capacity include genetics, biological factors like diseases, environmental factors and behavioural factors like exposure to loud noise.

1.1.1 *Normal hearing*

Normal hearing refers to hearing thresholds of 20 dB or better in both ears (see Table 1.1). This section describes the anatomy of the human ear and the process of hearing in healthy individuals.

The human ear consists of three parts: the *outer ear* including the pinna and the ear canal, the *middle ear* including the tympanic membrane, the tympanic cavity and the auditory ossicles (malleus, incus and stapes), and the *inner ear* including the cochlea and the balance organ (see Figure 1.1).

The pinna is mainly made of cartilage and skin and it protects the ear canal, though it's primary function is to collect incoming sound pressure waves and guiding them into the ear canal. Additionally, the pinna provides important information about the source of sounds, as the reflection of incoming sound pressure waves is influenced by the direction and elevation of the sound source (Pickles, 2015 Chapter 2). Along the ear canal (∼2.5 cm; Johansen, 1975) the sound pressure waves travel to the tympanic membrane and cause this membrane to vibrate. Certain frequency ranges are significantly amplified in the ear canal (Wiener and Ross, 1946) caused by it's resonance characteristics. Resonance is caused by the interaction of arriving sound waves and sound waves that are reflected from the tympanic membrane (Goldstein, 2002). Based on the anatomical characteristics of the ear canal, e.g. the length and volume, and the size of the pinna, the amount of amplification can vary up to 15-20 dB observed for frequencies between 2 and 5 kHz (Wiener and Ross, 1946).

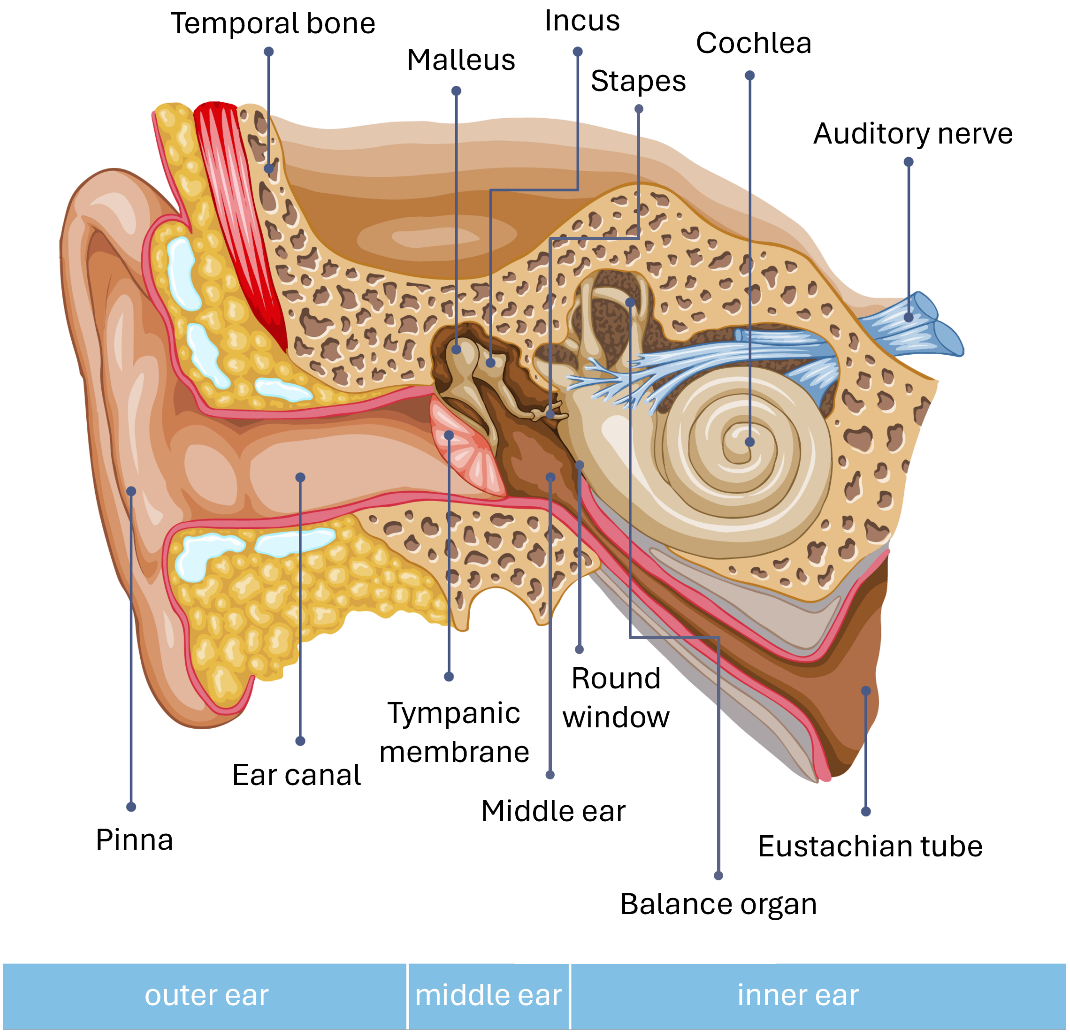

Figure 1.1: Anatomy of a normal hearing ear. Adapted with permission from "Schneider Hörberatung" (https://www.hoersysteme.ch/wissen-rund-ums-hoeren/das-ohr-ohr-anatomie/)

Outer and *middle ear* are separated by the tympanic membrane which directly transmits the sound energy to the malleus. The malleus transfers the energy to the incus and successively to the stapes. These auditory ossicles lie in the air-filled cavity called *middle ear*. The footplate of the stapes transmits the energy to the liquid-filled cochlea via the oval window. In order that, due to reflection, most of the energy does not get lost at the barrier between the middle and the inner ear (air-fluid barrier), the auditory ossicles enable the ear to perform an impedance adaptation (Durrant and Lovrinic, 1995). This adaptation is realised by a small lever effect of the auditory ossicles and by a concentration of the energy area of the tympanic membrane on the smaller area of the stapes footplate, which enables a sufficient transmission from the low density air-filled cavity of the middle ear to the high density fluid-filled inner ear.

The *inner ear* comprises the cochlea and the balance organ. The cochlea has a coiled structure with approximately 2 3/4 turns (e.g. Biedron, Westhofen, and Ilgner, 2009; Hardy, 1938; Kawano, Seldon, and Clark, 1996) and a length of 35 mm (e.g. Kawano, Seldon, and Clark, 1996). At the entry of the cochlea, also called base, the cochlea has two membrane covered openings: the oval and the round window. While the oval window is used to transmit the sound energy from the middle ear to the inner ear, the round window allows movement of the incompressible fluid inside the cochlea by vibration with the inverted phase of the oval window. As depicted in figure 1.5 the cochlea consists of three distinct compartments: scala vestibuli (top), scala tympani (bottom) and scala media (middle). The scala vestibuli and scala tympani are filled with perilymph (low K^+ and high Na^+), whereas the scala media is filled with endolymph (high K^+ and low Na^+). The partitions are separated by different membranes, namely the Reissner's membrane, separating the scala media and the scala vestibuli, and the basilar membrane, separating the scala media and the scala tympani.

A human ear involves approximately 15000 receptor cells (Úlehlová, Voldřich, and Janisch, 1987) enclosed in the organ of Corti. This is located at the top of the basilar membrane, is covered by the tectorial membrane and reaches into the scala media. The receptor cells inside the organ of Corti are divided into one row of inner and three rows of outer hair cells. If the fluid inside the cochlea is set into movement at the oval window, this movement will be transferred to the perilymph in the scala vestibuli, the Reissner's membrane and the endolymph in the scala media. This wave subsequently builds up, travelling in the direction of the apex and hence is called travelling wave. The base of the basilar membrane is narrow and stiff, while the apex is soft and flexible (La Rochefoucauld and Olson, 2007; Emadi, Richter, and Dallos, 2004; Gummer, Johnstone, and Armstrong, 1981; Oghalai, 2004; Von Békésy, 1960). Different sound frequencies lead to a maximal displacement at different parts of the basilar membrane. High frequency sounds travel only a small distance, hence lead to maximal displacement at the basal part of the basilar membrane, and low frequency sounds travel through the whole basilar membrane to the apex before running out of energy, hence leading to maximal displacement at the apical part of the basilar membrane (Culler et al., 1943). Thereby, the tonotopy of the cochlea is established, which is a systematic organisation of frequencies and each position on the basilar membrane is maximally displaced by a characteristic frequency. Displacement of the basilar membrane deflects the outer and inner hair cells.

On average a human cochlea is connected to 31000 auditory nerve fibres (Rasmussen, 1940). Inner hair cells connect to Type I fibres (see e.g. Pickles, 1988) receiving about 90 % of the afferent auditory nerve fibres (Spoendlin and Schrott, 1989). Each inner hair cell connects with approximately 10-30 Type I fibres (Liberman, Dodds, and Pierce, 1990). Outer hair cells connect to approximately 10 % (Type II) afferent fibres. Each fibre connects to several outer hair cells (see e.g. Pickles, 1988).

The deflection of the stereocilia of the outer hair cells in one direction causes the cells to depolarize or hyperpolarise dependent on the direction (Bear, Connors, and Paradiso, 2020 Chapter 11). The reaction to these potential changes differs between the inner and outer hair cells. Due to the motor protein prestin, which is expressed in mammalian outer hair cells (Zheng et al., 2000), the outer hair cells can

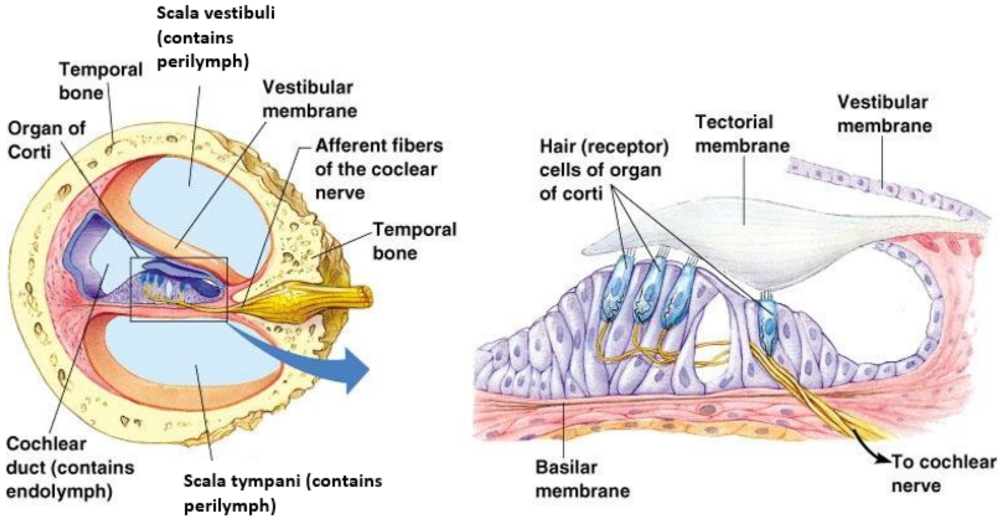

Figure 1.2: A detailed image of the cross section of a cochlea is shown on the left and the organ of corti with hair cells is shown on the right (Bear and Connors, 2007)

shorten or elongate in response to depolarisation or hyperpolarisation, respectively (Brownell et al., 1985). With the movement outer hair cells can actively amplify the basilar membranes' movement (Liberman et al., 2002), a phenomenon that is called the cochlear amplifier (e.g. Davis, 1983). When recognising the movement of the basilar membrane, the outer hair cells provide mechanical energy in a feedback loop, amplifying the stimuli they initially responded to, namely the travelling wave (e.g. Hudspeth, 1997). Additionally, the cochlear amplifier generates otoacoustic emissions (e.g. Kemp, 1978), which represent the emissions of the mechanical energy from the cochlear. These can be sensed by a microphone placed in the outer ear canal to prove the correct functioning of the outer hair cells. The absence of this otoacoustic emissions is an indicator for a damage of the outer hair cells (e.g. Kemp, Ryan, and Bray, 1990).

On the other hand, the deflection of the stereocilia of the inner hair cells opens mechanosensitive K^+ channels. There an influx of positive ions is caused by the potential gradient between the endocochlear potential and the cytosol of the inner hair cells and the cell becomes depolarised. This causes an opening of Ca^+-dependent channels, leading to an influx of ions that release the neurotransmitter glutamate into the cleft between the inner hair cells and the terminals of the afferent nerve fibres. When the neurotransmitter bind to the nerve terminals, an action potential is generated in the ganglion cells. Several relay stations of the central auditory system are passed on the way up to the auditory cortex (figure 1.3; e.g. Kandel et al., 2000). First the auditory nerve forwards the signal to the ipsilateral cochlear nucleus in the brainstem. Afterwards the signal is sent from the cochlear nucleus to the medial nucleus of the trapezoid body and the superior olivary nucles (both in the brainstem). The signal passes the lateral lemniscus (brainstem), where great parts of the acitvity cross the midline to the contralateral auditory nuclei and reach the inferior colliculus in the midbrain. Finally, the signal is send to the auditory cortex (Brodmann Area (BA) 41 and 41; Brodmann, 1909) via the medial geniculate body of the thalamus. Due to the traveled way, the excitation is strongest in the contralateral auditory cortex.

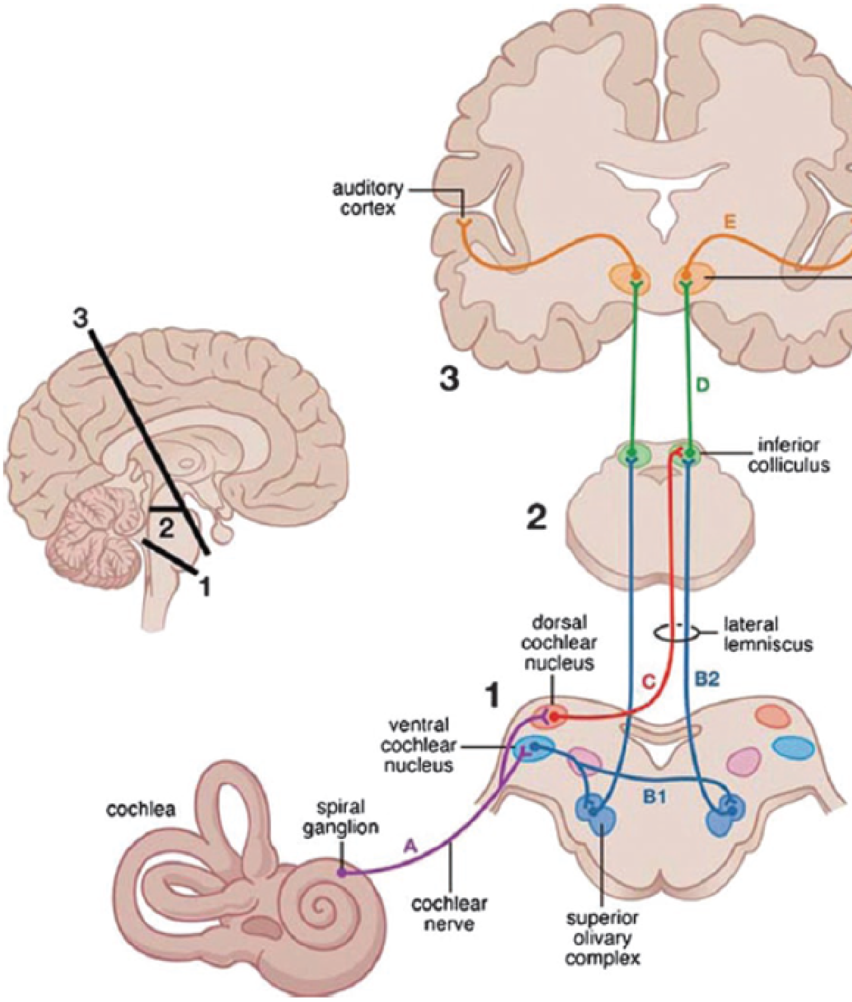

Figure 1.3: The ascending auditory pathway (Hall and Paltoglou, 2016)

1.1.2 *Types of hearing loss*

Individuals with a hearing loss (HL) greater than 20 dB in one ear are considered "hard of hearing" up to "deaf", depending on the severity (see table 1.1). Figure 1.4 depicts some typical sounds and their intensity level in an audiogram. The curved blue area is often called "speech banana" due to it's shape, and it covers the intensity and frequency range of conversations in quiet environments (Ross, 2004). Since the most important speech sounds are represented in this range, even a moderate hearing loss (35-50 dB HL) makes the understanding of speech at normal conversational levels challenging. Therefore, the goal of all supplies is to bring the hearing threshold into the range of the speech banana. Regarding the onset of the HL the affected individuals are classified as congenitally deaf (HL onset before birth), pre-lingually deaf (HL onset prior to language acquisition), peri-lingually deaf (HL onset during language acquisition) or post-lingually deaf (HL onset after language acquisition). Different types of hearing loss are known, dependent on the impairment of the auditory system, and comprise *conductive hearing loss*, *sensorineural hearing loss*, *neural hearing loss* and *central hearing loss* (e.g. Kral and O'Donoghue, 2010; Zahnert, 2011).

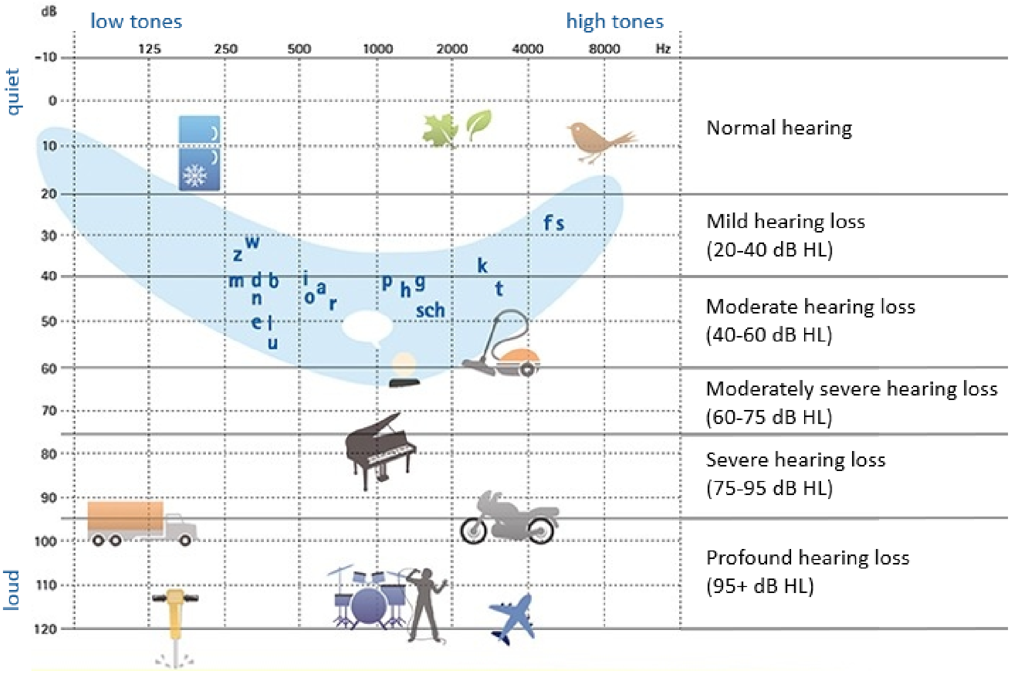

Figure 1.4: Daily sounds in an audiogram. As in typical audiograms the frequency is depicted on the horizontal axis with low frequencies/tones on the left and high frequencies/tones on the right, and the hearing level is depicted on the vertical axis with low intensities (quiet) at the top and high intensities (loud) at the bottom. Adapted with permission from Phonak, Copyright © Phonak

Conductive hearing loss is caused by complications in the ear canal or the middle ear which prevent sounds to reach the inner ear. This can be caused by e.g. obstructions (foreign body of cerumen) or malformations of the outer ear. Also diseases like otosclerosis or otitis media can cause this type of HL by fixating the ossicles. In some rare cases, a rupture of the tympanic membrane can cause conductive hearing loss. Most of the causes can be treated by medication or surgery, and if not the use of conventional hearing aids is sufficient. In the case of severe HL, when the conventional hearing aids do not provide a sufficient benefit, middle ear implants can serve as a solution.

Sensorineural hearing loss on the other side is caused by complications in the cochlea or the acoustic nerve. In this case, the hair cells in the inner ear are damaged, which is not reversible since mammalian hair cells do not regenerate naturally. Nevertheless, recent research attempts to find ways to regenerate mammalian hair cells for the treatment of sensorineural hearing loss (Parker, 2011). The most common form of sensorineural hearing loss is presbyacusis, which denotes age-related hearing loss, and affects about 40 % of people older than 65 years (e.g. Zahnert, 2011; Ries, 1994). It is specifically prominent in high frequencies due to an age-related degeneration of the outer hair cells in the base of the cochlea (e.g. Liu and Yan, 2007). Affected individuals are mostly treated with conventional hearing aids to stimulate their residual hearing. Some other causes of sensorineural hearing loss are acoustic trauma, genetic diseases, drugs, or infections. This kind of aetiolgies lead to the destruction of the outer and inner hair cells and therefore conventional hearing aids are not effective. Affected individuals can be supplied with a cochlear implant (CI, see section 1.2), which transforms acoustic into electrical signals and directly stimulates the acoustic nerve (Wilson and Dorman, 2008).

If conductive and sensorineural hearing loss are present in the same ear, the term *mixed hearing loss* is used.

A less common form of HL is *neural hearing loss*, which is caused by the loss of the auditory nerve. A common cause of this form is bilateral growth of vestibulocochlear schwannomas due to the genetic disease neurofibromatosis type II (NF2; e.g. Baser, Evans, and Gutmann, 2003; Slattery, 2015). Other possible causes are posttraumatic injuries of the nerve, nerve aplasia, or a complete ossification of the cochlea. Since the electrical signal could not be forwarded by the nerve, CIs are not beneficial for this group of patients. Instead they could be treated with auditory brainstem implants (ABI, e.g. Schwartz et al., 2008) or auditory midbrain implants (AMI, e.g. Lim, Lenarz, and Lenarz, 2009). This kind of implants electrically stimulate more central parts of the auditory system.

The rarest form of HL is *central hearing loss*, which is caused by disturbances within the central auditory pathway or the auditory cortex. It does not implicitly lead to complete deafness, since affected individuals are often still able to perceive tones. They rather suffer from impairments in speech processing, especially in difficult hearing situations including noise or the need to localise sounds (Zahnert, 2011). This type of HL is caused by physical trauma, inflammations, tumours, or brain infarcts and can not be treated with any kind of aids or implants.

Grade	Hearing threshold in better hearing ear in dB	Hearing experience in a quiet environment for most adults	Hearing experience in noisy environment for most adults
Normal hearing	< 20	No problem hearing sounds	No or minimal problem hearing sounds
Mild hearing loss	20 to < 35	Does not have problems hearing conversational speech	May have difficulty hearing conversational speech
Moderate hearing loss	35 to < 50	May have difficulty hearing conversational speech	Difficulty hearing most speech and talking part in conversation
Moderately severe hearing loss	50 to < 65	Difficulty hearing conversational speech; can hear raised voices without difficulty	Difficulty hearing most speech and talking part in conversation
Severe hearing loss	65 to < 80	Does not hear most conversational speech; may have difficulty hearing and understanding raised voices	Extreme difficulty hearing speech and talking part in conversation
Profound hearing loss	80 to < 95	Extreme difficulty hearing raised voices	Conversational speech cannot be heard
Complete or total hearing loss / deafness	95 or greater	Cannot hear speech and most environmental sounds	Cannot hear speech and most environmental sounds
Unilateral	< 20 in the better ear, 35 or greater in the worse ear	May not have problem unless sound is near the poorer hearing ear. May have difficulty in locating sounds	May have difficulty hearing speech and talking part in conversation, and in locating sounds

Table 1.1: Current WHO rating of hearing loss (WHO, 2021). The table provides the grade/categorisation due to the hearing threshold range in the better ear. Additionally the hearing experience in quiet and noisy environments is described for each threshold range.

Currently, a cochlear implant (CI) is the only clinically available neural prosthesis that can substitute a human sense (Macherey and Carlyon, 2014). The CI is a bionic device compensating the loss of functional hair cells in the cochlea by the direct stimulation of the residual intact auditory nerve fibres (Carlson, 2020). Figure 1.5 illustrates the essential components of a CI system nowadays, which consists of a sound processor (1) with a transmitter coil (2), an implant (3) with a receiver coil and an electrode array (4). The sound processor is equipped with microphones and is usually placed behind the patients' ear. It transforms the recorded acoustic sound information into a set of digitally coded sounds and sends the information transcutaneously through radio-frequency via the transmitter coil to the receiver coil. The coils are connected by magnets. The electrical information are forwarded to the acoustic nerve via the electrode array, which is placed into the scala tympani of the cochlea (Wilson and Dorman, 2008). The electrodes evoke activation of the peripheral auditory nerve by delivering currents that are projected to the central nervous system. Depending on the manufacturer, the electrode array consists of 12, 16 or 22 electrodes. These electrodes provide the tonotopic stimulation of the auditory nerve by placing them at different tonotopic locations inside the cochlear. The central nervous system interprets the signals as meaningful sounds like speech and environmental sounds. Taken together, the inner and the middle ear are replaced by the CI, as it bypasses the normal acoustic sound transmission through the tympanic membrane and the auditory ossicles (Müller, 2005).

The first clinically used CI was implanted in 1961 by the Americans William House and John Doyle (Deep et al., 2019; Wilson and Dorman, 2008) and it consisted of a single electrode used to provide sound awareness (Zeng, 2004). Nowadays CI implantation became a standard clinical surgery and approximately 750.000 patients receive this prosthesis worldwide (Cullington et al., 2022), including nearly 50.000 in Germany (Lenarz, 2017).

LIMITATIONS OF A CI The fact that approximately 3000 inner hair cells are compensated for by up to 22 electrodes makes it understandable that a cochlear implant provides a different and limited auditory impression. The frequency range is narrowed from 20 to 20.000 Hz divided into 1400 frequency steps in natural acoustic hearing (Zeng, 2004; Zeng, Tang, and Lu, 2014), to approximately 200-8500 Hz with coarser frequency steps (depending on the number of electrodes and the strategy used in the regarding implant) in the electrical hearing via a CI (Limb and Roy, 2014). Consequently, crucial limitations appear in the intensive, temporal and spectral processing (Zeng, 2004). Nevertheless, CI users normally reach a good speech understanding in quiet listening environments within a few months after implantation (Blamey et al., 2012; Holden et al., 2013), whereas situations with additional noise or multiple concurrent speakers remains challenging (Wilson and Dorman, 2008; Müller-Deile, Schmidt, and Rudert, 1995), because it is difficult to extract the relevant speech information. Moreover, music perception is notably limited, since the frequency representation of CIs is not fine-grained enough (Drennan and Rubinstein, 2008).

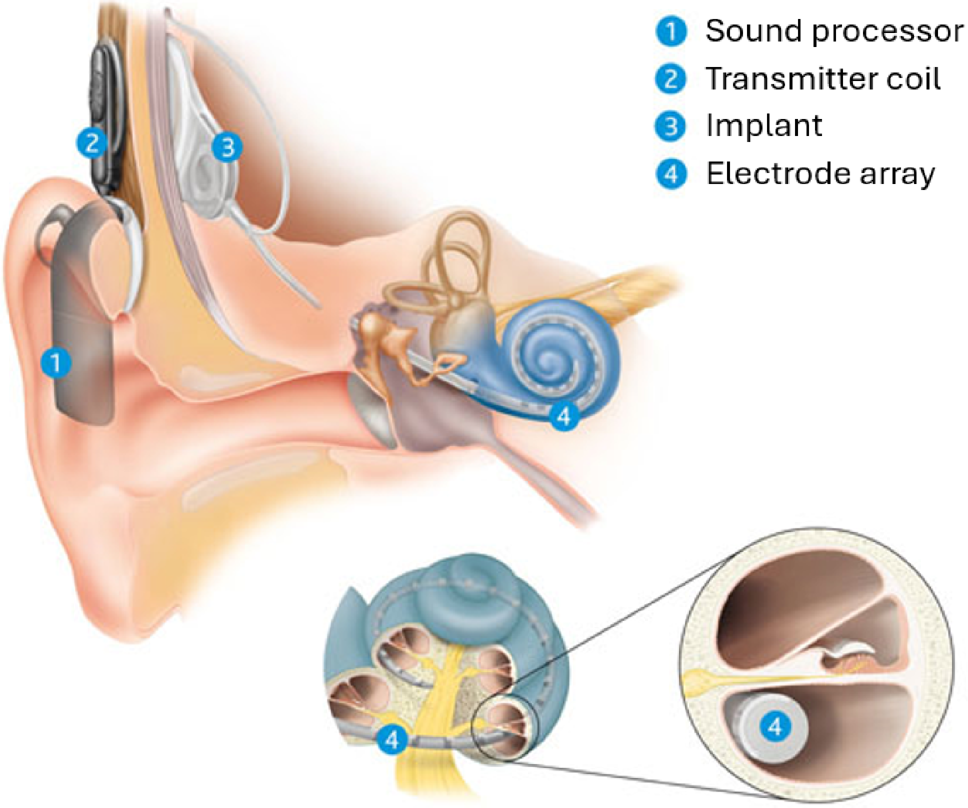

Figure 1.5: Basic components of a cochlear implant including the sound processor with the transmitter coil, the implant with the receiver coil, and the electrode array inside the scala tympani of the cochlear. Copyright © Cochlear Limited 2014

However, over the past 35 years, the CI manufacturers and CI clinicians worked in close scientific cooperation to significantly improve the technology (Dhanasingh and DeSaSouza, 2022). This resulted in improved CI features, such as noise reduction algorithms to improve hearing in noisy environments (Caldwell, Jiam, and Limb, 2017; Wolfe et al., 2015; Müller-Deile et al., 2008).

1.2.1 *User groups*

A cochlear implant can benefit different groups of individuals with sensorineural hearing loss. While in the early days of CIs, exclusively patients with profound bilateral hearing loss were supplied with a CI on one side, the indications have broadened in the past decades (e.g. Deggouj et al., 2007; Sampaio, Araújo, Oliveira, et al., 2011).

Congenitally, respectively pre-lingually, deaf children are supplied with a CI as soon as possible with the age limited of six months. In this group an early treatment with a CI is crucial for language acquisition (Sharma and Campbell, 2011).

Further, the focus turned to bilateral CIs, since there is increasing evidence of advantages of bilateral over unilateral implants, especially for speech-in-noise and spatial hearing (Gantz et al., 2002; Litovsky et al., 2006; Litovsky, Parkinson, and Arcaroli, 2009).

Besides *bilateral* CI users, also *bimodal* CI users benefit from a CI on one ear and (in most cases) a conventional hearing aid on the contralateral ear (e.g. Hamzavi et al., 2004). This group has residual hearing in at least one ear and is usually supplied with a CI on the poorer ear. If the residual hearing in the implanted ear is especially good in the low frequencies, a CI with a shorter electrode can be implanted to avoid damage of the cochlear hair cells near the apex that code low frequencies. In combination with this short electrode, a conventional hearing aid can be used at the same ear, hence establishing a combined electro-acoustic hearing (e.g. Von Ilberg et al., 2011).

In recent years, the margins for CI indication have even been expanded to include patients with unilateral hearing loss, also called single-sided deaf (SSD). Although these patients experience maximal asymmetric auditory input and hence processing (Gordon, Jiwani, and Papsin, 2013; Kral, 2013), it has been shown that CI implantation is highly advantageous. As well as in bimodal or bilateral CI users, the restoration of the binaural hearing in this patient group results in better sound localisation, speech-in-noise understanding and quality of life (Kitterick, Lucas, and Smith, 2015).

Right ear advantage Although it is often assumed that binaural hearing is symmetrical, some studies found a right ear advantage (REA), stating that by presentation of two competing speech signals, one to each ear, the right ear shows a better speech recognition compared to the left ear (Kimura, 1961a, Kimura, 1961b). Kimura (1967) described this phenomenon using the structural model of the REA. It says that each ear's input has a stronger representation in the contralateral hemisphere of the brain when compared to the ipsilateral hemisphere. Since the left hemisphere, in most individuals, is specialised for language functions, the performance of the right ear processing speech stimuli is better compared to the left ear. Support for this model was provided by brain imaging studies showing bilateral activation in the superior temporal lobe evoked by speech sounds in dichotic listening conditions, with significantly enhanced activation in the left than in the right hemisphere (Hugdahl et al., 1999; Van Den Noort et al., 2008). Another explanation of this effect was given by Poeppel (2003), stating that the left hemisphere is specialised for the processing of rapidly fluctuating acoustic signals, while the right hemisphere is more proficient at the processing of slower temporal changes. Therefore, the rapid temporal changes in speech signals, such as formant transitions, could explain the left-hemispheric advantage for speech recognition.

The REA was also examined in CI users by different previous studies. Some show an advantage of the right CI in children that were implanted with bilateral CIs simultaneously (e.g. Henkin et al., 2014), others found a REA in unilaterally implanted adults (Sharpe et al., 2016; Mosnier et al., 2015). A systematic review by Kraaijenga et al. (2018) concluded, that most studies reveal a REA both in prelingually deafened children and postlingually deafened adults and that it may therefore be advantageous to implant the right ear when other prognostic factors do not speak against it.

1.2.2 *Rehabilitation after implantation*

The rehabilitation after cochlear implantation is thought to be successful if the affected individual not only regained the ability to hear, but also the ability to understand speech without lip reading, to use the telephone and to understand speech in difficult hearing situations like noisy environments (Dazert et al., 2020). The implantation alone does not lead to these results, since each patient needs its own individual fitting of the speech processor. The fitting is performed by CI audiologists/technicians, who individually determines the stimulation parameters such as the electrical stimulation current intensity (Hoppe, Hocke, and Digeser, 2018; Dazert et al., 2020). The most important parameters are the comfort-level (C-level), which is the current at which sounds are perceived as comfortable in volume, and the threshold-level (T-level), which is the current at which the sounds are just barely perceptible (Hoppe, Hocke, and Digeser, 2018).

The first fitting of the speech processor takes places after a healing phase, which differs due to the supplying institution, around 3 to 6 weeks after surgery. There the speech processor is switched on for the first time and the patients experience their first auditory impressions in their new hearing situation. Most patients do not perceive speech at first, but rather noise or chirps (Deep et al., 2019). Numerous subsequent fitting sessions take place in the following time, mostly accompanied by speech and language therapy, as well as by regular clinical audiometric tests and medical examinations (Diller, 2009). No matter how long a patient is wearing the CI, a yearly follow-up check is inevitable to examine the hearing abilities, the speech processor settings, and the technical issues, as well as to address any concerns.

Factors affecting the outcome Regardless of the settings and intensive speech training during rehabilitation, speech intelligibility varies greatly between individuals and it is affected by individual factors. These factors include the aetiology of hearing loss, the duration of hearing loss, the duration of hearing aid use prior to implantation, the age at implantation and the hearing ability prior to implantation (Zhao et al., 2020; Blamey et al., 2012; Blamey et al., 1992; Lazard et al., 2012b). Additionally, some surgical factors are thought to have an impact, like the placement of the electrode (Holden et al., 2013), the insertion depth (James et al., 2019), the implants' brand and the amount of active electrodes inside the cochlea (Lazard, Collette, and Perrot, 2012). Whilst the literature is fairly unanimous that these factors affect the jearing outcome, the extend of each factor varies greatly between studies (Zhao et al., 2020). By now the largest cohort of CI users (N = 2735) was analysed by Goudey et al. (2021), who included three different clinics in three countries and 21 indivual factors to predict the CI outcome. Even this study was only able to explain a modest percentage of the variance in CI outcome, therefore suggesting not only a large number of included patients, but also longitudinal studies.

Other than the previously mentioned factors, neuroplasticity is also thought to play a crucial role for the CI outcome (Stropahl, Chen, and Debener, 2017). Neuroplasticity was shown to appear after auditory deprivation as well as due to the limited auditory input after CI implantation (Lazard et al., 2012b; Lazard, Collette, and Perrot, 2012; Lazard et al., 2012a). Previous studies revealed for instance correlations between longer periods of deprived hearing and CI experience with a higher degree of cortical reorganisation (Giraud et al., 2001a; Green et al., 2005; Sandmann et al., 2015; Oh et al., 2003). Because of its crucial role in individuals suffering from hearing loss and in CI users, neuroplasticity is explained in more detail in the following section.

1.3 NEUROPLASTICITY

Neuroplasticity is the brains' ability to reorganise in a functional or structural way, which can occur in early stages during development, but can also be triggered by intrinsic factors or external experience in the mature brain. In the human brain, neuroplasticity is observed throughout the whole life span (e.g. Jäncke, 2009). Different forms of neuroplasticity are distinguished, namely *experience-independent*, *experience-expectant* and *experience-dependent* plasticity (Kolb et al., 2013). While *experience-independent* plasticity occurs during the prenatal development and is not influenced by external factors (e.g. Kolb et al., 2013), *experience-expectant* and *experience-dependent* plasticity are triggered by external information and by experience (e.g. Greenough, Black, and Wallace, 1987). If the utilised information is omnipresent in the environment of all members of the same species, one speaks of *experience-expectant* plasticity, and if the experience is limited to the single affected subject, one speaks of *experience-dependent* plasticity. The latter can occur throughout the whole lifespan and therefore affects already fully established neuronal networks. In many cases structural changes affect synaptic contacts, whereby the number of contacts can either increase or decrease. These structural changes also relate to functional changes as indicated by alterations in strength, spectral and temporal selectivity, and the latency of neural responses (Jakkamsetti, Chang, and Kilgard, 2012).

Accordingly, in cochlear implant patients, *experience-dependent* plasticity plays a crucial role, since the brain has to deal with new hearing situations, both during auditory deprivation and after implantation.

1.3.1 *In deafness*

Individuals that are affected by congenital or early deafness tend to rely strongly on their remaining senses like vision or touch. In previous research two hypotheses have been reported regarding the characteristics of the effects, namely the *perceptual deficit hypothesis* and the *sensory compensation hypothesis*. The congenital or early deaf individuals show both intra- and cross-modal plasticity.

Previous studies showed enhanced visual event-related potentials to peripheral visual stimuli in early deaf individuals over temporal and frontal regions when compared to NH listeners (N150 component; Neville, Schmidt, and Kutas, 1983), which was later shown to originate in the visual cortex and hence called intra-modal plasticity (Bavelier et al., 2000; Neville and Lawson, 1987). This enhanced visual activity was solely observed for moving stimuli in the periphery and activated the middle temporal (MT) and medial superior temporal (MST) area, which are regions involved in motion processing (Bavelier et al., 2000). To rule out the use of sign language as the cause of these plastic changes, Bavelier et al. (2001) did a follow-up study and revealed that the effects are a true consequence of deafness, not related to the use of sign language. Behavioural data supported these results, as deaf individuals performed better in conditions with moving stimuli in the periphery. Another study by Bottari et al. (2011) revealed an impact of auditory deprivation in early cortical processing steps (C1 and P1 component), more precisely congenital and early deaf individuals exhibited a double peak of the C1 and P1 component that was not present in NH controls when stimulated with a visual warning signal. The early deaf individuals even showed a negative correlation between the P1 amplitude and the reaction times to the visual targets, whereas NH controls only showed a relationship between electrophysiological and behavioural data at later cortical stages (Bottari et al., 2011).

The recruitment of sensory deprived cortical areas by the remaining sensory systems is called cross-modal plasticity and it is thought to be the cause for several superior skills regarding vision and touch in congenital or early deaf individuals (see e.g. Bavelier, Dye, and Hauser, 2006; Merabet and Pascual-Leone, 2010). Previous research found a larger sensitivity for vision as indicated by greater visual fields (e.g. Buckley et al., 2010; Codina et al., 2011), enhanced skills for the detection of visual stimuli (e.g. Bottari et al., 2010; Heimler and Pavani, 2014), superior skills in motion processing (Hauthal et al., 2013) and also increased sensitivity for tactile stimuli (e.g. Levänen and Hamdorf, 2001) in congenital or early deaf individuals. Those behavioural observations were found to be in line with a recruitment of the unexploited auditory cortex by the remaining modalities. For instance, Finney, Fine, and Dobkins (2001) and Fine et al. (2005) found a significant activation of the right auditory cortex of deaf individuals, not of the hearing control group, when stimulated with peripheral moving dot patterns. The authors ruled out that the cross-modal activation of the auditory cortex was due to sign language by including a group of hearing signers, which did not reveal a visual activation of the auditory cortex (Fine et al., 2005), and therefore concluded that auditory deprivation was the cause. Similarly, Finney et al. (2003) obtained visual activation of the right auditory cortex within the first hundreds of milliseconds in a MEG study. Since the right hemisphere plays a role in auditory motion processing, they suggested that the early stages of visual motion processing overtook this unexploited area. Further, deaf individuals have been shown to recruit the auditory cortex in visual dynamic change detection tasks, accompanied by a decreased activation of visual areas (Bottari et al., 2014). Kral (2013) indicated that cross-modal plasticity involves specific regions of, rather than the whole, auditory cortex, which is in line with the fact that only certain functions of the remaining modalities are enhanced instead of the modalities in general. Therefore, auditory deprivation seems to have rather selective effects, not affecting the primary auditory cortex (see Kral et al., 2003), but higher-order or association areas. Additionally, applied methods are not always allowing concrete conclusions about the reorganised neural generators (e.g. Finney et al., 2003; Levänen, Jousmäki, and Hari, 1998), so no firm conclusions can be drawn.

All mentioned results are primarily obtained in congenital or early deaf individuals and may not fully apply to individuals with a late onset of hearing loss. Only limited evidence of cross-modal reorganisation of the auditory cortex in postlingually deafened individuals is present in the literature. Some studies found reduced auditory activity in postlingually deafened individuals during resting state (Lee et al., 2003), while others revealed activity in temporal areas during a speech-reading task, which are areas known to be activated in hearing controls during auditory processing (Lee et al., 2007). Lazard et al. (2011) and Lazard et al. (2013) found evidence for a decrease in non-speech sound memory and reorganisation of non-speech networks.

Overall, the effects of cross-modal plasticity can either be described as beneficial or detrimental. They seem to be greatly beneficial for the time of deprivation, since the brain tries to compensate for the drawback caused by the loss of the deprived modality, by expanding the remaining sensory modalities.

1.3.2 *In CI users*

The outcome of the treatment with a CI is dependent on many factors, some of them known to be mechanisms of intra- and cross-modal plasticity. Alterations of the plasticity, both intra- and cross-modal, have been observed for the auditory and also for the visual modality (for a review see Heimler, Weisz, and Collignon, 2014; Stropahl, Chen, and Debener, 2017). The mechanisms can differ due to the timepoint the deafness occurs, but also due to the time point of hearing restoration via a CI.

The auditory system needs early acoustic experience to develop in a normal way (e.g. Knudsen, 2004; Kral et al., 2002), which is not the case in congenital or early deaf individuals. Maturation of the auditory system in these individuals, which was forfeited during the time of deprivation, has to catch upt after the restoration of hearing via a CI (Kral et al., 2006). Nevertheless, they are in general able to rapidly adapt to the new electrical input via the CI, ending up in comparably good speech recognition outcomes (Fryauf-Bertschy et al., 1997; Hammes et al., 2002). This can be explained by the fact that the brain's capability of neural plasticity (in this case of the auditory cortex) is largest during the first period of life (e.g. Kral and Tillein, 2006). Following animal studies that showed increasing synaptic activity (Kral et al., 2006) and growing areas of cortical activation (Klinke et al., 1999) leading to stronger activations of higher-order cortical regions (Kral and Eggermont, 2007), studies found activation of both, the primary and higher-order auditory areas, in early implanted deaf children (Gilley, Sharma, and Dorman, 2008; Nishimura et al., 1999). Late implanted children showed less activation of higher-order auditory areas (Naito et al., 1997), as well as poorer speech recognition outcomes, when compared to early implanted children (see e.g. Hinderink et al., 1995; Kral and O'Donoghue, 2010; Kral and Sharma, 2012; Niparko et al., 2010). These results support the idea of a sensory period for cochlear implantation (Niparko et al., 2010; Ponton et al., 1996; Sharma, Dorman, and Kral, 2005; Sharma et al., 2007). Although children implanted before the age of 2.5 years have a stronger benefit in speech recognition outcomes (e.g. Connor et al., 2006), the end of this sensitive period does not mean the end of the brains' plasticity in general, but a limitation (see e.g. Kral et al., 2006). Kral et al. (2005) proposed the decoupling hypothesis, stating that a missing auditory input during the sensitive period affects thalamo-cortical and cortico-cortical feedback circuits of the primary auditory cortex, resulting in a functionally disconnection of the primary and higher-order cortices. Further, some electrophysiological studies emphasised a sensitive period for CI implantation in early deaf children (Sharma, Dorman, and Kral, 2005; Sharma et al., 2007), by showing that children implanted before the age of 3.5 years develop auditory event-related potentials (AEPs) similar to NH children, and that children implanted after the age of 7 years develop prolonged latencies in the AEPs when compared to NH children. Mostly, the P1 and N1 component are used to control for normal maturation of the auditory cortex (Sharma, Campbell, and Cardon, 2015), because their primary generators are located in higher order auditory cortices (Kral and Eggermont, 2007; Liegeois-Chauvel et al., 1994). The N1 component can be observed in children implanted before the age of 3.5 years (Sharma and Dorman, 2006), but not in late implanted children (Ponton and Eggermont, 2002), which points to an insufficient activation of higher order auditory regions and with that to poorer speech recognition scores (Giraud et al., 2001a). Contrarily, the P1 component, which has generators in primary and in higher order auditory areas (e.g. Liegeois-Chauvel et al., 1994), can also be seen in late implanted CI users (Ponton and Eggermont, 2002), but with an abnormal morphology and latency (Sharma, Campbell, and Cardon, 2015). Hence it is hypothesised that the primary auditory cortex in late implanted early deaf children is functioning at least to some extent. Additionally to these intra-modal changes, also cross-modal reorganisation has been shown in late implanted individuals revealing activity in the temporal cortex as a response to visual motion, which negatively correlates with speech recognition scores (Buckley and Tobey, 2011). This, in line with different other studies, provides evidence for the idea that cross-modal reorganisation of the auditory cortex restricts good speech recovery (Buckley and Tobey, 2011; Sharma, Campbell, and Cardon, 2015).

On the other hand, postlingually deafened individuals have a fully developed auditory system, which might have been degraded or undergone cross-modal changes due tor the period of deafness. Their restored hearing ability via a CI does not match the old acoustic hearing, thus they have to learn the new characteristics of the artificial input and the evoked neural activity (Kral and Tillein, 2006). Accordingly, plastic changes also play an important role for the adaptation process in postlingually deafened CI users, which require neural plasticity in an extent exceeding commonly observed changes in healthy adults.

Although the initial outcomes right after implantation are often highly limited, postlingually deafened adults mostly show good speech recognition abilities within the first months of CI use (Krueger et al., 2008; Oh et al., 2003; Sandmann et al., 2015). Since the auditory cortex seems to not be able to process the input provided by the implant to its full extent at the initial state (Sandmann et al., 2015) and the input does not change remarkably over the time of CI use, the improvements in speech recognition abilities have to be related to changes in the auditory processing.

It is supposed that these improvements are related to the brains ability to adapt to the new artificial input by means of plastic changes over the time of CI use. Correspondingly, previous PET studies found cortical activation in postlingually deafened CI users right after the initial switch on in response to sounds in the primary, as well as in the secondary auditory cortex and auditory association areas (e.g. Naito et al., 1997). These results were confirmed by another study showing contralateral auditory cortex activation within the first week after the initial switch-on of the processor in primary and non-primary auditory areas, whereas the speech discrimination was not possible this early (Giraud et al., 2001b). This longitudinal study also found a more primary auditory cortex focused activation and a left hemispheric activation by speech signals, which is typically language related, after one year of CI use. In line with some other longitudinal studies (e.g. Burdo et al., 2006; Pantev et al., 2006; Purdy and Kelly, 2016; Sandmann et al., 2015; Suárez et al., 1999; Woldorff et al., 1993) the feasibility of a fast adaptation of the auditory system to the new artificial input by mechanisms of intra-modal plasticity is revealed. The strongest adaptation was shown to be within the first six months of CI use (Pantev et al., 2006), with a larger number of neurons firing in general and a stronger synchronisation of neural responses as the underlying cause for increased auditory cortex activity. Sandmann et al. (2015) even showed a faster adaptation to the new input, who reported improvements in speech recognition and frequency discrimination, plus enhanced and faster neural responses, already eight weeks after the initial switch-on of the processor. These results underline the auditory systems' ability to preserve its plasticity, even after a period of deafness, which is supported by the positive relationship between speech recognition improvements and increased auditory cortex activation (e.g. Green et al., 2005; Olds et al., 2016). Cross-modal changes were also found in the Broca area, with lower activation in postlingually deafened CI users as compared to NH listeners and simultaneous stronger activation of the temporal voice-sensitive area (TVA), while performing a speech-reading task (Rouger et al., 2012). These plastic changes seem to reverse with CI use, revealing the possibility of ongoing cross-modal plasticity. Additionally, since the functional changes occur in the auditory and the visual system, Rouger et al. (2012) suggested the use of audiovisual integration to facilitate the mechanisms right after CI implantation. A debate about the beneficial and detrimental effects of cross-modal plasticity and the speech recognition outcome is ongoing in the literature (e.g. Chen et al., 2016; Doucet et al., 2006; Giraud et al., 2001b; Giraud et al., 2001a; Sandmann et al., 2012). While some studies found a negative relationship between the amount of cross-modal reorganisation after CI implantation and the CI outcome (e.g. Rouger et al., 2012; Sandmann et al., 2012), others found positive relationships between the activation of the visual cortex by auditory stimulation (cross-modal reorganisation in the direction of the visual system) and the CI outcome (Chen et al., 2016; Giraud et al., 2001b; Giraud et al., 2001a). Chen et al. (2016) found that good speech recognition ability was ensured as long as the visual activity in the auditory cortex was weaker then the auditory activity in the visual cortex. Thus, the auditory and visual processing change in adaptation to the new input and cross-modal reorganisation is not always detrimental. Some EEG studies were even able to distinguish between good and poor CI performers, showing that good CI performers have greater VEPs over occipital electrode sites, while poor CI performers have stronger activity over anterior occipito-temporal electrode sites (e.g. Doucet et al., 2006; Kim et al., 2016). Additionally, a positive correlation between the enhanced cross-modal reorganisation in the auditory cortex and lip reading, as well as face recognition abilities was found (Stropahl et al., 2015). However, Sandmann et al. (2012) revealed a negative correlation of the enhanced cross-modal reorganisation and the CI outcome. Another study pointed to better CI outcome (six months of CI use) for postlingually deafened CI users with stronger activity of the visual cortex in response to visual stimulation directly after implantation (Strelnikov et al., 2013).

To sum up, postlingually deafened CI users show both, intra- and cross-modal reorganisation in the auditory and visual cortex. In the period of deafness, cross-modal reorganisation might have a compensatory role by strengthening the remaining modalities and after the restoration of the hearing ability it might facilitate the CI users' performance by a closer integration of the auditory and visual system.

1.3.3 *Multisensory interactions*

Situations in the real-life are frequently not unisensory, but include the interaction of different modalities. Especially spoken language communication includes auditory and visual input (lip movements, facial expressions and gestures) to order it successfully (Drijvers and Özyürek, 2017; Grant and Seitz, 1998; Sumby and Pollack, 1954), especially in difficult hearing situations such as background noise (Sumby and Pollack, 1954; Ross et al., 2007). For hearing impaired individuals and CI users it is even more important, since the auditory input provided by the CI is limited in the spectral and temporal domain (Drennan and Rubinstein, 2008) and CI users normally have problems with speech recognition in noisy environments (Müller-Deile, Schmidt, and Rudert, 1995; Hochmair-Desoyer et al., 1997). Hence, the integration of other modalities like vision can considerably complement the degraded auditory input.

One of the most known audiovisual effects is the so called McGurk effect. The effect was first described by McGurk and MacDonald (1976) and the experiment consists of different syllables that are presented in auditory, visual and audiovisual conditions. The audiovisual syllables are presented either congruent or incongruent. In incongruent conditions, NH listeners typically report the auditory representation of the syllable or a fusion percept, which is caused by the visual influence. This pattern was also observed in CI users with good speech recognition ability, whereas CI users with poor speech recognition ability primarily report the visual representation of the syllable (Tremblay et al., 2010).

Different brain regions were shown to be included in multisensory processing (e.g. parietal cortex and superior temporal sulcus), where the neurons receive inputs from different senses and combine them according to various constraints (Driver and Noesselt, 2008). However, also regions that were thought to be unisensory were shown to be included in multisensory processing, for instance by connections between the auditory and visual cortices while processing audiovisual speech (Giraud et al., 2001a; Strelnikov et al., 2015). Auditory deprivation and the duration of

CI use affect the degree of multisensory integration, as late implanted early deaf children show a visual dominance while processing audiovisual speech (Schorr et al., 2005) and a reduced ability to integrate the visual information into the limited auditory input (Gilley et al., 2010). In postlingually deafened CI users, a longer time of CI use is related to stronger audiovisual integration (Desai, Stickney, and Zeng, 2008) and they show a higher perceptual gain for congruent audiovisual speech conditions when compared to auditory only conditions (Rouger et al., 2008). Regarding incongruent audiovisual input, previous studies found differences between good and poor CI users, as seen in a stronger reliance on the visual information in poor performers when compared to good performers and NH listeners (Champoux et al., 2009; Desai, Stickney, and Zeng, 2008; Landry et al., 2012; Tremblay et al., 2010). Unfortunately it is not yet well understood how these behavioural results are related to intra- and cross-modal plastic changes in the visual and auditory cortex of CI users. Some first EEG studies addressed this issue and revealed enhanced visual modulations of auditory cortical responses in CI users when compared to NH listeners (Schierholz et al., 2015) or an audiovisual benefit for CI patients if complementing (congruent) visual information is available (Radecke et al., 2022). The altered multisensory interactions in CI users could be considered to be integrated into the auditory rehabilitation by multisensory training programs (Rouger et al., 2008).

1.4 METHODS

For this thesis, a variety of behavioural analysis was performed. Particularly these measures include hit rates (percentage of correct responses), response times and the efficiency (hit rate divided by response time). Additionally, demographic information, clinical tests measuring the hearing ability, various questionnaires, cognitive tests, rating scales, and other supplementary test were conducted to answer the research questions of the different projects. Detailed explanations for the measures can be found in the original publications, respectively. Since the used electrophysiological measures are more complex, this chapter focuses on a detailed description of the background, the measurement and the analysis of the electrophysiological data.

1.4.1 *Electroencephalography and other techniques*

Various techniques are available to study neuroplasticity in the human brain, such as functional magnetic resonance imaging (fMRI), Positron Emission Tomography (PET), functional near-infrared spectroscopy (fNIRS), Magnetoencephalography (MEG), and Electroencephalography (EEG; Giraud et al., 2001b). Some of these techniques have drawbacks when implemented for research purposes in CI users. For instance, PET is an invasive method involving the injection of a radioactive tracer and therefore difficult to examine in several recording sessions in the same patients for prospective longitudinal studies because the doses of the tracers are highly restricted (Giraud et al., 2001b). Regarding fMRI, it is only possible to perform it at low-power up to 3 T with some implants and certain precautions must be taken.

Additionally, the magnet of the implant generates large artefacts, preventing the study of neuroplasticity at least in the ipsilateral auditory cortex (Kim et al., 2015; Majdani et al., 2008). Contrarily, fNIRS, MEG and EEG are non-invasive and safe, but they measure different mechanisms. While fNIRS measures the tissues absorption of near-infrared light to assess the cerebral hemodynamic response with low temporal resolution of a few seconds (Ferrari and Quaresima, 2012), MEG and EEG measure the immediate correlate of cortical activity with a high temporal resolution of about 1 ms or better. All three techniques are hence suitable to study neuroplasticity in CI users, even though they have different complications. The spatial resolution of fNIRS is lower than that of the other functional imaging techniques and it cannot measure deeper than about 1 cm below the brains' surface, but the temporal resolution is quite high and it is of low costs (Wilcox and Biondi, 2015). On the other hand, MEG is an expensive method and the CI causes strong artefacts in the signal, but it can be used in CI users under certain conditions (Pantev et al., 2006). Finally, as shown in many previous studies, EEG is an effective tool to study neuroplasticity in CI users (e.g. Sandmann et al., 2015; Schierholz et al., 2015; Sharma, Dorman, and Spahr, 2002). The data gathered by this method is also influenced by artefacts following acoustic stimulation caused by the CI, but these can be reduced by means of an independent component analysis (ICA; Debener et al., 2008; Viola et al., 2012). The ICA is a method for the separation of linearly mixed sources in a dataset. Hence the artefacts, that are typically independent of each other, can be separated from the signal. Given it's excellent temporal resolution, EEG allows to track the single steps of cortical processing and therefore the investigation of fast brain dynamics or the tracking of the timecourse of auditory, visual and audiovisual speech processing steps (Biasiucci, Franceschiello, and Murray, 2019; Michel and Murray, 2012). By the use of the so called "electrical neuroimaging", the spatial information and the likely origin of the EEG signal can be obtained by using topographic and source analyses (Michel and Murray, 2012). When used correctly, it is thereby possible to study multisensory processing in CI users (Stevenson et al., 2014), and hence the analytical approaches of electrical neuroimaging ate used in the projects included in this thesis. All details of the used methods are explained in the following sections.

1.4.2 *Event-related potentials*

Event-related potentials (ERPs) are transient voltage changes as a response to internal or external sensory, cognitive or motor events (Luck, 2014 Chapter 1). Since the discussed projects mainly deal with auditory and visual event-related potentials (AEPs and VEPs), these are briefly introduced in the next sections.

AUDITORY EVENT-RELATED POTENTIALS After an auditory stimulus, the brain responds with various AEPs, which are classified into early, mid and late auditory responses (Picton, 2010).
Early AEPs can again be subdivided into responses up to 2-3 ms, i.e. electrocochleographic responses (EChochG; Ferraro, 2010) and responses up to 10 ms, i.e. auditory brainstem responses (ABRs; Stone et al., 2009). ECochGs are used for diagnostic purposes or for the monitoring of the cochleas' and auditory nerves' function

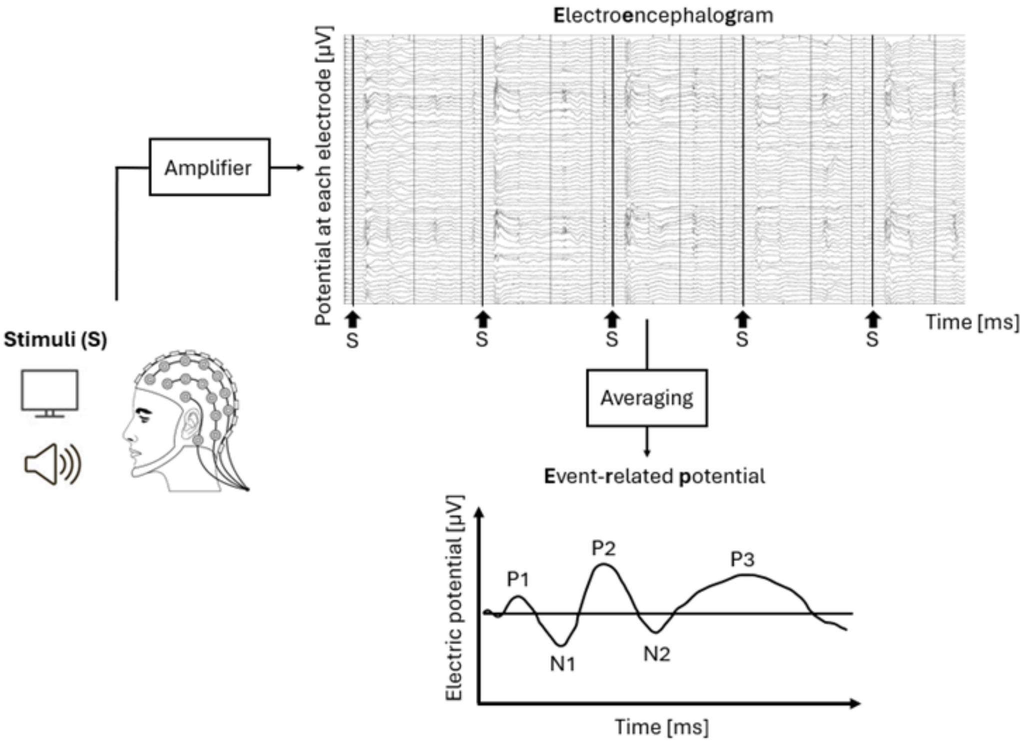

Figure 1.6: Schematic representation of the acquisition of the EEG signal. The EEG is recorded via electrodes on the scalp, while auditory and/or visual stimuli are presented. Defined trigger markers (S) mark the beginning of each trial and are used to extract individual segments/single trials from the continuous EEG signal. All single trials are averaged to one ERP waveform reflecting time- and phase-locked neural activities, that can be associated with the processing of the presented stimuli.

during surgery. They are recorded from the external ear canal or from the tympanic membrane and comprise cochlear microphonics (CM), the summation potential (SP) and the compound action potential (CAP; Eggermont and Odenthal, 1974). ABRs on the other hand are measured with surface electrodes placed on the skull and originate at different stages on the auditory pathway, from the cochlea to the auditory midbrain. The ABRs are conventionally labelled by Roman numerals (wave I to VI; Jewett and Williston, 1971) and they are used to measure the function of the auditory system and to estimate peripheral hearing loss in a clinical purpose (Stone et al., 2009). Since the ABRs are of automatic nature, they are especially useful in patients that are not able to perform active testing, like infants (Stapells, 2011). Therefore, they are part of the newborn hearing screening in combination with other measures like the otoacoustic emissions (Gravel et al., 2005).

In a later time window (up to 50 ms; Luck, 2014 Chapter 3) the mid-latency responses (MLRs) can be recorded, which are thought to originate from the thalamus and parts of the auditory cortex. These are the earliest responses that are modulated by attention (e.g. Woldorff, Hansen, and Hillyard, 1987) and are named due to their polarity with the capital letters P (positive) or N (negative), respectively, followed by a small letter or number (Mendel and Goldstein, 1969). MLRs are used to evaluate

the function of the auditory pathway, for the localisation of lesions in the auditory pathway, for the detection of hearing thresholds in the low-frequency range, or for the evaluation of cochlear implants (Kraus et al., 1993).
Lastly, the late auditory responses, or cortical AEPs, occur around 50-500 ms after stimulus onset (Goff, 1978) and can be subdivided into Exogenous/obligatory (P1, N1, P2) and endogenous/cognitive (P3, N400) components (Cone-Wesson and Wunderlich, 2003; Kraus and Nicol, 2009). While endogenous components are influenced by the attention and performance of the participant and are usually elicited by the active performance of cognitive tasks (Cone-Wesson and Wunderlich, 2003), exogenous components are highly influenced by external factors like the characteristics of the acoustic stimulus. Despite that they can also be modulated by higher order cognitive processes like attention and memory (Picton and Hillyard, 1974; Tremblay et al., 2001; Woldorff, Hansen, and Hillyard, 1987) and they originate in the primary auditory cortex and associated cortices (Lütkenhöner and Steinsträter, 1998; Picton et al., 1999). Similar to the MLRs, the late AEPs are named by a capital letter indicating the polarity (P or N) and a number, which can either indicate the latency (e.g. N100 as a negative peak around 100 ms), or the position of the component (e.g. N1 as the first negative peak; Davis and Zerlin, 1966). One component, more precisely the MMN (mismatch negativity; Näätänen et al., 2007), is an exception, since it can be seen as endogenous and exogenous (Kraus and Nicol, 2009).

Visual event-related potentials Following a visual stimulus, the brain responds with VEPs, which can also be divided into different components. Contrarily to the AEPs, the most important VEPs occur in a late time range of 80-200 ms, and are (mostly) labelled in the same way as the AEPs, so by the polarity and a number referring to the position of the component. The exception is the C1, which has its maximal peak around 80-100 ms and can have either a negative or a positive polarity, depending on the location of the stimulus inside the visual field (e.g. Clark, Fan, and Hillyard, 1994; Jeffreys and Axford, 1972). This can be explained by the special anatomy of the primary visual cortex, more precisely the folding in the calcarine fissure, where the C1 is thought to originate (Clark, Fan, and Hillyard, 1994; Di Russo et al., 2002). The following P1 at around 100-130 ms (Di Russo et al., 2002) is generated in the extrastriate cortex (Clark, Fan, and Hillyard, 1994; Di Russo et al., 2002) and previous studies showed that it already can be modulated by attention (Hillyard, Vogel, and Luck, 1998; Luck, Woodman, and Vogel, 2000) and arousal (Vogel and Luck, 2000). Similarly, the N1 at around 150-200 ms after stimulus onset, originates in various areas of the extrastriate cortex (Di Russo et al., 2002) and it consists of several subcomponents, which can be modulated by spatial attention (e.g. Hillyard, Vogel, and Luck, 1998). A special subcomponent at around 170 ms after visual stimulus onset is the N170, which is thought to be especially involved in face processing (Bentin et al., 1996). It was shown to originate in the gyrus fusiformis and has larger amplitudes in response to faces than compared to other objects (e.g. Bentin et al., 1996; Stropahl et al., 2015).

1.4.3 *Data analysis*

A wide variety of EEG data analysis methods are available and known for different research questions. These include more traditional methods on the sensor level like peak detection in predefined regions of interest (ROIs) and more objective measures like peakdetection on the global field power (GFP). It is also possible to investigate the different frequency information based on time-frequency methods. Additionally, recent research focused on other methods like the topographic and source analyses, the latter including connectivity measures. The following paragraphs describe the methods used in the projects that are discussed in this thesis.

Sensor level: Peak detection The traditional way of EEG analysis is the peak detection of event-related potentials (ERPs) in predefined ROIs. There the collected data of certain electrodes is grouped and the peak voltage (amplitude), as well as the exact time of the peak (latency) is analysed within a specific time window (Michel and Murray, 2012). Previous research figured out that specific electrode sites most prominently reflect certain neural processes within specific time windows after the onset of the stimulus. These electrode sites and time windows are dependent on the stimulus condition (auditory, visual, tactile, etc.) and on its complexity. Auditory stimuli, for example, are known to be most prominent at vertex electrodes. Here one can normally see a complex consisting of three consecutive peaks, namely the N1 at around 75-150 ms, followed by the P2 at around 150-250 ms, followed by the N2 at around 150-275 ms (Näätänen and Picton, 1987; Crowley and Colrain, 2004). Visual stimuli, on the other hand, are known to be most prominent over occipital electrode sites and are also pronounced as a complex of three consecutive peaks. These include the P1 at around 100-130 ms, the N1 at around 100-200 ms and the P2 at around 200-300 ms after stimulus onset (Luck, 2014). Another component, most prominently evoked by faces, is the N170, which is a subcomponent of the N1. It is most prominent over lateral occipital electrode sites at around 170 ms after stimulus onset. Therefore, different researchers choose electrodes and time windows due to their experiments. Prior studies with CI patients used electrode sites around the vertex for auditory stimuli (e.g. Finke et al., 2016) and occipital electrode sites for visual stimuli (e.g. Sandmann et al., 2012). In the case of this thesis, the method of defined channels was used in project 1.

A more objective approach for the analysis on the sensor level is the global field power (GFP). This method does not require any a priori knowledge about the electrode sites to use, but it uses the standard deviation of the activity across all scalp electrodes and hence is a reference-independent measure of the response strength (Lehmann and Skrandies, 1980; Murray, Brunet, and Michel, 2008). In the case of this thesis, the GFP approach was used in project 2 and 3.

Sensor level: Topographic analysis An ERP component is not only defined by its latency and polarity, but also by the distribution of voltage on the scalp, also known as topography (Luck, 2014). Therefore, a topographic analysis is crucial to identify the components correctly. In general the topography does not randomly change over time, but remains stable for a set period of time. A change of topography happens within milliseconds and indicates a change in the orientation and/or distribution of the dipoles within the brain (Vaughan, 1982; Lehmann, 1987). The stable time windows are called microstates (Michel and Koenig, 2018). Since distinct topographies correspond to different neural generators, a topographic analysis can be used to test for differences in topography between groups, conditions or time points, which conclude different underlying neural generators (Michel and Murray, 2012). One objective approach for this is the analysis of the global map dissimilarity (GMD; Lehmann and Skrandies, 1980), which is independent of the signal strength (Murray, Brunet, and Michel, 2008). To analyse the GMD, the software CARTOOL (Brunet, Murray, and Michel, 2011) was used to calculate the so called "topographic" ANOVA (TANOVA; Murray, Brunet, and Michel, 2008). For more details see the methods section in the publication of project 2 or 3. If this analysis indeed shows distinct topographies for different groups, conditions or time points, it is an indicator for distinct neuronal generators (Vaughan, 1982), which can not be explained solely on the basis of the GMD. To unravel whether the differences in topographies are caused by different generators or by a latency shift, a hierarchical clustering analysis with group and/or condition and/or time point averaged data can be applied. Here, the most prominent topographies within the time windows of interest are identified, more precisely the minimal number of topography maps explaining the greatest variance in the dataset (Murray, Brunet, and Michel, 2008). Again, the software CARTOOL is suitable for this analysis. The distribution on single-subject level of the predominant topographic maps can be explored by a single-subject fitting analysis (Murray, Brunet, and Michel, 2008). This gives, for instance, the respective *map presence*, indicating how dominantly or frequently specific topographic maps are present, or the *first onset of topographic maps*, corresponding to the latency. This method was used in the publications 2 and 3.

SENSOR LEVEL: TIME-FREQUENCY ANALYSIS To get a deeper understanding of the underlying processes in EEG signals, *time-frequency analysis* techniques have been developed in the past decades, which include an additional parameter, namely the frequency distribution.

In general, time-frequency analysis is based on variations of the Fourier transform, which converts a waveform into sets of sine waves of different frequencies, phases, and amplitudes. Since the standard Fourier transform gives single values representing the power (squared amplitude) for each frequency over an entire epoch, therefore removing the temporal information, it is not suitable for EEG signal analysis. Consequently, a method providing the power of a given frequency at each time point in the waveform is needed. Since the power is not defined for a single time point, it has to be approximated by the middle latency of short time windows surrounding each time point. Basic approaches for this are a *moving window* version of the Fourier transform or a *wavelet* analysis (Sifuzzaman, Islam, and Ali, 2009; Morales and Bowers, 2022).

Performing a Fourier transform for several consecutive time windows on each trial is called the *moving Fourier analysis* (Makeig, 1993). Each Fourier transform provides a power value for each frequency, which is assigned to the midpoint of the regarding time window. Afterwards the time window slides one time point further and the next Fourier transform is performed. Unfortunately this method drops some temporal resolution, because the calculated power at each time point reflects an entire time window centred around that point. In the end all trials are averaged. This method has two drawbacks. First, it acts as if the average power within each time window is the power of the midpoint, even though the entire window equally contributes to the result. Second, the time windows are of the same size for each frequency, which gives lower precision for low frequencies and higher precision for high frequencies (Gray and Goodman, 2012).

The *wavelet* approach addresses both these problems. The first problem of treating every time point within the window equally is addressed by using wavelets that give the greatest weight to the center of the time window. These wavelets are for instance created by multiplying a 10-Hz sine wave and a Gaussian bell curve (Gabor function; Movellan, 2002). Some of the temporal resolution is still lost, but the problem is reduced by the lower influence of more distant time points. The second problem of different precision for different frequencies is solved by using wavelets of different widths for each frequency. The lower the frequency, the broader the time window. Multiple identical wavelets that differ in width are called a *wavelet family*, and in the case of Gabor functions the family is called *Morlet wavelet family*. To calculate the power at a given frequency and time point, the mathematical operation convolution is used. A convolution produces a third function from two existing ones, where the values of one function are replaced by the mean weighted by the other function including surrounding values. Hence the first function is "blurred".

Previous research revealed that each frequency range is associated with different levels of arousal in the human brain (Herrmann, Fichte, Freund, et al., 1979). Table 1.2 shows the five most prominent frequency ranges and their regarding associated function.

The lowest frequency range is the delta oscillation, which is, in combination with theta oscillations, a compartment of the P3 ERP (Başar-Eroglu et al., 1992). The source of these oscillations is thougth to be the frontal and cingulate cortex, and they are a part of neural networks that work in inhibitory manners (Harmony, 2013). By inhibiting some stimuli, delta oscillations play a role in cognitive processes like attention.

Cortical theta oscillations are assumed to reflect the communication with the hippocampus and different cortical regions, especially the prefrontal cortex, therefore they are associated with memory processes (Klimesch, 1999). Besides, human EEG theta activity from the frontal cortex plays a role in executive functions, regulating other brain structures via inhibition.

During sensory stimulation, EEG alpha oscillations are modulated (Schürmann and Başar, 2001) and they reflect memory and attentional processes (Klimesch, 1997; Hanslmayr et al., 2011). By exhibiting an inverse correlation with cognitive performance, alpha oscillations are suggested to inhibit task-irrelevant cortical structures (Jensen and Mazaheri, 2010).

When performing motor tasks, modulations of human EEG beta oscillations have been observed (Neuper and Pfurtscheller, 2001). They are also modulated during cognitive tasks that require sensorimotor interaction (Kilavik et al., 2013). The integration of these two aspects resulted in the hypothesis of beta activity reflecting whether the current sensorimotor state is expected to remain stable or to change soon (Engel and Fries, 2010).

Lastly, gamma-band oscillations are thought to reflect physiological activation of cortical tissue (Merker, 2013) . More precisely gamma oscillations are related to attentive processing of information (Fries et al., 2001; Womelsdorf and Fries, 2006), conscious perception (Singer, 1999), and active maintenance of memory contents (Herrmann, Munk, and Engel, 2004).

Denotation	**Frequency range**	**Cortical area**	**Associated function**
δ	0.5-3 Hz	frontal and cingulate cortex	Sleep
θ	4-7 Hz	hippocampus / frontal cortex	Deeply relaxed, inward focus
α	8-12 Hz	strongest in occipital regions	Relaxed, passive attention, top-down processing
β	13-30 Hz	strongest in frontocentral regions	Anxiety dominant, active, external attention, relaxed
γ	>30 Hz	temporal cortex	Concentration, cognitive and perceptual processes

Table 1.2: Different frequency bands in EEG signals, their associated cortical areas and cortical functions

In this thesis projects 3 and 4 include time-frequency analysis and focus on the θ, α and β frequency range. More details can be found in the respective publications.

SOURCE LEVEL Because of its excellent temporal resolution, sensor ERPs recorded on the scalp can be used to study neuronal dynamics, particularly the timecourse of the perceptual and cognitive processes. Neural processes, however, are characterised by a spatio-temporal interaction of different cortical areas, and even the processing of simple sounds includes information from several cortical areas that have to be integrated within milliseconds (Shahin et al., 2007). Therefore, the scalp electrodes measure signals that are generated by a combination of several distinct neural sources and the signal differs according to the strength of each source (Silva, 2013). That is the reason that the spatial origin of the measured signal cannot be analysed and interpreted if only sensor level data is considered (Stropahl et al., 2018). As described previously, different topographies across groups, conditions or time points are mainly caused by different underlying neural sources, and hence it is important to complement these analyses by source modelling (Silva, 2013; Michel et al., 2004).

Importantly, the source modelling of ERP signals underlies the "inverse problem",

which states that the location, orientation and amplitude of the dipole sources are not determined uniquely based on the electrode potentials measured on the scalp. A particular voltage distribution could originate from a large number of different dipole configurations, and it is not possible to infer which one is the original one based on the scalp-recordings (Luck, 2014). Hence the source analysis can not provide an accurate picture of the neural origins of the ERP signals, unlike other measurement techniques (i.e. fMRI), but there are some approaches to approximate the underlying neural origins. One is the *non-parametric distributed source model*, which makes the problem linearly solvable by assuming the positions and possible directions of a large number of dipoles, so that only the amplitudes need to be recovered. Another one is the *parametric concentrated source model*, which solves the optimal positions, orientations and amplitudes for just a small number of dipoles (Grech et al., 2008; Sorrentino and Piana, 2017).
For the projects discussed in this thesis, the software Brainstorm (Tadel et al., 2011) was used for source analysis, since many precious studies with deaf individuals and CI users conducted source analysis with this software (Stropahl et al., 2015; Stropahl et al., 2018; Prince et al., 2021; Bottari et al., 2020). The exact applied procedure is described in more detail in the publication of the regarding projects.

SOURCE LEVEL: CONNECTIVITY ANALYSIS Neuronal oscillations provide an underlying mechanism for coordinational flow of information within networks of functionally specialised brain areas (Singer, 1999; Varela et al., 2001; Fries, 2005; Fries, 2015; Siegel, Donner, and Engel, 2012). These oscillations reflect synchronised rhythmic excitability fluctuations of local neuronal ensembles (Buzsáki and Wang, 2012) and, when synchronised, facilitate the flow of information between different nodes in the network (Womelsdorf et al., 2007). By changing the strength, pattern, or frequency of the oscillations, the brain can dynamically coordinate the informational flow between different brain regions.
Since neural oscillations and the synchronisation of these between different brain-areas is vital for normal brain function, various quantitative methods have been applied to evaluate the neuronal synchrony (functional connectivity) in electrophysiological data. The measures can be divided into directed and non-directed types of estimates, with non-directed measures trying to capture interdependence between signals without a reference to the direction and directed measures trying to establish a statistical causation from the data based on the assumption that causes precede or even predict their effects (Wiener, 1956; Granger, 1969; for a review about most of the functional connectivity measures see Bastos et al., 2015). In project 3, the envelope correlation measure was applied to capture the functional connectivity between the visual and auditory cortex, as well as between the hemispheres of these cortices, respectively. For a more detailed description of this measure see the publication of this project.

1.5 AIM OF THIS THESIS

The overall aim of this thesis is to gain a better understanding of the auditory, visual and audiovisual speech processing in postlingually deafened individuals who are provided with a CI. Therefore, the results of different studies are discussed, including unilaterally and bilaterally deafened individuals, in cross-sectional and longitudinal studies.

In the first project "Side-of-implantation effect on functional asymmetry in the auditory cortex of single-sided deaf cochlear-implant users" (chapter 2) SSD individuals were investigated by means of their auditory processing of syllables on their CI ear as well as their NH ear. This is a special group of participants, because they were not provided with a CI on the deaf ear due to their intact contralateral ear until a few years ago (Arndt et al., 2011a; Buechner et al., 2010; Zeitler and Dorman, 2019). Therefore studies with SSD CI users are rare, however, recent studies provided evidence of beneficial effects in sound localisation, speech-in-noise intelligibility, as well as quality of life due to restored binaural hearing (Kitterick, Lucas, and Smith, 2015). Regarding the auditory processing, some studies found delayed processing via the CI ear in SSD CI users when compared to the NH ear (Bönitz et al., 2018; Finke et al., 2016), but it is by now unknown whether these individuals process stimuli received via their NH ear in the same way as NH listeners. Furthermore, the question of whether the side of implantation has an impact on the outcome has not been answered in SSD CI users yet, whereas in CI users with bilateral hearing loss it has been shown to evoke an altered auditory-cortex asymmetry (Sandmann et al., 2009). To contribute to this research field, we concentrated on the three questions: 1) Do SSD CI users show differences in auditory speech processing between the CI ear and the NH ear? 2) Does the side of implantation affect auditory speech processing with the CI ear of SSD CI users? 3) Does the side of stimulation affect auditory speech processing with the NH ear of SSD CI users, and is this pattern different in NH controls?

In the second project "Electrophysiological differences and similarities in audiovisual speech processing in cochlear implant users with unilateral and bilateral hearing loss" (chapter 3) we compared CI users with bilateral hearing loss, CI users with unilateral hearing loss, and NH controls regarding their auditory and audiovisual speech processing, as well as their lip reading abilities. Only a few existing studies compared the two groups of CI users and they reported behavioural differences in speech-in-noise perception (Williges et al., 2019) and speech perception with concurrent talkers (Bernstein et al., 2016), but none conducted EEG analysis on audiovisual speech processing. Hence, this study concentrated on the analysis of ERPs resulting from audiovisual speech stimuli in the three mentioned groups by using methods from electrical neuroimaging (Michel, 2009). More precisely, the underlying temporal dynamics of cross-modal plastic changes are systematically compared as well as the lip reading ability.

In the third project "Changes in visually and auditory attended audiovisual speech processing in cochlear implant users: A longitudinal ERP study" (chapter 4) postlingually deafened individuals were examined in a prospective longitudinal study. From the timepoint before CI implantation until six months of CI use they were measured with EEG at three timepoints while performing audiovisual speech perception tasks. The main aim of this project was to identify deprivation and CI induced changes in audiovisual speech processing, as well as the impact of attentional focus on either the auditory or visual representation of speech. Since most previous studies focused on the auditory and visually modulated auditory processing in CI users (Schierholz et al., 2015; Layer et al., 2022) the examination of the audiovisual signal itself was a different approach. The incorporation of different attentional focuses additionally allowed to study effects of (top-down) direction of attention on (bottom-up) audiovisual processing.

In the forth project "Reduced visual-cortex reorganisation before and after cochlear implantation relates to better speech recognition ability" (chapter 5) the purely visual speech processing was examined in postlingually deafened individuals receiving a CI. Previous research revealed altered visual processing in deaf individuals (Bavelier et al., 2000) as well as in CI users (Sandmann et al., 2012), but mostly in cross-sectional studies, not being able to identify the timepoint at which the cortical alterations appear. Hence, our approach tried to fill this gap by answering the question whether the alterations previously observed in CI users were deprivation or CI induced. Moreover, we aimed to contribute to the attempt of a prediction of the CI outcome prior to implantation by examining the relationship between visual cortical processing prior to implantation and speech intelligibility after six months of CI use. We did this by answering the following questions: 1) Is there a difference in the cortical (sensory) processing of static and articulating faces between postlingually deafened individuals (before implantation) and NH listeners? 2) Do postlingually deafened individuals (before implantation) and NH listeners differ in their allocation of attention to static and articulating faces? 3) Does CI experience affect the cortical (sensory) processing and allocation of attention in visual conditions with static and articulating faces? 4) How do visual cortical alterations in CI users relate to the CI outcome, as measured by an auditory monosyllabic word test?

All in all, this thesis comprises a variety of research questions regarding the speech processing of different CI user groups in visual, auditory and audiovisual conditions. The following chapters present the original publications, including a detailed summary, respectively. The final chapter provides a general discussion of the results and the current literature in this field of research.

Part II

PUBLICATIONS

This part comprises the publications that are discussed in this thesis. For each publication the author contributions are presented, as well as a synopsis. Afterwards the published document is included.

2

SIDE-OF-IMPLANTATION EFFECT ON FUCTIONAL ASYMMETRY IN THE AUDITORY CORTEX OF SINGLE-SIDED DEAF COCHLEAR-IMPLANT USERS

This chapter is based on the following publication:

Weglage, A., Müller, V., Layer, N., Abdel-Latif, K. H., Lang-Roth, R., Walger, M., & Sandmann, P. (2022). Side of-implantation effect on functional asymmetry in the auditory cortex of single-sided deaf cochlear-implant users. Brain Topography, 35(4), 431-452.

Author contributions:
Anna Weglage: Literature review; participant recruitment; data acquisition; data analysis; interpretation and presentation of results to research group; discussion of findings and further procedures; writing initial manuscript draft; incorporating suggestions of co-authors; submission to journal; presentation of results at national conference. **Verena Müller**: Conceptualisation; advisory role (CI technician); participant recruitment; partially writing of part "stimuli"; proofreading of manuscript. **Natalie Layer**: Assistance in data acquisition; assistance in data analysis; group discussions; proofreading of manuscript. **Khaled H. Abdel-Latif**: Programming; partially writing of part "stimuli"; proofreading of manuscript. **Ruth Lang-Roth**: Conceptualisation; proof-reading of manuscript. **Martin Walger**: Conceptualisation; proof-reading of manuscript. **Pascale Sandmann**: Supervisor of Anna Weglage; programming of the experiment; pilot measurements; central role in project conceptualisation; funding acquisition; suggestions; discussions; assistance in writing manuscript and proofreading of manuscript.

SYNOPSIS

OBJECTIVES The input via a CI is highly different compared to the natural hearing (Gordon, Jiwani, and Papsin, 2013; Kral, 2013), therefore SSD CI users are exposed to a maximally asymmetric hearing experience. In the past it was thought to be unnecessary to treat SSD patients with a CI due to the intact ear (Arndt et al., 2011a; Buechner et al., 2010), but nowadays it is known that the implantation of this patient group improves sound localisation, speech-in-noise intelligibility and quality of life due to the restored binaural hearing (Kitterick, Lucas, and Smith, 2015). Nonetheless, it is not known if the side of implantation influences the benefit in those patients and if the speech processing via the NH ear of SSD CI users is comparable to monaurally tested NH listeners. Therefore, this EEG study investigated the side-of-implantation effect in auditory speech processing, comparing the CI ear with the NH ear of SSD CI users, as well as a NH control group. Furthermore, it is demonstrated that the chosen experimental design is usable to objectively determine the proficiency of the SSD CI users.

METHODS The data of the SSD CI users and NH controls was recorded using a 32 channel EEG, while performing an auditory two-deviant oddball paradigm. The auditory stimuli consisted of the three syllables /ki/, /ka/ and /ti/, of which /ki/ was the frequent standard syllable and /ka/ and /ti/ were the infrequent deviant syllables. The SSD CI users were tested with their CI and NH ear separately and the task was to press a button when perceiving an infrequent deviant syllable. The NH controls were also tested monaurally, one ear with the original stimuli and one with a vocoded version. These vocoded stimuli were degraded to imitate the sound quality of a CI (Shannon et al., 1995). It was hypothesised that the differentiation between /ki/ and /ti/, which only differ in the consonant and hence in the place of articulation, is harder than between /ki/ and /ka/, which differ in the vowel, especially for non-proficient SSD CI users.

ANALYSIS Hit rates and response times of the button presses were analysed, as well as the N1, P2 and P3b ERP components.On the sensor level, the N1 and P2 components were analysed regarding their amplitude and latency in a fronto-central ROI. The P3b, which is a marker of the capability of the central auditory system to discriminate between standard and deviant sounds (Polich, 2007; Henkin et al., 2015), was analysed regarding it's amplitude and latency in a parietal ROI. Subsequently, a source analysis was performed, comparing the activity in the ipsi- and contralateral auditory cortex. The research questions were approached by the statistical analysis of the sensor and source level, including the between-subjects factor "group" (proficient vs. non-proficient SSD CI users, left vs. right implanted SSD CI users) and the within-subjects factors "stimulation side" (NH vs. CI ear), "stimulus type" (standard vs. deviant 1 vs. deviant 2), and "hemisphere" (left vs. right, only in source analysis).

RESULTS Matching the hit rates, that were poorer for the non-proficient SSD CI users, it was also possible to differentiate between proficient and non-proficient SSD CI users based on the electrophysiological data. Both the N1 and P3b component showed reduced and/or prolonged peaks for the non-proficient as compared to the proficient SSD CI users. When comparing the syllable processing of the CI ear and the NH ear of the SSD CI users, prolonged response times were found for the CI ear, as well as reduced and/or prolonged ERP components. By contrast, the comparison between original and vocoded syllable processing in the NH listeners did not reveal any statistically significant differences, neither at the behavioural nor at the sensor ERP level. At the source level, an enhanced functional asymmetry in the auditory cortex was found for the left-ear than for the right-ear implanted SSD CI users. This asymmetry was depicted by an enhanced auditory-cortex activation in the left than the right hemisphere. Interestingly, the asymmetry was observed independent of whether the presentation of the syllable was via the CI or the NH ear. For the NH listeners the same pattern of functional asymmetry as in the left-implanted SSD CI users was found within the auditory cortex when comparing the vocoded syllable processing between left and right stimulation. Additionally, the comparison of the NH ear of the SSD CI users with the NH listeners revealed alterations in the functional asymmetry in the auditory cortex. The left-ear implanted SSD CI users again showed greater activity in the right hemisphere than the right-ear implanted SSD CI users, while the NH listeners did not show these effects.

DISCUSSION The results confirm that speech processing is harder via the CI ear than via the NH ear in SSD CI users and that the N1 and P3b ERP components can be used to assess the proficiency in syllable discrimination. Furthermore, a side-of-implantation effect was found for left-implanted SSD CI users when stimulated via their NH and CI ear, which could also be observed in NH controls when they were stimulated with vocoded syllables (simulated CI input) via the left ear. Contrarily, the comparison of the NH ears of the SSD CI users with the NH listeners only revealed the functional asymmetry in the SSD CI users. These observed side-of-implantation effects appear to originate in cortical reorganisation due to temporal deafness and/or the limited auditory input via a CI. In sum, the findings demonstrate that experience-related functional changes in the auditory cortex and stimulus degradation caused by a CI affect the cortical speech processing in SSD CI users. This knowledge can be utilized to improve the rehabilitation success in this patient group.

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ORIGINAL PAPER

Side-of-Implantation Effect on Functional Asymmetry in the Auditory Cortex of Single-Sided Deaf Cochlear-Implant Users

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Abstract

Cochlear implants (CIs) allow to restore the hearing function in profoundly deaf individuals. Due to the degradation of the stimulus by CI signal processing, implanted individuals with single-sided deafness (SSD) have the specific challenge that the input highly differs between their ears. The present study compared normal-hearing (NH) listeners (N = 10) and left- and right-ear implanted SSD CI users (N = 10 left, N = 9 right), to evaluate cortical speech processing between CI- and NH-ears and to explore for side-of-implantation effects. The participants performed a two-deviant oddball task, separately with the left and the right ear. Auditory event-related potentials (ERPs) in response to syllables were compared between proficient and non-proficient CI users, as well as between CI and NH ears. The effect of the side of implantation was analysed on the sensor and the source level. CI proficiency could be distinguished based on the ERP amplitudes of the N1 and the P3b. Moreover, syllable processing via the CI ear, when compared to the NH ear, resulted in attenuated and delayed ERPs. In addition, the left-ear implanted SSD CI users revealed an enhanced functional asymmetry in the auditory cortex than right-ear implanted SSD CI users, regardless of whether the syllables were perceived via the CI or the NH ear. Our findings reveal that speech-discrimination proficiency in SSD CI users can be assessed by N1 and P3b ERPs. The results contribute to a better understanding of the rehabilitation success in SSD CI users by showing that cortical speech processing in SSD CI users is affected by CI-related stimulus degradation and experience-related functional changes in the auditory cortex.

Keywords Single-sided deafness · Cochlear implants · Event-related potential · Oddball paradigm · Hemispheric asymmetry · Cortical plasticity

Introduction

Cochlear implants (CIs) can (partially) restore the hearing of individuals with severe to profound sensorineural hearing loss by direct electrical stimulation of the auditory nerve (Zeng et al. 2011). Compared to normal acoustic hearing, the sounds transmitted by a CI are limited in the spectral and temporal domain and have a smaller dynamic range (Drennan, 2008). Therefore, CI recipients need to adapt to the highly artificial inputs after implantation. However, the speech understanding with a CI remains limited and highly variable across the patients (Lenarz et al. 2012; Roberts et al. 2013). Previous studies have shown that different individual factors contribute to this variability in CI outcome, among them peripheral factors (e.g. positioning of the electrode array), cortical reorganisation as induced by auditory deprivation (before cochlear implantation) and by the (limited) electrical hearing with a CI (after cochlear implantation) (Lazard et al. 2012b; Lazard et al. 2012a, b, c).

The clinical margins for CI indication have been extended over the last years, now including single-sided deaf (SSD) individuals (Arndt et al. 2011a, b; Buechner et al. 2010). SSD CI users are to be distinguished from bilateral (CI on both ears) and bimodal (CI on one ear and hearing aid on the contralateral ear) CI users, since in SSD CI users the

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signal quality of the input highly differs between the two ears, and the normal-hearing (NH) ear typically remains the dominant communication channel. This leads to maximal asymmetric auditory processing in this group of patients (Gordon et al. 2013; Kral et al., 2013). Nevertheless, Arndt et al. (2011a, b) showed improved hearing abilities in SSD patients aided with a CI compared to alternative treatments like contralateral routing of signal (CROS) or bone-anchored hearing aids (BAHA). SSD CI patients particularly benefit in sound localisation, speech understanding in noise and quality of life due to the restored binaural hearing (Kitterick et al. 2015). However, it remains not well understood whether the extent of the benefits in SSD CI users depends on the side of implantation. Similar to the findings from CI users with bilateral hearing loss (Mosnier et al. 2014), first results point to a right-ear advantage for speech recognition ability in SSD CI patients as well (Wettstein and Probst, 2018). In addition to the largely unresolved question regarding the side-of-implantation effects, it remains unclear whether SSD patients—when tested with only the NH ear—show the same speech processing capabilities as NH listeners who use only one of their ears (Arndt et al. 2019; Maslin et al. 2015). To better understand these effects on the CI outcome in SSD CI users, the current study systematically compared speech processing between left- and right-ear implanted SSD users on the one hand, and between these two patient groups and NH listeners on the other hand.

After cochlear implantation, speech intelligibility is typically assessed via behavioural measures, in particular word and sentence tests (Haumann et al. 2010; Hey et al. 2016, 2014; Hahlbrock, 1953; Hochmair-Desoyer et al. 1997). Event-related potentials (ERPs) however allow the *objective* evaluation of speech processing in CI users with a high temporal resolution (Luck, 2014). Previous studies have used ERPs in the electroencephalogram (EEG) to study cortical auditory processing in CI users (Beynon et al. 2005; Finke et al. 2016; Finke et al. 2015; Henkin et al. 2009; Sandmann et al. 2010; Sandmann et al. 2009; Groenen et al. 2001). Most of these studies applied an auditory oddball paradigm, in which a frequent standard sound and an infrequent deviant sound were pseudorandomly presented, meaning that a deviant sound is followed by at least two standard sounds. Using this type of paradigm allows the study of the N1 ERP (negativity around 100 ms post stimulus) and the P2 ERP (positivity around 200–250 ms post stimulus). These ERPs are elicited in response to both the standard and deviant sounds and originate mainly from the auditory cortex (Crowley and Colrain, 2004; Näätänen and Picton, 1987). An additional deviant-related P3b response (positivity around 300–650 ms) is elicited if the central auditory system can discriminate between the standard and the deviant sound (Henkin et al. 2009). It has been widely assumed that the P3b reflects the evaluation and classification of incoming auditory events (for a review, see Polich, 2007).

Most of the previous EEG studies on CI users have used an auditory oddball paradigm to study N1, P2 and P3b ERPs in individuals with *bilateral* hearing loss (Beynon et al. 2005; Finke et al. 2016, 2015; Henkin et al. 2009). ERPs of postlingually deafened adult CI users seem to be reduced in amplitude and prolonged in latency when compared to NH listeners, suggesting that CI users have difficulties in the sensory (N1, P2) and higher-level cognitive processing (P3b) of the limited CI input (Beynon et al. 2005; Finke et al. 2016; Henkin et al. 2014; Henkin et al. 2009; Sandmann et al. 2009). Moreover, adult CI users with bilateral hearing impairment show functional changes in the auditory cortex contra- and ipsilateral to the CI ear after implantation (Finke et al. 2015; Green et al. 2005). It is therefore not surprising that this group of patients can show altered functional asymmetry in the auditory cortex when compared to NH listeners, suggesting that auditory deprivation and/or cochlear implantation induce changes in the normal pattern of cortical response asymmetries. In contrast to implanted children with SSD (Lee et al. 2020; Polonenko et al. 2017), not much is known about functional changes in the adult auditory cortex of SSD CI patients. Knowledge about plasticity in the ipsi- and contralateral auditory cortex in SSD patients could help to understand the factors contributing to the CI outcome in these individuals. Thus, one principal aim of the present study was to evaluate the side-of-implantation effect on the functional asymmetry in the auditory cortex of adult SSD CI users.

Most of the previous studies using the oddball paradigm have been restricted to one stimulus pair (Billings et al. 2011; Sasaki et al. 2009). However, it is of clinical interest to develop a time-optimized multi-deviant oddball paradigm, which allows assessing multi-attribute auditory discrimination 'profiles'. In the present study, we used a two-deviant oddball paradigm with one standard syllable and two types of deviant syllables of different acoustic–phonetic demand. In addition to NH controls, left- and right-ear implanted SSD CI users were tested sequentially on both ears. We systematically compared the behavioural and electrophysiological measures within and between the different groups of adult participants, which allowed us to address the following research questions:

(1) Can a two-deviant oddball paradigm be used to objectively evaluate the speech discrimination ability in SSD CI users?
(2) Do SSD CI users show differences in speech processing between the CI ear and the NH ear?
(3) Is there a side-of-implantation effect on speech processing via the *CI ear* in SSD CI users?

(4) Is there a side-of-stimulation effect on speech processing via the *NH ear* in SSD CI users and in NH listeners?

Following recent results on adult SSD CI users, we expected differences in behavioural and ERP measures between the CI ear and the NH ear in SSD CI users (Bönitz et al. 2018; Finke et al. 2016). In accordance with previous observations on the CI users with *bilateral* hearing loss, we hypothesised an altered functional asymmetry in the auditory cortex of SSD CI users when compared to NH listeners (Sandmann et al. 2009).

Material and Methods

Participants

Nineteen single-sided post-lingually deafened CI users participated in this study (six male; two left handers). All of them had no history of neurological or psychiatric disorders. All participants used their CI at a daily basis (15.5 ± 0.7 h/day) for at least ten months (mean = 18 months; sd = 8 months). The age ranged from 37 to 66 years (mean = 53.26 years; sd = 8.49 years). The duration of deafness before implantation varied from two months to 36 years (mean = 69 months; sd = 115 months). Since this variable is difficult to determine, anamnestic conversations were used to determine the time point at which a conventional hearing aid was no longer sufficient to understand speech. The duration of deafness was then calculated as the period between this time point and the cochlear implantation. All subjects were unilaterally implanted with a CI, nine of them on the right side and ten on the left side. Apart from two participants, all of the CI users were right-handed, as assessed by the Edinburgh inventory (Oldfield, 1971). According to previous studies with SSD CI users (Bönitz et al. 2018; Finke et al. 2016), the four pure tone average (4PTA–over 0.5, 1,2 and 4 kHz) of the contralateral NH ear was ≤ 30 dB. Speech comprehension was tested using the Freiburg monosyllabic word test (Hahlbrock, 1970) and the Oldenburg sentence test (Wagener et al. 1999), the latter conducted with and without background noise. Here, all stimuli were presented via a loudspeaker placed at a distance of 1.6 m from the listeners head located at 0° in a soundproofed booth. Additionally, ten age-matched NH controls participated in this study (two male). Their age ranged from 41 to 70 years (mean = 53.2 years; sd = 9.37 years). Detailed information about the implant systems and the demographic variables of the participants can be found in Table 1.

Stimuli

The stimuli consisted of three different syllables which were taken from the Oldenburg logatome (OLLO) corpus, providing natural spoken language stimuli (Welge-Lüßen et al. 1997). The stimuli were generated by cutting the syllables /ki/, /ti/ and /ka/ out of the available logatomes from one speaker (male speaker 2, V6 “normal spelling style” and N3 “dialect”). All syllables had a duration of 300 ms and were normalised using the RMS function of the Adobe Audition software. The syllables differed by the place of articulation in the consonant contrast (/k/ vs. /t/) (Henkin et al. 2009) and by phonetic features in the vowel contrast (/a/ vs. /i/), in particular the vowel height and the vowel place (Micco et al. 1995). The German vowels /i/ and /a/ differ in the central frequencies of the first (F1) and second formant (F2). The formant values of /a/ are 730 Hz for F1 and 1284 Hz for F2. Regarding the vowel /i/, the formant values are 278 Hz (F1) and 2139 Hz (F2). In the German language, these formant values indicate the highest contrast between vowels, which should be perceivable by most of the CI users (Groenen et al. 2001). Unlike the aforementioned vowels, the contrast of the consonants /k/ vs. /t/ is very small, only differing in their place of articulation. The syllables /ki/ and /ti/ differ in rapid spectral changes in the transition of F2, which represents the articulatory movement from the consonant to the vowel (Kent, 1997). Those characteristics are very difficult to distinguish for CI users. In this study, we deliberately used one easier (/ki/ vs. /ka/) and one more difficult stimulus contrast (/ki/ vs. /ti/) to study the effects of auditory discrimination ability on behavioural and ERP measures in SSD CI patients.

In addition to the auditory oddball task with “original”, unprocessed syllables, the NH control group performed three additional blocks with degraded, “vocoded” syllables. This adjusted sound condition allowed to analyse the effects of stimulus degradation comparable to CI processing (Shannon et al. 1995). A noise vocoder was used to degrade the syllables (Gaudrain and Başkent, 2015). The MATLAB code is available online (see Gaudrain, 2016). The vocoder filtered the signal into four bands using 12th order, zero-phase Butterworth bandpass filters. The band boundaries were equally spaced based on a 35-mm basilar membrane distance (Greenwood, 1990) across a frequency range between 0.2 and 20 kHz. To extract the temporal envelope, the output of each band was half-wave rectified and low-pass filtered at 250 Hz (zero-phase fourth order Butterworth filter). The envelope was then multiplied by a wide-band noise carrier, and the resulting signal was summed across bands.

Task and Procedure

The experimental paradigm consisted of an auditory oddball task. The participants were presented with a frequent

Table 1 Demographic variables, audiologic information and implant information of the participants

ID	Age [years]	Handed-ness	CI side	Group	Processor	Etiology (details)	Duration deafness [months]	CI use [months]	PTA CI ear [dB]	PTA NH ear [dB]	Freiburg Monosyllabic test (65 dB) [%]	OLSA quiet [%]	OLSA noise [dB]
vp03	51	Right	Right	Non-proficient	CP910	Morbus meniere	19	24	32.5	19.75	75	96	– 3.2
vp04	38	Right	Right	Proficient	Opus	Sudden deafness	12	36	31.5	3.5	40	97	1.4
vp06	62	Right	Right	Non-proficient	CP910	Cholesteatoma surgery	312	15	34.25	30	30	47	20.1
vp10	43	Right	Right	Non-proficient	CP910	Sudden deafness	12	19	25.75	14.5	65	89	−0.7
vp11	63	Right	Right	Proficient	CP910	Otitis media	18	12	34.25	14.75	10	23	Not applicable
vp14	61	Right	Right	Non-proficient	CP1000	Sudden deafness	7	11	24	15	65	90	– 0.4
vp15	55	Right	Right	Non-proficient	CP1000	Cogan 1 syndrome	3	10	22.5	10	95	99	– 2.6
vp18	49	Right	Right	Proficient	Sonnet	Otosclerosis	48	17	32.75	23.75	80	77	1.2
vp19	37	Right	Right	Non-proficient	Sonnet	Unknown	26	19	38.5	29	30	91	-0.7
vp01	58	Right	Left	Non-proficient	CP910	Sudden deafness	84	25	26	12	65	95	– 0.7
vp02	56	Left	Left	Proficient	CP910	Sudden deafness	30	12	36.5	4.25	10	7	Not applicable
vp05	48	Right	Left	Proficient	CP910	Sudden deafness	144	32	23.5	12	100	98	– 1.1
vp07	55	Right	Left	Non-proficient	CP910	Sudden deafness	432	20	43.5	8	55	64	4.3
vp08	53	Left	Left	Proficient	CP910	Sudden deafness	5	32	33.75	15.75	50	79	2.4
vp09	57	Right	Left	Non-proficient	CP910	Sudden deafness	21	10	31.25	11.5	55	92	– 1.2
vp12	66	Right	Left	Non-proficient	CP910	Unknown	120	15	29.5	30	70	94	0.5
vp13	63	Right	Left	Proficient	CP1000	Stapes surgery	19	10	37	12.5	55	75	0.7
vp16	54	Right	Left	Proficient	Sonnet	Acute hearing loss	10	14	28.75	16	80	100	– 2.6
vp17	43	Right	Left	Proficient	CP1000	Petrous bone fracture	2	11	22.5	6.25	55	78	6.1

standard syllable (/ki/, 80% probability) and two infrequent deviant syllables (/ka/ and /ti/, 10% probability each). The participants were instructed to respond to deviant syllables via a button press of a computer mouse. The total of 800 trials were separated into three blocks with reasonable breaks in between. If a participant showed short response times, the inter-stimulus interval of 1400 ms was shortened accordingly. Hence, the measurement time added up to a maximum of 19 min (800 trials × 1400 ms) per ear. The stimuli were presented in a pseudo-randomised order with the constraint that a deviant syllable was preceded by at least three standard syllables. This was, however, not known by the participants. Prior to the experiment, a short training was performed at each ear. The participants sat in a comfortable chair in a sound attenuated booth. To avoid eye movements, the participants were instructed to look at a fixation cross on a computer monitor throughout the task.

In the *CI-only listening condition*, the processor of the CI users was put inside an aqua case from the manufacturer Advanced Bionics (https://www.advancedbionics.com) to avoid an additional stimulation of the NH ear. An earphone was inserted through a hole of the aqua case, where it was directly positioned over the microphone input of the CI. In general, all processors only fit into the aqua case with the compact batteries, which were provided by the clinic for each measurement. A long coil cable was used to connect the processor to the implant.

In SSD CI users, the use of an aqua case (in combination with an insert earphone) is advantageous compared to the stimulation via *direct connect* or loudspeakers for the following two reasons. First, the patients used CI processors from different manufacturers. A presentation of the stimuli via *direct connect* was not used to avoid an additional potential bias through the different ways of stimulus transfer into the different types of sound processors. Second, stimulus delivery via a *loudspeaker* would have been inappropriate, as this condition prevents a sufficient (passive) stimulus masking of the NH (i.e., non-tested) ear (Park et al. 2021).

Regarding the *NH-only condition* in SSD CI users and NH listeners, the stimuli were presented via inserted earphones positioned in the external auditory canal. The contralateral ear, that is, non-tested ear, was masked with an earplug in all conditions and groups. In general, the audio input level was calibrated to an acoustical input at 65 dB SPL. In addition, the participants performed a subjective rating before the start of the experiment. The loudness was readjusted to ensure that it was set to a moderate level in each individual, which is equivalent to a level of 60–70 dB SPL (e.g. Sandmann et al. 2009). This adjustment is important, since recent auditory brain imaging studies showed that the loudness can affect cortical activation (Zhou et al. 2022).

To have a measure of the subjective listening effort, participants were asked after every block of the experiment to rate the effort of understanding the syllables on a scale between zero (no effort at all) and five (very demanding). In addition, we asked the participants to rate the difficulty to perform the task on a similar scale (between zero (no effort at all) and five (very demanding)).

Data Recording and Analysis

Behavioural Data: Auditory Oddball Task

The percentage of hit rates (hits) and individual mean response times (RT) of correct trials were analysed. Correct responses were defined as the occurrence of a button press in response to deviant syllables from 200 to 1200 ms following stimulus onset.

Electrophysiological Data: Recording and Data Processing

The EEG was continuously recorded with a BrainAmp DC amplifier from 30 active electrode sites, placed according to the extended 10/20 system (Brainproducts, http://www.brainproducts.com). An additional electrode was placed under the left eye for recording electrooculography (EOG), and the reference electrode was placed on the nose. The EEG was digitized at 1000 Hz, and the impedance was kept below 5 kΩ throughout the recording.

The data was analysed with EEGLAB (Delorme and Makeig, 2004) running in the MATLAB environment (R2020a; Mathworks). The EEG was downsampled to 500 Hz and offline filtered with a FIR-filter, using a high pass cut-off frequency of 0.1 Hz and a maximum possible transition bandwidth of 0.2 Hz (two times the cut-off frequency) plus a low-pass cut-off frequency of 40 Hz and a transition bandwidth of 2 Hz. For both filters, the Kaiser-window (beta = 5.653, max. stopband attenuation = -60 dB, max. passband deviation = 0.001) approach was used (Widmann et al. 2015). This approach maximises the energy concentration in the main lobe, thus averaging out noise in the spectrum and reducing information loss at the edges of the window (Widmann et al. 2015). Missing channels located over the region of the speech processor and transmitter coil were removed (mean and standard error: 0.6 ± 0.6 electrodes; range: 0–2 electrodes). The EEG data of the CI ear was segmented into epochs from − 100 to 400 ms relative to the stimulus onset, and it was baseline corrected (− 100 to 0 ms). Similar to previous studies, an independent component analysis (ICA) was then applied to the segmented data to identify the electrical CI artefact which spatially and temporally overlaps with auditory brain activity (Debener et al. 2007; Sandmann et al. 2010, 2009). After applying the ICA weights to the original (down-sampled and filtered (0.1–40 Hz) continuous EEG) data, all components that could be assigned to the electrical CI artefact were removed. Subsequently, the EEG datasets of both sides (CI ear: after first ICA-based artefact reduction; NH ear: original, i.e. down-sampled and filtered (0.1–40 Hz)) were merged and segmented into 2 s dummy segments. Segments exceeding an amplitude threshold criterion of four standard deviations were removed, and a second ICA was applied. All components assigned to ocular artefacts and other sources of non-cerebral activity were removed (Jung et al. 2000). Afterwards, the removed channels over the CI were interpolated using a spherical spline interpolation, a procedure still allowing good dipole source localisation of auditory event-related potentials (ERPs) in CI users (Debener et al. 2007; Sandmann et al. 2009). Only correct responses (hits for deviant syllables and correct rejections for standard syllables) were included for ERP analysis. Subsequently, a peak analysis of ERPs was performed on single-subject averages measured at different regions-of-interest (ROIs). We defined a frontocentral and a parietal ROI based on the grand average computed across all conditions and participants. The *frontocentral ROI* included the channels FCz, FC1, FC2, Fz and Cz and was used to analyse the N1 and P2 ERPs. The *parietal ROI* included the channels Pz, P3, P4, CP1 and CP2 and was used for the peak detection of the P3b component. For ERP quantification, individual peak amplitudes and latencies were measured by detecting the maximum and latency of ERP peaks in commonly used latency bands of the N1, P2 and P3b ERPs (Luck, 2014; Picton, 2010; N1: 80–160 ms; P2: 180–300 ms; P3b: 300–900 ms).

Source Analysis

Cortical source activities were computed using the Brainstorm software (Tadel et al. 2011) and following the tutorial of Stropahl et al. 2018. Brainstorm applies the method of dynamic statistical parametric mapping of the data (dSPM; Dale et al. 2000). This method uses the minimum-norm inverse maps with constrained dipole orientations to estimate the locations of the scalp-recorded electrical activity of the neurons. It seems to localise deeper sources more accurately than standard minimum norm procedures, but the spatial resolution remains blurred (Lin et al. 2006). Prior to source estimation, the EEG data was re-referenced to the common average. Single-trial pre-stimulus baseline intervals (− 200 to 0 ms) were used to calculate individual noise covariance matrices and thereby estimate individual noise standard deviations at each location (Hansen et al. 2010). As a head model, the boundary element method (BEM) as implemented in OpenMEEG was used, providing three realistic layers and representative anatomical information (Gramfort et al. 2010; Stenroos et al. 2014). Source activities were evaluated in an a-priori defined auditory region-of-interest (ROI). The definition of the ROI was based on the Destrieux-Atlas implemented in Brainstorm (Destrieux et al. 2010). The used auditory ROI comprised four smaller regions of the original atlas (G_temp_sup-G_T_transv, G_temp_sup-Plan_tempo, Lat_Fis-post, S_temporal_transverse). These regions were combined using the “merge scouts” feature in Brainstorm and approximated Brodmann areas 41 and 42. Peak activation magnitudes and latencies within this ROI were extracted for each individual participant. The activation data is given as absolute values with arbitrary units based on the normalisation within the dSPM algorithm.

Statistical Analyses

The subsequent statistical analysis was performed in R (Version 3.6.3, R Core Team 2020, Vienna, Austria). To address the four different research questions, the amplitudes and latencies of auditory ERPs were analysed separately on the sensor level (frontocentral ROI on head surface: N1, P2; parietal ROI on head surface: P3b) and on the source level (ERP source analysis: activation in ipsi- and contralateral auditory cortex at N1 latency). This was done by computing mixed ANOVAs with the between-subject factor “group” (proficient/non proficient CI users or left/right implanted patients) and the within-subject factors “stimulation side” (CI/NH), “stimulus type” (standard/deviant 1/deviant 2) and “hemisphere” (left/right). Significant interactions and main effects ($p < 0.05$) were followed-up by paired t-tests, and the Holm-Bonferroni approach was used for the correction of multiple comparisons (Holm, 1979). In the case of violation of spericity, a Greenhouse–Geisser correction was applied.

Results

Question 1: Can a Two-Deviant Oddball Paradigm Be Used to Objectively Evaluate the Speech Discrimination Ability in SSD CI Users?

Behavioural Results

The mean RTs of the nineteen SSD CI users were analysed with a two-way ANOVA, including the within-subject factors “stimulated ear” (CI, NH) and “stimulus type” (deviant 1, deviant 2). A significant main effect of “stimulated ear” ($F_{1,13} = 23.82$, $p_{adj} \leq 0.001$, $\eta^2 = 0.22$) was followed up by pairwise comparisons, revealing faster RTs when syllables were presented via the NH ear compared to the CI ear ($p \leq 0.001$). A significant main effect of “stimulus type” ($F_{1,13} = 8.56$, $p_{adj} = 0.012$, $\eta^2 = 0.08$) was followed up by pairwise comparisons, revealing faster response times for deviant 1 compared to deviant 2 ($p = 0.04$).

In contrast to the RTs, the hit rates showed a more complex pattern of results. While all participants could reliably discriminate deviant 1 from the standard sound (CI: 90.86 ± 0.07%, NH: 92.17 ± 0.05%), only some of the participants were able to reliably differentiate deviant 2 from the standard sound. Hence, the group of participants (including both the left- and right-ear implanted SSD CI users) was divided into two subgroups (proficient, non-proficient CI users) based on the median split in the behavioural performance (median of hit rate = 37.5%). In the following, these subgroups are referred to as proficient (performance > 37.5%) and non-proficient CI users (≤ 37.5%).

The hit rates of the participants were analysed using a three-way mixed ANOVA, with the between-subject factor "group" (proficient, non-proficient) and the within-subject factors "stimulated ear" (CI, NH) and "stimulus type" (deviant 1, deviant 2). A significant three-way interaction ($F_{1,17} = 147.84$, $p_{adj} \leq 0.001$, $\eta^2 = 0.62$) was followed up by simple two-way interactions and pairwise comparisons. As expected, there was a significant difference between the two groups for the *stimulation of the CI ear* (Fig. 1b): The proficient users had higher hit rates for deviant 2 when compared to the non-proficient users ($p \leq 0.001$). By contrast, there was no group difference for the *stimulation of the NH ear*.

Comparing the response times between the proficient and non-proficient CI users revealed no significant difference between the two groups, neither for the CI ear nor for the NH ear.

ERPs: Proficient vs. Non-Proficient CI Users

The grand average ERPs from both the NH ear and the CI ear revealed an N1 and P2 response (Fig. 1c, Supplementary Fig. 1). In addition, the grand average ERPs showed a P3b ERP around 400–600 ms, which was observed in response to both deviant types in the proficient CI users, but which was restricted to deviant 1 in the non-proficient CI users (Fig. 1c).

In a first step of the ERP analysis, we focused on the N1 and P2 ERPs. We computed a two-way mixed ANOVA for the *N1 and P2 ERPs*, with the between-subject factor "group" (proficient, non-proficient) and the within-subject factor "stimulus type" (deviant 1, deviant 2). This was done separately for the stimulation over the CI ear and the NH ear. Regarding the *stimulation over the CI ear*, we found a main effect of "group" for the N1 amplitude ($F_{1,17} = 4.16$, $p_{adj} = 0.057$, $\eta^2 = 0.16$) and the N1 latency ($F_{1,17} = 5.68$, $p_{adj} = 0.029$, $\eta^2 = 0.14$), respectively. The pairwise comparisons revealed a significantly enhanced and prolonged N1 ERP for the non-proficient CI users when compared to the proficient CI users (averaged over all three stimulus types; amplitude: $p = 0.02$; latency: $p = 0.03$). No group differences were found in the P2 component (Supplementary Fig. 1a).

For the *stimulation over the NH ear*, we found no group effect for the N1 ERP, but a main effect of "stimulus type" ($F_{1,17} = 42.99$, $p_{adj} = 0.001$, $\eta^2 = 0.16$), which was followed up by pairwise comparisons. This analysis revealed an enlarged N1 amplitude for deviant 2 compared to deviant 1 (averaged over both groups; $p = 0.01$). Regarding the P2 component,

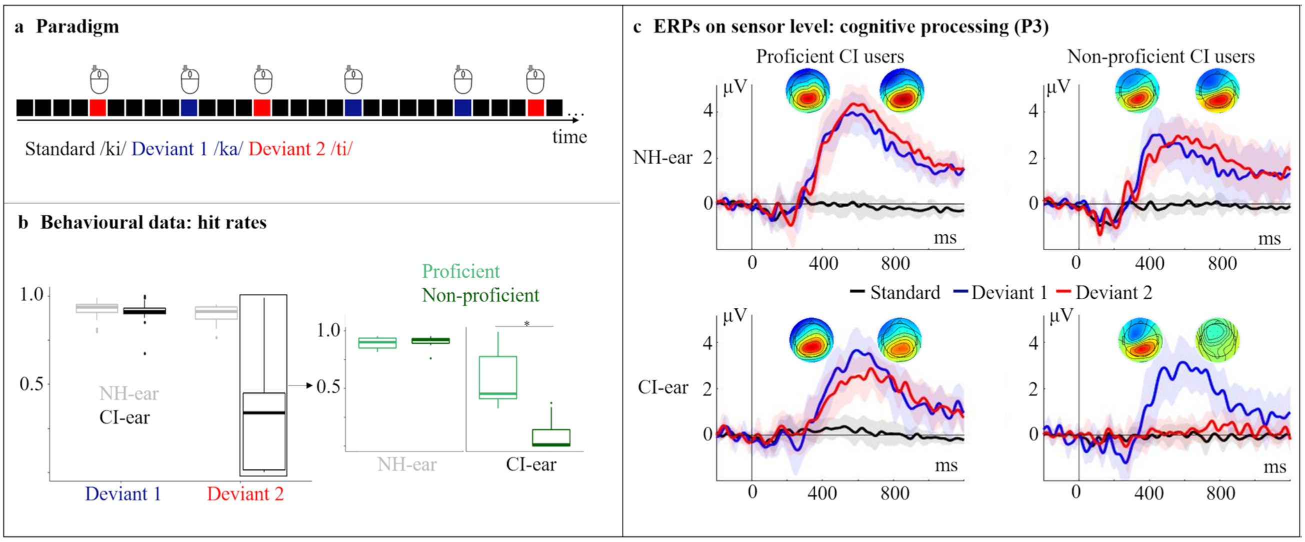

Fig. 1 **a** Depiction of the oddball paradigm with frequent standard and two deviant syllables. **b** Hit rates for the NH- and the CI-ear separately for both deviant types plus the separation into two groups based on the hit rates for deviant 2. **c** ERPs showing the objectification of the groups by the P3 component with topographic plots. The shaded areas indicate the 95% confidence intervals. For illustration purposes, the ERPs are low-pass filtered (10 Hz). The left topography belongs to deviant 1 (blue line) and the right topography belongs to deviant 2 (red line), respectively. Time range for topographic plots: 555–575 ms

we found a significant two-way interaction between the factors "group" and "stimulus type" ($F_{1,17} = 4.56$, $p_{adj} = 0.048$, $\eta^2 = 0.03$). The subsequent pairwise comparisons showed a greater P2 amplitude for deviant 2 for non-proficient CI users compared to the proficient CI users ($p = 0.047$).

In a second step, we focused on the P3b ERP. We computed a two-way mixed ANOVA with the between-subject factor "group" (proficient, non-proficient) and the within-subject factor "stimulus type" (deviant 1, deviant 2) separately for the CI ear and the NH. For *stimulation* via *the CI ear*, the analyses revealed a two-way interaction between the factors "group" and "stimulus type" ($F_{1,17} = 6.13$, $p_{adj} = 0.002$, $\eta^2 = 0.13$), showing a significantly enhanced P3b amplitude for the proficient CI users specifically for deviant 2 when compared to the non-proficient CI users ($p \leq 0.001$). No group difference was observed for the *stimulation* via *the NH ear* ($p = 0.21$). However, the stimulation via the NH ear showed a main effect for "stimulus type" ($F_{1,17} = 8.6$, $p_{adj} = 0.009$, $\eta^2 = 0.13$), resulting in a significantly prolonged P3b latency for deviant 2 when compared to deviant 1 ($p = 0.03$). Furthermore, we found a significant positive correlation between the P3b amplitude and the hit rate of deviant 2 in both groups (proficient CI-users: $R = 0.8$, $p = 0.009$; non-proficient CI-users: $R = 0.85$, $p = 0.002$).

In sum, the results concerning question 1 revealed that ERPs, which are recorded in the context of a two-deviant oddball paradigm, show differences in initial sensory and later cognitive speech processing between different subgroups of SSD CI users. Specifically, non-proficient and proficient SSD CI users can be distinguished on the basis of the N1 and P3b amplitudes (for stimulation via the CI ear) as well as on the basis of the P2 amplitude (for stimulation via the NH ear). These findings suggest that the two-deviant oddball paradigm can be used to assess speech discrimination proficiency in SSD CI users.

Question 2: Do SSD CI Users Show Differences in Speech Processing Between the CI Ear and the NH Ear?

Since not all participants were able to reliably identify deviant 2, this condition was removed for further statistical analyses.

Behavioural Results: CI Ear vs. NH Ear (SSD CI Users)

The comparison of the behavioural results for deviant 1 between the CI ear and the NH ear in SSD CI users (regardless of the side of implantation) showed no differences in hit rates but significantly faster response times (Fig. 2a) for the stimulation of the NH ear compared to the CI ear ($t(18) = -5.12$, $p \leq 0.001$, $d = 0.92$). Furthermore, the listening effort for syllable processing via the CI ear was significantly enhanced compared to the NH ear ($t(18) = -2.14$, $p = 0.047$, $d = 0.50$).

ERPs on Sensor Level: CI Ear vs. NH Ear (SSD CI Users)

Figure 2 shows the ERPs in response to the standard and deviant 1, separately for the CI ear and the NH ear. The "stimulus type" (standard, deviant 1) x "stimulated ear" (CI, NH) ANOVA revealed a significant main effect of "stimulated ear" for the N1 amplitude ($F_{1,18} = 16.54$, $p_{adj} \leq 0.001$, $\eta^2 = 0.13$) and latency ($F_{1,18} = 8.72$, $p_{adj} = 0.009$, $\eta^2 = 0.13$), respectively. The follow up pairwise comparisons revealed a smaller N1 amplitude ($p = 0.001$) and a prolonged N1 latency ($p = 0.002$) for the CI ear compared to the NH ear (averaged over both stimulus types). Similarly, the P2 amplitude revealed a significant main effect of "stimulated ear" ($F_{1,18} = 12.10$, $p_{adj} = 0.003$, $\eta^2 = 0.07$), resulting in a significantly smaller amplitude for the CI ear than for the NH ear ($p = 0.02$). Paired t-tests between the P3b amplitudes and latencies of deviant 1 showed a prolonged latency for the CI ear compared to the NH ear ($t(18) = -27.27$, $p = 0.014$, $d = 0.62$) but no ear difference in the P3b amplitude (Fig. 2c).

ERPs on Source Level: CI Ear vs. NH Ear (SSD CI Users)

Figure 2d shows the source activity separately for the two stimulation conditions (CI ear, NH ear) in the bilateral auditory cortex. Given that the ERP analysis on the sensor level did not reveal a significant effect of "stimulus type" (standard, deviant 1), the ERP analysis on the source level was restricted to the averages computed across the two stimulus types. The paired t-tests revealed a significantly delayed cortical response at N1 latency for the stimulation via the CI ear when compared to the NH ear ($t(18) = 29.64$, $p = 0.008$, $d = 0.72$). No significant difference was found for the amplitude of the source activity at N1 latency range.

Behavioural and ERP Results: Vocoded vs. Original Sounds (NH Listeners)

To evaluate whether the observed differences between the CI ear and the NH ear originate from the CI-related degradation of the stimuli (hypothesis 1) or from cortical plasticity (hypothesis 2), we compared the behavioural and ERP results between the two stimulus conditions "vocoded" and "original" syllables (separately for the two stimulus types: standard/deviant 1) within the group of NH listeners.

Regarding the *behavioural results*, the NH control group did not show any significant difference between the vocoded and the original syllables (Supplementary Fig. 2a). But the subjective listening effort for syllable processing with

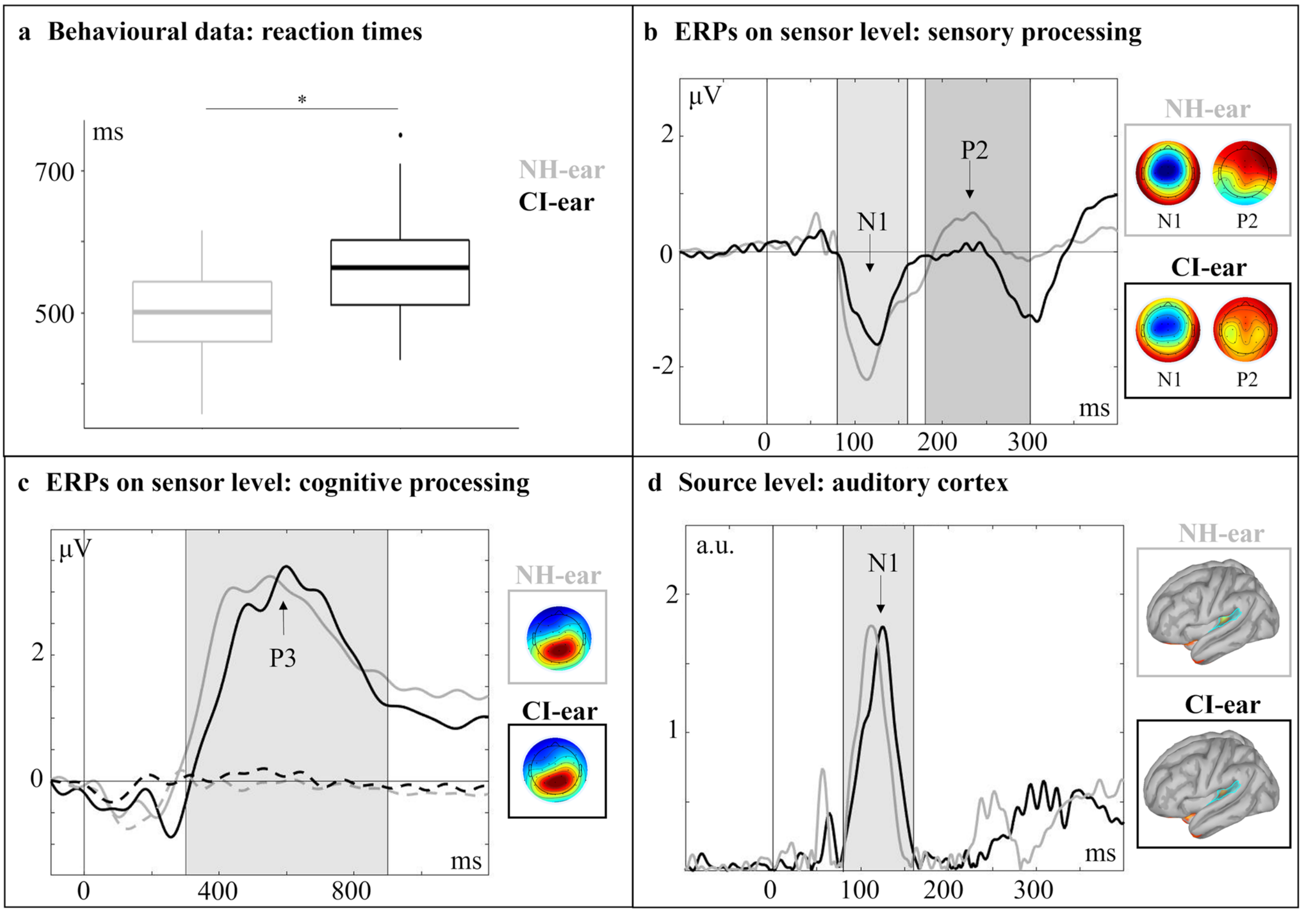

Fig. 2 Comparisons between the NH- and the CI- ear in SSD patients on different levels. **a** Faster reaction times for stimulation over the NH-ear for deviant 1. **b** ERP-averages across standard and deviant 1 show a smaller and prolonged N1 component and a smaller P2 component for stimulation over the CI-ear. Time range for topographic plots: N1 = 100–130 ms (NH-ear)/110–140 ms (CI-ear), P2 = 220–250 ms. **c** ERPs to deviant 1 show a prolonged P3 component for stimulation over the CI-ear. Dotted lines represent responses to the standard syllable. Time range for topographic plots: 530–570 ms (NH-ear)/580–620 ms (CI-ear). **d** Source analysis shows a response in the auditory cortex at N1 latency which is delayed for stimulation via the CI. The blue area represents the used region of interest, red areas show activation. Time points for brain plots: 118 ms (NH-ear)/134 ms (CI-ear)

vocoded stimuli was significantly enhanced compared to the original stimulation ($t(9) = -2.42$, $p = 0.039$, $d = 0.78$).

Concerning the *ERPs on the sensor level*, the supplementary Fig. 2b shows the waveforms of the NH control group separately for the “vocoded” and “original” stimulus conditions. The two-way ANOVA with the within-subject factors “condition” (vocoded/original) and “stimulus type” (standard/deviant 1) revealed no main effects and no significant interaction for the N1 ERP. However, the same ANOVA computed separately for the P2 ERP revealed a significant main effect of “condition” ($F_{1,9} = 17.69$, $p_{adj} = 0.002$, $\eta^2 = 0.15$), resulting in a significantly larger P2 amplitude for the stimulation with vocoded syllables compared to the stimulation with the original syllables ($p = 0.02$). Finally, paired t-tests comparing the P3b ERP between the two stimulus conditions (vocoded/original) revealed no statistical difference in P3b amplitudes and latencies.

Concerning the *ERPs on the source level*, the supplementary Fig. 2d shows the source waveforms in the bilateral auditory cortex separately for the “vocoded” and “original” stimulus conditions. Paired t-tests comparing the two simulation conditions (vocoded/original) showed no statistical difference in the source activity at the N1 latency range, neither for the amplitude nor for the latency.

In sum, the findings on question 2 revealed that syllable processing via the CI ear—when compared to the NH ear—results in prolonged response times, enhanced subjective listening effort, and ERPs with reduced amplitudes (N1, P2) and prolonged latencies (N1, P2, P3b). These results suggest that the CI-related stimulus degradation leads to difficulties in speech processing in SSD CI users, not only at initial sensory but also at later cognitive processing stages.

Question 3: Is there a Side-of-Implantation Effect on Speech Processing via the CI Ear in SSD CI Users?

Behavioural Results and ERPs on sensor level: Left CI vs. right CI (SSD CI users)

The group of nineteen SSD CI users was divided into two subgroups according to the implantation side. Ten participants were implanted on the left ear and nine on the right ear (Table 1). For the behavioural results (hit rates, response times) and the ERPs (amplitude and latency of N1, P2, P3b ERPs), we computed unpaired t-tests between the groups (left-implanted, right-implanted) separately for the CI ear and the NH ear. However, the results did not show any statistical differences between the left- and right-ear implanted SSD CI users.

ERPs on Source Level: Left CI vs. Right CI (SSD CI Users)

Figure 3a shows the activity in the left and right auditory cortex separately for left- and right-ear implanted SSD CI users when stimulated over the CI. A two-way mixed ANOVA with the between-subject factor “group” (left/right implanted) and the within-subject factor “hemisphere” (left, right) revealed a significant two-way interaction ($F_{1,17} = 9.043$, $p_{adj} = 0.008$, $\eta^2 = 0.17$). Post-hoc t-test revealed a hemispheric difference for the left-implanted group ($p = 0.031$), with enhanced activity in the right than left auditory cortex. By contrast, the right-implanted group did not show a hemispheric difference in auditory-cortex activation.

Does the Side-of-Implantation Effect Arise from the Stimulus Degradation Through the CI or from Intra-Modal Plasticity in the Auditory Cortex?

To verify whether the observed hemispheric differences between the two SSD groups arise from the stimulus degradation through the CI (hypothesis 1) or from intra-modal plasticity in the auditory cortex (hypothesis 2), we compared the behavioural and ERP results between the two stimulus conditions “vocoded” and “original” syllables (separately for the two stimulation sides: left/right) within the group of NH listeners. We computed two-way ANOVAs including the

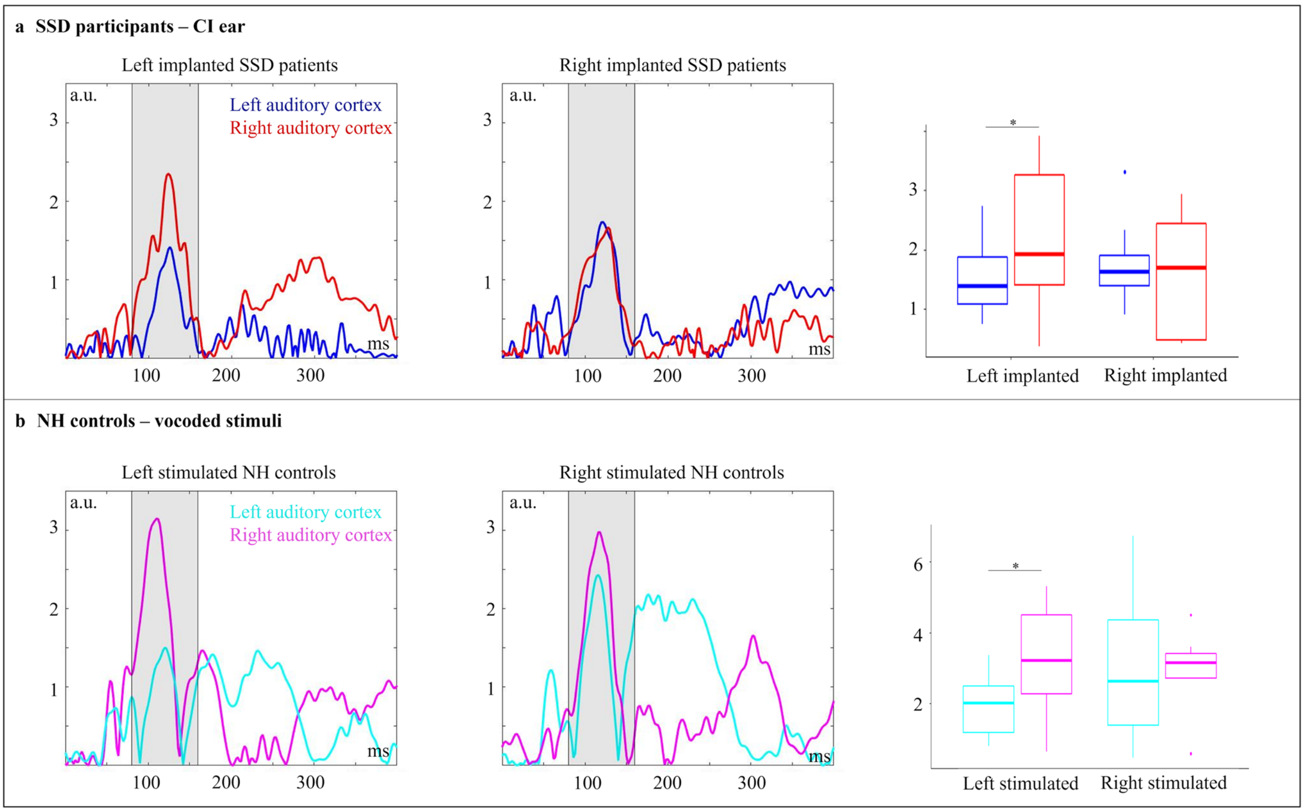

Fig. 3 Activitiy in the left and right auditory cortex shows differences in the latency range of the N1 component for the groups. **a** Mean activities plus boxplots for all SSD patients, separated by implantation side, stimulated via the CI are shown. **b** Mean activities plus boxplots for all NH control subjects, separated by the stimulation side, for the stimulation with vocoded syllables are shown. Hemispheric asymmetries specifically for left implanted SSD patients and left stimulated NH controls, as indicated by enhanced N1 amplitude in the right compared to left auditory cortex

within-subject factors “side of stimulation” (left/right) and “condition” (original/vocoded stimuli).

Regarding the behavioural results, we observed a significant main effect of “side of stimulation” for the hit rates ($F_{1,19}=14.26$, $p_{adj}=0.001$, $\eta^2=0.10$), which was due to a higher hit rate for stimulation via the right ear when compared to the left ear (averaged over both conditions; $p=0.006$). All other analyses revealed no statistical differences between the stimulation sides, neither in response times, nor in ERP measures (amplitudes and latencies of N1, P2, P3b ERPs).

Figure 3b illustrates the activity in the left and right auditory cortex for the NH control group when stimulated with vocoded syllables via the left and right ear. A two-way ANOVA with the within-subject factors “side of stimulation” (left/right) and “hemisphere” (left/right) revealed a significant two-way interaction ($F_{1,9}=9.85$, $p_{adj}=0.012$, $\eta^2=0.07$). Post-hoc t-tests showed a hemispheric difference in auditory-cortex activation for the stimulation of the left ear ($p=0.028$), with an enhanced activation in the right than left auditory cortex. By contrast, there was no hemispheric difference in auditory-cortex activation for the stimulation of the right ear.

In sum, the results concerning question 3 revealed no side-of-implantation effect on *behavioural* speech discrimination abilities in SSD CI users, although the NH listeners showed in general enhanced hit rates for the right-ear than the left-ear stimulation condition (i.e., regardless of whether the syllables were “original” or “vocoded”). In contrast to the behavioural findings, however, the ERP analyses revealed a side-of-implantation effect on auditory cortex functions for the SSD CI users, with enhanced hemispheric difference in auditory-cortex activation for the left-ear than the right-ear implanted individuals. A consistent pattern of hemispheric asymmetry was observed in the NH listeners, in particular when these individuals were tested with vocoded stimuli, that is, in approximated sound conditions. This suggests that the side-of-implantation effect on auditory-cortex asymmetry mainly originates from the CI-related degradation of the stimuli (i.e., confirmation of hypothesis 1).

Question 4: Is there a Side-of-Stimulation Effect on Speech Processing via the NH Ear in SSD CI Users and in NH Listeners?

Behavioural Results and ERP Results on Sensor Level: Left Side vs. Right Side in SSD CI Users and NH Controls

We statistically compared the behavioural and ERP measures (for “original” syllables) for the NH ear of SSD CI users between the left and right implanted patients, hence the side-of-implantation effect on the NH ear. No differences were found for any behavioural measures, nor for the sensory ERP components (N1, P2). The t-test between the two groups for the higher-cognitive P3b component revealed a statistically significant difference in latency ($t(16,98)=-3.18$, $p=0.005$, $d=1.45$), with a prolonged latency for the right SSD CI users (NH ear on the left side). The same analysis for the NH control group did not show any differences between the sides of stimulation.

ERPs on Source Level: Left Side vs. Right Side in SSD CI Users and NH Controls

Figure 4a shows the activation of the left and right implanted SSD patients in the left and right auditory cortex when stimulated over their NH ear. A two-way mixed ANOVA with the between-subject factor “group” (left/right implanted) and the within-subject factor “hemisphere” (left/right) showed a significant two-way interaction ($F_{1,17}=5.91$, $p_{adj}=0.026$, $\eta^2=0.08$). Post-hoc tests revealed a hemispheric difference in auditory-cortex activation for the stimulation via the right NH ear (left implanted group; $p=0.009$), with greater activation in the left than right auditory cortex. By contrast, there was no hemispheric difference in the right-implanted SSD group when stimulated via the (left) NH ear. Additionally, a trend for a difference between the two SSD groups (when stimulated via the NH ear) was observed in the left auditory cortex, showing more activation for the stimulation of the right NH ear (left-implanted SSD users) compared to the left NH ear (right-implanted SSD users; $p=0.076$).

The comparison of the two NH ears of the NH control group revealed no significant hemispheric differences in auditory-cortex activation, neither for the stimulation of the left nor the right ear (Fig. 4b).

In sum, the findings concerning question 4 revealed that stimulation via the NH ear in SSD CI users resulted in comparable *behavioural* speech discrimination abilities between left-ear and right-ear implanted individuals. However, the two groups of SSD CI users differed in the pattern of functional asymmetries in the auditory cortex. When stimulated via the NH ear, the left-ear implanted SSD CI users (NH ear on the right side) revealed a stronger auditory-cortex asymmetry than the right-ear implanted individuals (NH ear on the left side). The NH listeners in general showed a less pronounced side-of-stimulation effect. These results suggest a side-of-implantation effect on speech processing via the NH ear for SSD CI users, possibly caused by implantation-side specific alterations in the ipsilateral and contralateral auditory cortex as induced by temporary deafness and/or degraded sensory input after implantation (i.e., confirmation of hypothesis 2).

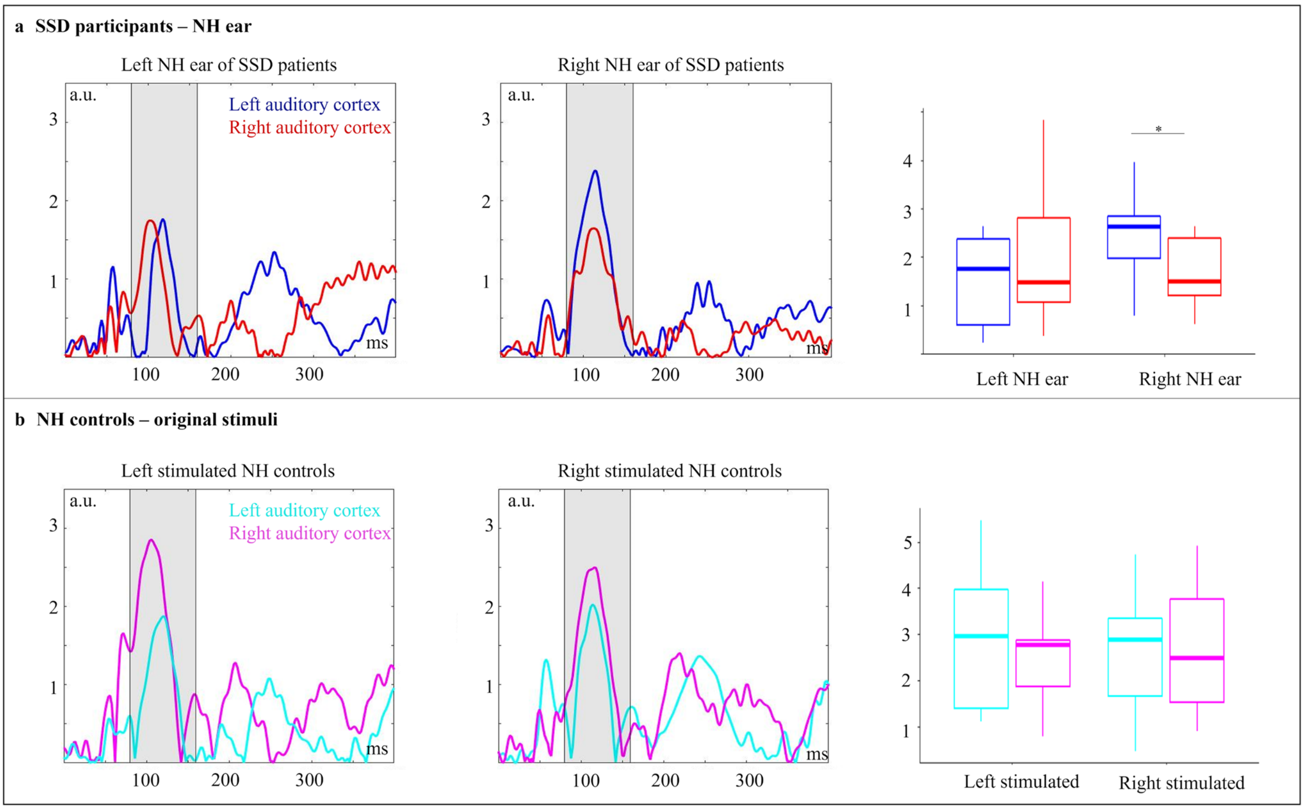

Fig. 4 Activity in the left and right auditory cortex shows differences in the latency range of the N1 component for the groups. **a** Mean activities plus boxplots for all SSD patients, separated by implantation side, stimulated via the NH ear are shown. The left NH ear belongs to the right implanted SSD patients and the right NH ear belongs to the left implanted SSD patients. **b** Mean activities plus boxplot for all NH control subjects, separated by the stimulation side, for the stimulation with original syllables are shown. Hemispheric asymmetries specifically for right NH ear of the SSD patients, as indicated by enhanced N1 amplitude in the left compared to right auditory cortex

Discussion

The present study compared event-related potentials (ERPs) between left-ear and right-ear implanted single-sided deaf (SSD) cochlear implant (CI) users on the one hand, and between these two patient groups and normal-hearing (NH) controls on the other hand. We used a two-deviant-oddball paradigm and ERP source analysis to evaluate differences in cortical speech processing between acoustic and electrical hearing as well as between proficient and non-proficient SSD CI users. Our results revealed that proficient and non-proficient CI users can be distinguished on the basis of N1 and P3b ERPs to speech sounds. Further, the results suggest that processing via the CI is more difficult than via the NH ear, as indicated by longer response times, higher subjective listening effort and ERPs with reduced amplitudes (N1, P2) and prolonged latencies (N1, P2, P3b; Finke et al. 2016, 2015; Henkin et al. 2009; Sandmann et al. 2009). Further, we found a stronger contralateral dominance of activation in the auditory cortex at N1 latency for left-ear than right-ear implanted SSD CI patients, regardless of whether these individuals were tested with the CI ear or the NH ear. A contralateral dominance for left-ear stimulation was also observed in the NH control group, which however was particularly present in the "vocoded" sound condition. We conclude that SSD CI users show a side-of-implantation effect on speech processing over both the CI and the NH ear. The next paragraphs focus on the four research questions addressed in the present study.

Question 1: Can a Two-Deviant Oddball Paradigm Be Used to Objectively Evaluate the Speech Discrimination Ability in SSD CI Users?

Speech recognition ability after cochlear implantation is heterogeneous, meaning that many patients reach open-set speech recognition ability while others do not (Blamey et al. 2013). Such variability can also be observed in SSD CI users (Speck et al. 2021), as confirmed by the current results. Although all of our CI users were able to discriminate between the syllables /ki/ (standard) and /ka/ (deviant 1), several CI users showed difficulties in the discrimination of the syllable contrast /ki/ (standard) versus /ti/ (deviant 2). These findings were expected because the vowel contrast /i/ versus /a/ (deviant 1) is the highest possible contrast in the German language. By contrast, the consonant contrast /k/ versus /t/ (deviant 2) mostly refers to rapid spectral changes in the transition of the second formant (F2), making it more difficult to be distinguished. Not surprisingly, half of our CI users showed a hit rate below 37.5% for deviant 2, which confirms previous observations of impaired discrimination ability in CI users (Sandmann et al. 2010). It seems that difficulties with electrical hearing are caused by different factors, among them the limited spectral and temporal information provided by the implant, the spread of neural excitation in the cochlea, as well as physiological deficiencies in the auditory nerve (Drennan, 2008; Friesen et al. 2001; Kral, 2007; Nadol et al. 1989; Wilson and Dorman, 2008). Auditory deprivation not only reduces metabolism in the auditory cortex contralateral to the hearing-impaired ear (Speck et al. 2020) but also induces a reorganisation of the central auditory system, which may impair the cortical adaptation to the new artificial CI signal after implantation (Lee et al. 2001; Sandmann et al. 2012). Taken together, it seems that several individual factors contribute to the variability in speech discrimination ability observed in SSD CI users.

Our results on the stimulation via the CI ear also revealed a relationship between the (behavioural) auditory discrimination ability and objective ERP measures. CI users who were *better* able to discriminate between the syllables /ki/ and /ti/—here referred to as proficient CI users—showed a *reduced* and *delayed* N1 ERP when compared to the non-proficient CI users, who showed impaired syllable discrimination ability (Supplementary Fig. 1a: bottom left and right; Supplementary Fig. 1b). Importantly, the factor “age” cannot explain the reduced N1 ERPs in the proficient CI users, as the two groups had a comparable age, and a supplementary analysis revealed that the correlation between N1 ERPs and age was not significant (Supplementary Fig. 1c). Thus, our results suggest that the N1 ERP can distinguish between proficient and non-proficient CI users. Similarly, previous neuroimaging studies have suggested significantly different cortical activation patterns between lower and higher CI performers (Kessler et al. 2020), and an association between the recruitment of the auditory cortex and improvement in speech recognition ability over the first months after cochlear implantation (Sandmann et al. 2015).

Despite agreements with previous findings, the present ERP results indicate that the *non-proficient* CI performers revealed an *enhanced* N1 response when compared to the proficient CI performers, which however contradicts previous observations from positron-emission-tomography (PET) studies, reporting an *enhanced* cortical activation for individuals with *better* speech recognition ability (Giraud et al. 2001; Green et al. 2005). This discrepancy in results may be explained by differences in methodology, including the measurement technique (PET versus EEG), the task (passive versus active), the type of auditory stimuli (words versus syllables), and the tested groups of CI users (bilateral hearing loss versus SSD). In general, an enhanced N1 amplitude (observed in non-proficient CI users) indicates a larger population of activated neurons in the auditory cortex, a stronger synchronisation of this neural activity, or a combination thereof. Thus, the current results may point to an enhanced recruitment and/or more synchronised neural activity in the auditory cortex in the non-proficient as compared to the proficient CI users. It is likely that these functional alterations in non-proficient CI users reflect an enhanced allocation of attentional resources to process small acoustic changes in speech sounds in the context of a discrimination task.

It has been previously suggested for CI users with bilateral hearing loss that ERPs can be used to objectively evaluate the auditory discrimination ability (Henkin et al. 2009; Sandmann et al. 2010; Soshi et al. 2014). Most of these previous studies used an auditory oddball paradigm and focused on the P3b response, which is elicited by infrequent, task-relevant changes in stimuli, and which shows maximal amplitudes over parietal scalp locations (Polich and Comerchero, 2003). Different models exist to describe the P3b component (Verleger, 2020). For instance, the P3b has been proposed to be a correlate of decision making (O’Connell et al. 2012), and to reflect voluntary attention to the task-relevant target stimuli (Polich, 2007). However, the elicitation of such a response requires that the individual can distinguish the acoustical differences between the task-relevant and task-irrelevant events. Indeed, previous results with CI users have pointed to a connection between the behavioural discrimination ability and the P3b ERP. They have revealed that the P3b in response to deviant sounds is comparable between CI users (with bilateral hearing loss) and NH listeners if the acoustic cues are well distinguishable by the participants (Henkin et al. 2009). However, in situations with more difficult stimulus contrasts, the CI users’ P3b response was reduced in amplitude and prolonged in latency (Henkin et al. 2009). The current study with SSD CI users confirms these previous observations. Our proficient and non-proficient CI users were well able to discriminate the syllable contrast /ki/ versus /ka/ (deviant 1), both when tested via the NH ear and via the CI ear (Fig. 1b), and the P3b amplitude elicited to this syllable contrast was comparable across groups and stimulated ears (Fig. 1c). However, we found group differences in the P3b for the syllable contrast /ki/ versus /ti/ (deviant 2), specifically when the CI users were tested via the CI ear (Fig. 1c: bottom left and right). Proficient CI users, but not non-proficient CI users, showed a P3b in response to deviant 2. Additionally, we found significant correlations between the hit rates and the P3b amplitude in both groups, pointing to a direct connection between the discrimination ability and the P3b amplitude. Taken together, our results confirm previous studies by showing that the P3b is an appropriate ERP component to study higher-order cognitive processing in SSD CI users (Bönitz et al. 2018; Finke et al. 2016; Wedekind et al. 2021). Further, our results extend previous findings by demonstrating that the P3b can serve as an objective index for the behavioural speech discrimination ability in SSD CI users. Regarding the clinical application of the P3b, however, future studies should replicate and extend our results with more complex stimuli, for instance words. The use of similar stimuli in ERP recordings and common clinical test procedures (e.g., Freiburg monosyllabic word test) would allow even better comparability between the results of the electrophysiological P3b response and the behavioural word recognition ability obtained by speech audiometry.

Our results provide further evidence that ERP measures, in particular the N1 and the P3b, can differentiate between proficient and non-proficient CI users. This is consistent with other studies, reporting that ERPs measures—in particular the mismatch negativity (MMN; latency around 150–200 ms) and the P3b (latency around 300–650 ms) — can distinguish between CI users who have better versus lower abilities to discriminate speech sounds (Henkin et al. 2009; Turgeon et al. 2014). Thus, there is converging evidence that objective ERP measures can be used to assess behavioural speech recognition ability in CI users. However, the application of an EEG paradigm in the clinical context poses the challenge that the recording time should be as minimal as possible. Pakarinen et al. (2009) proposed a fast multi-feature paradigm for the recording of the mismatch negativity (MMN) to different speech sounds in the same recording session. Although this type of paradigm is very promising, the MMN is recorded in a passive condition and thus has a much smaller signal-to-noise ratio when compared to the P3b response. It is therefore reasonable to design a time-efficient *active* oddball paradigm, which allows to measure the more pronounced P3b in response to several speech stimuli and in a time short enough to avoid problems with vigilance, motivation, or restlessness of the patient. Our results are promising as they demonstrate that a two-deviant oddball paradigm is suitable to assess syllable discrimination proficiency in SSD CI users. Further, our findings extend previous reports by showing that cortical AEPs can be used in SSD CI users to objectify not only the detection (Távora-Vieira et al. 2018) but also the discrimination of speech sounds. Thus, our results suggest that this paradigm could be useful in the clinical context, as it allows the objective monitoring of the auditory rehabilitation in different acoustic dimensions after cochlear implantation. To extend our findings, which are limited to syllables, the paradigm should be extended to more complex speech stimuli such as words. Importantly, the objective ERP measures could indicate whether the custom setting of the CI is sufficient for detailed speech discrimination ability, and whether renewed adjustments in certain frequency ranges could be useful. This is particularly important for patients with an ambiguous constellation of behavioural results.

Question 2: Do SSD CI Users Show Differences in Speech Processing Between the CI Ear and the NH Ear?

Our participants showed slower response times for the processing of syllables via the CI ear compared to the NH ear. This is consistent with recent work on SSD CI users, showing for the CI ear prolonged behavioural responses not only to sinusoidal tones (Bönitz et al. 2018) but also to words (Finke et al. 2016). Given the temporally and spectrally limited signal quality of the CI input, it is highly likely that these slower response times reflect enhanced difficulties to process the speech sounds via the CI ear when compared to the NH ear (Beynon et al. 2005; Groenen et al. 2001; Kelly et al. 2005). This interpretation is supported by our observation that SSD CI users report an enhanced listening effort for syllable processing via the CI ear as compared to the NH ear.

Similar to the behavioural results, we found an effect of stimulation type (acoustic versus electric) on ERPs, not only on the sensor level but also in the auditory cortex. For the CI ear, the ERPs (on the sensor level) were smaller in amplitude (N1, P2) and prolonged in latency (N1, P3b). These results are consistent with previous EEG studies on SSD CI users (Bönitz et al. 2018; Finke et al. 2016; Legris et al. 2018). CI-related effects on ERPs are also suggested by the current N1 source analysis, showing a prolonged cortical response to syllables when processed via the CI ear as compared to the NH ear (Fig. 2d). In sum, our ERP results are consistent with our behavioural observations since they suggest difficulties in speech processing via the CI ear, both at initial sensory and later cognitive processing stages. It is likely that the ERP differences between the CI ear and the NH ear are caused by CI-related stimulus degradation and/or cortical reorganisation as induced by temporary deafness and/or cochlear implantation (e.g., Sandmann et al. 2015).

To analyse the specific effect of CI-related stimulus degradation on speech processing, we compared the behavioural and ERP results of NH listeners between the two stimulus conditions “original” and “vocoded” speech sounds. The behavioural results did *not* reveal significant differences in hit rates and response times between the two sound conditions (Supplementary Fig. 2a). Further, N1 ERPs were comparable for “original” and “vocoded” syllables, both on the sensor level (Supplementary Fig. 2d) and in the auditory cortex (Supplementary Fig. 2d). These results indicate that the NH listeners could well distinguish the different syllable pairs, regardless of the CI-related stimulus degradation. Further, our results suggest that the cortical speech processing at N1 latency was not significantly affected by stimulus degradation in NH listeners. Given that noise-band vocoder simulations used in NH listeners allow a good approximation to the performance levels of CI users (Friesen et al. 2001), our results indicate that the attenuated and prolonged N1 ERP for the CI ear in our SSD patients cannot be explained by the degraded CI input alone. It seems more likely that this latency effect for the CI ear is at least partially caused by intra-modal plasticity in the auditory cortex of SSD CI users. Indeed, a previous prospective longitudinal study on CI users (with bilateral hearing loss) has shown that the N1 latency reduces over the first year of implant use and approaches the levels of NH listeners, but remains delayed, even after one year of CI experience (Sandmann et al. 2015). This observation indicates limitations in the capacity of the auditory cortex to adapt to the CI signal after implantation. Taken together, our results suggest that differences in speech processing between the CI ear and the NH ear in SSD CI users are at least partially related to limitations in cortical adaptation to the implant signal, causing difficulties in the sensory and cognitive processing when speech is perceived via the CI ear.

Unlike our findings about the N1 ERP, we observed an effect of stimulus degradation on the P2 response in the NH control group, with *enhanced* P2 amplitude for the “vocoded” sounds when compared to the “original” sounds (Supplementary Fig. 2b). With regards to the SSD group, however, speech processing via the CI ear resulted in a *smaller* P2 amplitude when compared to the NH ear. Two different mechanisms may account for this group specific differences in P2 amplitude modulation, in particular 1) training-related alterations of sound representation, and 2) allocation of attentional resources. Regarding the *first mechanism*, previous EEG studies have proposed that the training-related enhancement of the auditory P2 response represents an electrophysiological correlate of perceptual learning, memory, and training (Ross and Tremblay, 2009; Tremblay et al., 2001). It seems that P2 amplitude modulations are associated with cortical changes induced by repeated stimulus exposure rather than the learning outcome itself (Tremblay et al. 2014). Thus, our result of a smaller P2 response for the CI ear in SSD CI users can be explained by the fact that the NH ear—when compared to the CI ear—is more experienced and is more exposed to auditory stimuli as it is the dominant communication channel in these individuals. Regarding the *second mechanism*, previous studies with NH listeners have suggested that both the N1 and the P2 ERPs are susceptible to attention (Crowley and Colrain, 2004). An enhanced ERP amplitude at P2 latency can be explained by the attentional shift towards auditory stimuli (Picton and Hillyard, 1974), and seems to be associated with stimulus categorisation (García-Larrea et al. 1992). Following these previous studies, we interpret the larger P2 amplitude for “vocoded” stimuli in the NH control group as reflecting an enhanced allocation of attentional resources to process the degraded and unfamiliar stimuli. It seems that in this difficult listening condition, the NH listeners’ speech processing is not automatic but explicit and therefore needs the additional recruitment of cognitive resources to reconstruct the limited speech signal (Rönnberg et al. 2013; Zekveld et al. 2010). This interpretation is supported by the finding that the NH control group reported an enhanced subjective listening effort in the “vocoded” than the “original” sound condition.

Question 3: Is there a Side-of-Implantation Effect on Speech Processing via the CI Ear in SSD CI Users?

It is currently not well understood, how the side of implantation affects the rehabilitation success in adult postlingually deafened SSD CI users. Recent results have pointed to a right-ear advantage for speech recognition ability in SSD CI users, independent from their pure tone thresholds (Wettstein and Probst, 2018). The authors have argued that this right-ear advantage in SSD CI users is mostly driven by the left-hemisphere dominance for speech processing. However, the current study could not replicate these previous findings, given that our behavioural results revealed no side-of-implantation effect on syllable processing. One may speculate that this lack of replication can be explained by the fact that the current study focused on syllables, whereas Wettstein and Probst (2018) presented four-syllabic numbers and monosyllabic words. The use of different stimulus types in the two studies obviously limits the comparability between the results. However, in addition to the EEG paradigm, our SSD CI users were also examined with standard clinical speech tests (Table 1). The results revealed no significant differences between left-ear and right-ear implanted SSD CI users regarding the pure-tone thresholds, the word recognition ability (assessed by the Freiburg monosyllabic word test) and the speech intelligibility (assessed by the Oldenburg sentence test). Thus, we speculate that the lack of a replication of a behavioural side-of-implantation effect may be related to the small sample size (used in the present study) in combination with the high variability in behavioural results observed in SSD CI users.

Our data revealed a significant hemispheric difference for the left-implanted participants, but not for the right-implanted participants, both for stimulation via the CI ear and the NH ear (Fig. 3a and Fig. 4a). For the stimulation via the *CI ear* (Fig. 3a), the left-implanted CI users showed a significantly enhanced activation in the right as compared to the left auditory cortex—referred to as contralateral dominance effect. For the stimulation via the *NH ear*, the left-implanted CI users (with a NH ear on the right side) showed a contralateral dominance effect as well, as indicated by a significantly enhanced activation in the left as compared to the right auditory cortex (Fig. 4a; see section “Question 4: Is there a side-of-stimulation effect on speech processing via the NH ear in SSD CI users and in NH listeners?” for a discussion of the side-of-implantation effect on the NH ear).

In contrast to children with SSD, who develop a normal lateralization to the contralateral auditory cortex when implanted at young age (Lee et al. 2020; Polonenko et al. 2017), not much is known about functional changes in the auditory cortex of postlingually deafened adult SSD CI patients. To discuss the observed differences in auditory-cortex asymmetry between our left- and right-ear implanted SSD CI users, it is important to keep two aspects in mind. First, the contralateral dominance of the auditory cortex has been described for monaural stimulation (Hine and Debener, 2007). In the human auditory system, the pathway from each ear to the contralateral cortical hemisphere consists of more nerve fibres than the pathway to the ipsilateral hemisphere (Rosenzweig, 1951). Therefore, monaural stimulation evokes stronger responses in the contralateral than in the ipsilateral hemisphere (Jäncke et al. 2002). Second, there is a relative hemispheric specialisation of the left and right auditory cortex for the processing of basic acoustic properties (Lazard et al. 2012a). Prior studies have suggested that the left auditory cortex is more proficient in the processing of fast temporal acoustic cues, which are largely contained in speech stimuli (Boemio et al. 2005; Poeppel, 2003). Conversely, the right auditory cortex seems to preferentially process slowly modulated signals and spectral aspects of sounds, which are largely contained in musical stimuli (Liegeois-Chauvel, 1999; Poeppel, 2003; Zatorre et al. 2002). Thus, the hemispheric differences during speech and music processing can be attributed to the *relative* specialisation of the two hemispheres for basic acoustic stimulus properties, in particular fast temporal versus slow spectrotemporal acoustic cues. It has been assumed that the auditory cortex’ preference for basic stimulus properties drives higher-order organisation for speech and music perception (Lazard et al. 2012a).

Our observation of a contralateral dominance effect for the left-ear implanted SSD CI users during speech processing seems to contradict previous results of left-hemisphere dominance for speech processing in NH listeners. However, a strong activation in the right auditory cortex in these patients can be explained by the combination of two factors. First, the left ear shows stronger projections to the contralateral than ipsilateral auditory cortex. Therefore, monaural stimulation of the left ear resulted in an enhanced activation in the right than left auditory cortex. Second, the CI processing remarkably reduces the quality of the speech sounds and affects the spectrotemporal properties of the presented syllables. Given the relative specialisation of the two hemispheres for basic acoustic stimulus properties, the CI-related stimulus degradation may have resulted in a relatively stronger right-than left-auditory cortex activation. Indeed, some of our SSD CI patients reported that the speech stimuli were perceived as more noise-like and less speech-like when presented via the CI than the NH ear.

Our results showed a contralateral dominance effect specifically for the left-ear but not for the right-ear implanted SSD CI users. This contrasts with the results of Sandmann et al. (2009), who found a stronger contralateral dominance effect for right- than left-ear stimulated CI users. This discrepancy in results can be due to different reasons. First, in the current study we used syllables, while Sandmann et al. (2009) used dyadic tones, i.e., musical sounds. Speech and musical stimuli are characterised by different acoustic properties. Given the relative specialisation of the left and right auditory cortex for basic stimulus properties (Poeppel, 2003; Zatorre and Belin, 2001), the discrepancies between previous and current results with regards to the pattern of cortical asymmetry could be explained by distinct stimulus properties, resulting in a different recruitment of the left and right auditory cortex. Another reason for discrepant findings between previous and current results is that the current study examined SSD CI users, whereas Sandmann et al. (2009) tested CI users with bilateral hearing loss. In contrast to the current study, the hearing ability of the second ear was reduced, and it was *not* matched between the left- and right-ear stimulated CI users. Given that auditory deprivation reduces the metabolism in the contralateral auditory cortex (Speck et al. 2020) and can induce cortical reorganization in the auditory cortex (Stropahl et al. 2017), the different pattern of hemispheric asymmetry in the auditory cortex might have arisen due to the confounding effect of the hearing loss in the second ear.

It may be argued that handedness is a factor confounding our results regarding functional hemispheric asymmetry, since the probability of a reversed lateralisation for language processing seems to be enhanced in left handers when compared to right handers (Hund-Georgiadis et al. 2002). However, previous studies using different methods have observed that the majority of right- *and* left-handed individuals show left-sided cerebral dominance for language processing, and only less than 10% of the left-handers show right-sided cerebral dominance for language processing (Khedr et al. 2002; Szaflarski et al. 2002). In addition, a supplementary analysis of our behavioural and ERP data revealed that the two left-handed CI-users lay within the normal range (as defined by mean ± 2 standard deviations) and therefore we conclude that the activity in the left and right auditory cortex was not confounded by the factor handedness.

Our results revealed a similar pattern of auditory-cortex asymmetry between the SSD CI users and the NH control group, when the latter group was presented with “vocoded” sounds (Fig. 3). Specifically, SSD CI users and NH listeners showed a contralateral dominance effect for the left-ear stimulation, with enhanced activation in the right as compared to the left auditory cortex. By contrast, no hemispheric difference was found for SSD CI users and NH listeners when they were stimulated via the right ear. Given these similarities between CI users and NH listeners (the latter tested with "vocoded" stimuli) and the fact that noise-band vocoder simulations allow a good approximation to sound conditions in CI users (Friesen et al. 2001), we conclude that the different pattern of contralateral dominance between left- and right-ear implanted CI SSD users is mainly driven by the CI-related stimulus degradation. Nevertheless, it is important to note that our sample size is limited, and the current study only allows conclusions to be drawn regarding the processing of syllables. Therefore, future studies should examine the functional asymmetry in the auditory cortex in further SSD CI users and for different auditory stimuli, in particular speech and musical sounds.

Question 4: Is there a Side-of-Stimulation Effect on Speech Processing via the NH Ear in SSD CI Users and in NH Listeners?

A recent multicentre study has reported a significant difference in the hearing threshold between the NH ear of SSD patients and the NH ears of age-matched NH listeners (Arndt et al. 2019). This observation points to a poorer peripheral hearing capacity for the intact ear of SSD patients when compared to NH listeners. Importantly, these previous results suggest that SSD CI users show behavioural alterations not only in the CI ear but also in the NH ear. It seems that these alterations in the NH ear are *not* induced by cochlear implantation, given that the hearing threshold of the NH ear appears to be comparable at the times before and after implantation (Speck et al. 2021). Further, alterations in the NH ear of SSD CI users are not limited to the hearing threshold but can also show up in other auditory tests. For instance, Maslin et al. (2015) have reported that in SSD CI users the intact ear is better able to discriminate intensity differences, suggesting perceptual improvements as induced by cortical plasticity following unilateral deafness.

The present study did also reveal a significant difference between the NH ear of SSD CI users and the matched NH ear of NH listeners with regards to the hearing threshold, but not with regards to the behavioural performance and hit rates in the auditory oddball paradigm. Thus, our results can confirm alterations in the intact ear of SSD CI users, at least on the peripheral hearing capacity. But we could not confirm these alterations on the behavioural level in the oddball paradigm. Several reasons may account for the lack of comparability between the two results in the present study. In addition to the small sample size and the high variability in behavioural measures across participants, there are methodological discrepancies between the two measurements (Arndt et al. 2019; Maslin et al. 2015; Speck et al. 2021), in particular in terms of the task (pure-tone audiometry/intensity difference limens vs. auditory oddball task) and the stimulus material (pure tones vs. syllables). It may be speculated, that alterations in the NH ear of SSD CI users are stimulus- and task-selective and may be revealed only under specific conditions.

As far as we are aware, the present study is the first to compare the NH ears of SSD CI users and NH listeners in the context of an auditory oddball paradigm. The ERP source analysis revealed that *stimulation of the right NH ear* of (left-implanted) CI users induced an enhanced activation in the left as compared to the right auditory cortex —referred to as contralateral dominance effect (Fig. 4a top right). By contrast, the NH listeners—when stimulated on the right ear—showed no hemispheric difference in auditory-cortex activation, although on the descriptive level, the activation in the left hemisphere was enhanced (Fig. 4a bottom right). Regarding the *stimulation of the left NH ear*, both the (right-implanted) SSD CI users the NH listeners showed no activation differences between the right and left auditory cortex (Fig. 4a top left and bottom left). These results suggest that specifically the group of left-ear implanted SSD CI users shows cortical alterations for speech-sound processing when stimulated via the (right) NH ear (Fig. 4a top right). Interestingly, the same group also revealed an enhanced contralateral dominance effect when stimulated via the CI ear (Fig. 3a top left; see also section "Question 3: Is there a side-of-implantation effect on speech processing via the CI ear in SSD CI users?" for a discussion of this effect).

The enhanced hemispheric asymmetry for the stimulation of the *right NH ear* in (left-implanted) SSD CI users may be explained by alterations in the left auditory cortex for the processing of rapidly changing stimulus properties contained in speech stimuli (Boemio et al. 2005; Poeppel, 2003). It can be speculated that these improvements are induced by temporary unilateral deafness and/or electrical afferentation with a CI. These improvements may reflect an optimised left-hemispheric speech processing, which is particularly important in difficult listening conditions with reduced or degraded auditory input (processing via the CI ear), but which also affects the processing of the normal acoustic input (processing via the NH ear). Alternatively, but not mutually exclusive, previous animal studies have shown that unilateral deafness results in an enhanced ipsilateral activation, which is due to an increased number and/or enhanced excitability of neurons that are responsive to the intact ear (McAlpine et al. 1997; Mossop et al. 2000). Regarding the current results, the *reduced* hemispheric asymmetry for the stimulation of the *left NH ear* in (right-implanted) SSD CI users may be explained by the fact that SSD patients show enhanced afferent input from the (left) intact ear to the (left) ipsilateral auditory cortex (Maslin et al. 2015). Thus, the speech processing via the *left NH* *ear* in right-implanted SSD CI users might evoke a strong activation in the *left* auditory cortex, which counteracts the contralateral dominance effect for left-ear stimulation. Taken together, our results provide first evidence of a side-of-implantation effect on functional auditory-cortex asymmetry in adult postlingually deafened SSD CI users, which is not limited to the CI ear, but which is also shown for the NH ear. However, in order to gain a better understanding of the cortical changes in the intact ear of SSD CI users, future studies are required to examine whether a similar pattern of results on hemispheric asymmetries can be observed with other types of stimuli, for instance musical sounds and more complex speech stimuli.

Limitations

One limitation of this study is the relatively small group size, which results in a low statistical power and therefore makes it difficult to draw conclusions that are transferable to the generality. However, we believe that our results point out important issues in single-sided deaf CI-users that are worth further research to support our findings of asymmetry in the auditory cortex depending on the side of implantation. Furthermore, we did not find correlations between our results of the EEG paradigm and the clinical speech tests reported in this manuscript. One important reason for this lack seems to be the fact that the syllable-discrimination task in the EEG paradigm (discrimination of phonetic contrasts) and the clinical speech tests (monosyllabic word test, Oldenburg Sentence Test (OLSA)) examine speech competencies on different linguistic levels. In particular, the comparison between the standard stimulus (/ki/) and the deviant 2 stimulus (/ti/) only relies on the consonant-contrast, which is very hard to discriminate for some CI-user, particularly in situations without any given context. A second reason could be our exploratory median split procedure. We used this procedure to divide our sample in equal group sizes, but it was not possible to get a division in *clearly poor* and *clearly high* CI performers. Further research should use more diverse and complex stimuli to differentiate the groups (proficient vs. non-proficient) on a more solid basis.

Conclusions

The present study used an auditory oddball task to examine cortical speech processing of the CI ear and the NH ear of SSD CI users. Given that non-proficient and proficient SSD CI users could be distinguished based on the N1 and P3b amplitude, we conclude that the time-efficient two-deviant oddball paradigm can be used to assess speech discrimination proficiency in SSD CI users. Further, our results suggest that the observed differences in cortical speech processing between the CI ear and the NH ear in SSD CI users are (at least partially) caused by limitations in the cortical adaptation to the implant signal, which leads to difficulties in the sensory and cognitive speech processing for the CI ear. Finally, we found a side-of-implantation effect on auditory-cortex asymmetry for both the CI ear and the NH ear. We suppose that these side-of-implantation effects originate from CI-related degradation of the stimuli and cortical reorganisation as induced by temporary unilateral deafness and/or degraded sensory input after implantation.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose. The authors have no competing interests to declare that are relevant to the content of this article.

Ethical Approval The study was approved by the Ethics Committee of Cologne University's Faculty of Medicine (application number 13–057) and was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki, 2013).

Consent to Participate Informed consent was obtained from all individual participants included in the study.

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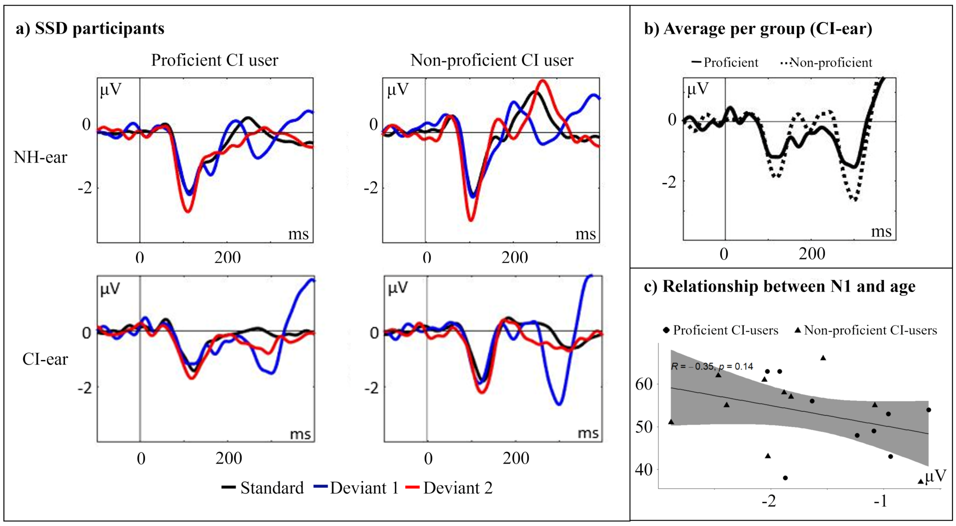

Figure 2.1: Supplementary Figure 1

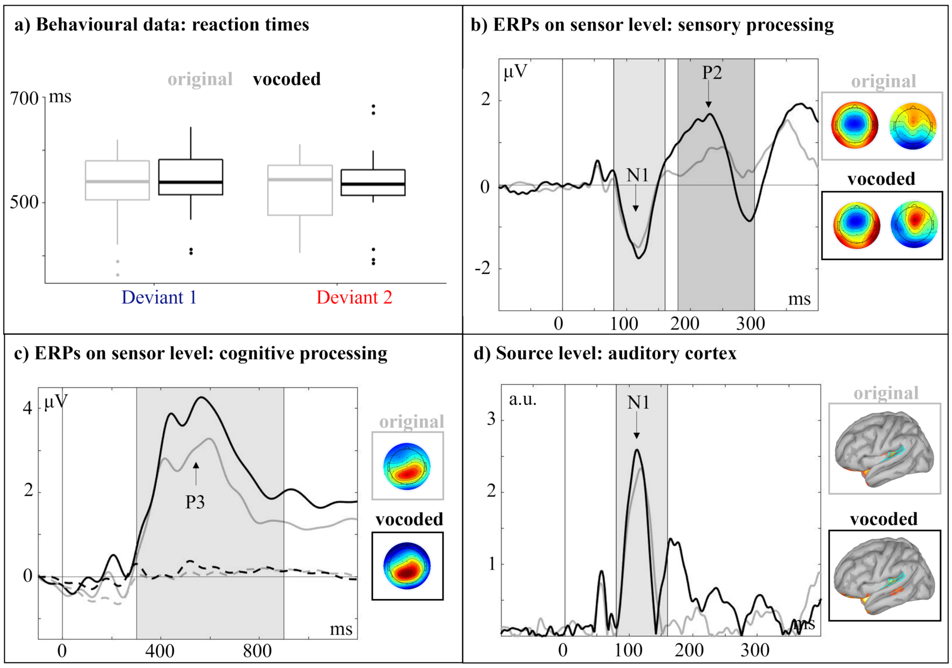

Figure 2.2: Supplementary Figure 2

3

ELECTROPHYSIOLOGICAL DIFFERENCES AND SIMILARITIES IN AUDIOVISUAL SPEECH PROCESSING IN COCHLEAR IMPLANT USERS WITH UNILATERAL AND BILATERAL HEARING LOSS

This chapter is based on the following publication:

Layer, N., **Weglage, A.**, Müller, V., Meister, H., Lang-Roth, R., Walger, M., Murray, M., & Sandmann, P. (2022). Electrophysiological differences and similarities in audiovisual speech processing in CI users with unilateral and bilateral hearing loss. Current Research in Neurobiology, 3, 100059.

Author contributions:
Natalie Layer: Conceptualisation; literature review; creation, editing and calibration of stimuli; programming of the experiment; pilot measurements; participant recruitment; data acquisition; data analysis; interpretation and presentation of results to research group; discussion of findings and further procedures; writing initial manuscript draft; incorporating suggestions of co-authors; submission to journal; presentation of results at national and international conferences. **Anna Weglage**: Assistance in data acquisition; assistance in data analysis; group discussions; proofreading of manuscript. **Verena Müller**: Advisory role (CI technician); initial assistance in participant enrolment; proofreading of manuscript. **Hartmut Meister**: Funding acquisition; conceptualisation; provision of software for stimuli generation; discussion; suggestions; proofreading of manuscript. **Ruth Lang-Roth**: Conceptualisation; proof-reading of manuscript. **Martin Walger**: Conceptualisation; proof-reading of manuscript. **Micah M. Murray**: Presentation of analytical method (topographic analysis); validation of analysis; discussions; suggestions; proofreading of manuscript. **Pascale Sandmann**: Supervisor of Natalie Layer and Anna Weglage; central role in project conceptualisation; funding acquisition; suggestions; discussions; assistance in writing manuscript and proofreading of manuscript.

SYNOPSIS

OBJECTIVES Due to the limited auditory input via a CI, affected individuals develop compensatory strategies to cope with the limitations. Especially CI users with bilateral hearing loss, who are either provided with two CIs or wear a CI and a hearing aid, show enhanced audiovisual interactions displayed by enhanced lip reading abilities as compared to NH listeners (Rouger et al., 2007) and cross-modal recruitment of the visual cortex for purely auditory stimulation (Chen et al., 2016; Giraud et al., 2001a). Previous research using EEG confirmed enhanced multisensory interactions in CI users with bilateral hearing loss for simple acoustic stimuli (Schierholz et al., 2015) and for speech stimuli (Layer et al., 2022; Radecke et al., 2022). However, these results were not yet shown for SSD CI users. Therefore, this study aims to extend the results of Layer et al. (2022), who showed multisensory interactions in CI users with bilateral hearing loss (in this study referred to as contralateral hearing device (CHD CI users) to the group of CI users with unilateral hearing loss (SSD CI users). For this purpose the lip reading ability, as well as the timecourse of auditory and audiovisual speech processing, was compared between CHD CI users, SSD CI users and NH controls.

METHODS This study included postlingual CHD CI users, who were fitted with a CI and a second CI or a hearing aid at the contralateral ear, SSD CI users, who were fitted with one CI and were NH on the contralateral ear, and NH controls. An 64 channel EEG was recorded while participants performed a speeded response task (the same task as in Layer et al., 2022). The stimuli consisted of the syllables /ki/ and /ka/ that were presented in an auditory (A), visual (V) and audiovisual (AV) conditions. These two syllables were assigned to one of two buttons on a computer mouse and participants were asked to press the corresponding button as fast as possible when receiving the syllable. Additionally, the task difficulty was enquired after each experimental block. To get a measure of the lip reading ability, an additional test with monosyllabic words was performed, similar to previous studies (Stropahl and Debener, 2017; Layer et al., 2022).

ANALYSIS Behavioural measures, particularly hit rates and response times, as well as ERP measures were evaluated for the EEG experiment. Regarding the ERP measures, an additive model (Barth et al., 1995) was used to investigate audiovisual interactions, similar to previous studies (Stevenson et al., 2014). In this model, the auditory response (A) was compared to the visually modulated auditory (AV-V) response, and a difference between those was supposed to be an indication of a non-linear multisensory interaction (e.g. Vroomen and Stekelenburg, 2010). On the sensor level, the global field power (GFP) was analysed for the N1 and P2 time window. The amplitudes and latencies in these time windows were compared between the groups (CHD CI, SSD CI, NH) and conditions (A, AV-V). Further, a hierarchical clustering was used to identify frequent topographic maps, that are afterwards used for a single-subject fitting analysis. Particularly the *map presence* and the *first onset* of the maps were analysed within the time windows of the N1 and P2 to explore group and/or condition differences. Finally, a source analysis was performed, again at the N1 and P2 time window, in the visual and auditory cortices. The peaks and latencies of the activity were statistically compared between the groups and conditions.

RESULTS On the behavioural level, the shortest response times were observed for audiovisual stimuli as compared to auditory- or visual-only stimuli, confirming multisensory integration for all participant groups. In line with that, the multisensory integration was also found in the ERP data, showing reduced activity for the visually modulated auditory condition (AV-V) as compared to the auditory (A) condition in both groups for the N1 and P2 component. Further, a difference in topography was found for the N1 component between the AV-V and the A condition, especially in the CHD CI users. Additionally, both CI user groups revealed superior lip reading abilities, delayed auditory-cortex responses and enhanced visual-cortex responses,when compared to the NH controls.

DISCUSSION Both the behavioural and the ERP results revealed and audiovisual benefit for the CI user groups and the NH listeners, depicted in shorter response times and a visual modulation of the auditory response. In addition, a stronger visual influence on the auditory processing due to altered topography was found for the CHD CI users as compared to the SSD CI users and the NH controls at N1 latency range. Still, both CI user groups show difficulties processing the limited CI input, reflected by delayed responses in the auditory cortex when compared to NH controls. This is compensated by enhanced lip reading abilities and a stronger recruitment of the visual cortex. The similar compensatory strategies between the two CI user groups were not hypothesised, because the SSD CI users still have an intact NH ear. Hence, it is concluded that those compensatory strategies are independent of the hearing threshold and supply of the contralateral ear. All in all, the findings revealed differences and similarities between the CI user groups, generally supporting the benefits of audiovisual information for all CI users. This should be taken into account for the rehabilitation of the CI users.

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Electrophysiological differences and similarities in audiovisual speech processing in CI users with unilateral and bilateral hearing loss

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Audiovisual speech perception

ABSTRACT

Hearing with a cochlear implant (CI) is limited compared to natural hearing. Although CI users may develop compensatory strategies, it is currently unknown whether these extend from auditory to visual functions, and whether compensatory strategies vary between different CI user groups. To better understand the experience-dependent contributions to multisensory plasticity in audiovisual speech perception, the current event-related potential (ERP) study presented syllables in auditory, visual, and audiovisual conditions to CI users with unilateral or bilateral hearing loss, as well as to normal-hearing (NH) controls. Behavioural results revealed shorter audiovisual response times compared to unisensory conditions for all groups. Multisensory integration was confirmed by electrical neuroimaging, including topographic and ERP source analysis, showing a visual modulation of the auditory-cortex response at N1 and P2 latency. However, CI users with bilateral hearing loss showed a distinct pattern of N1 topography, indicating a stronger visual impact on auditory speech processing compared to CI users with unilateral hearing loss and NH listeners. Furthermore, both CI user groups showed a delayed auditory-cortex activation and an additional recruitment of the visual cortex, and a better lip-reading ability compared to NH listeners. In sum, these results extend previous findings by showing distinct multisensory processes not only between NH listeners and CI users in general, but even between CI users with unilateral and bilateral hearing loss. However, the comparably enhanced lip-reading ability and visual-cortex activation in both CI user groups suggest that these visual improvements are evident regardless of the hearing status of the contralateral ear.

1. Introduction

A cochlear implant (CI) can help restore the communication abilities in patients with severe to profound sensorineural hearing loss by electrically stimulating the auditory nerve (Zeng, 2011). However, listening with a CI is completely different from conventional hearing, as the electrical signal provided by the CI transmits only a limited amount of spectral and temporal information (Drennan and Rubinstein, 2008). Consequently, the central auditory system must learn to interpret the artificially sounding CI input as meaningful information (Giraud et al., 2001c; Sandmann et al., 2015). The ability of the nervous system to adapt to a new type of stimulus is an example of neural plasticity (Glennon et al., 2020; Merzenich et al., 2014). This phenomenon has been investigated in various studies with CI users, manifesting as an increase in activation in the auditory cortex to auditory stimuli during the first months after CI implantation (Giraud et al., 2001c; Green et al., 2005; Sandmann et al., 2015). Additional evidence for neural plasticity in CI users comes from the observation that these individuals recruit

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visual cortices for purely auditory speech tasks (Chen et al., 2016; Giraud et al., 2001c); a phenomenon referred to as cross-modal plasticity (e.g. Glennon et al., 2020).

Previous research has shown that event-related potentials (ERPs) derived from continuous electroencephalography (EEG) are an adequate method for studying cortical plasticity in CI users (Beynon et al., 2005; Finke et al., 2016a; Sandmann et al., 2009, 2015; Schierholz et al., 2015, 2017; Sharma et al., 2002; Viola et al., 2012; Layer et al., 2022). The primary benefit of analysing ERPs is the high temporal resolution, which allows for the tracking of individual cortical processing steps (Biasiucci et al., 2019; Michel and Murray, 2012). For instance, the auditory N1 (negative potential around 100 ms after stimulus onset) and the auditory P2 ERPs (positive potential around 200 ms after stimulus onset) are at least partly generated in the primary and secondary auditory cortices (Ahveninen et al., 2006; Bosnyak et al., 2004; Näätänen and Picton, 1987). Current models of auditory signal propagation recognise that there is an underlying anatomy exhibiting a semi-hierarchical and highly parallel organisation (e.g. Kaas and Hackett, 2000). In terms of auditory ERPs this would suggest that prominent components, such as the N1–P2 complex, include generators not only within primary auditory cortices, but within a distributed network along the superior temporal cortices as well as fronto-parietal structures and even visual cortices. Moreover, top-down effects, such as attention or expectation of incoming auditory events mediated by the frontal cortex, can influence these auditory processes (Dürschmid et al., 2019). The majority of previous ERP studies with CI users have used auditory stimuli to show that the N1 and P2 ERPs have a reduced amplitude and a prolonged latency in comparison to normal-hearing (NH) individuals. This observation suggests that CI users have difficulties in processing auditory stimuli (Beynon et al., 2005; Finke et al., 2016a; Henkin et al., 2014; Sandmann et al., 2009) and is consistent with previous behavioural results of impaired auditory discrimination ability in CI users (Sandmann et al., 2010, 2015; Finke et al., 2016a,b).

Although multisensory conditions more likely represent everyday situations, only a few ERP studies so far have been conducted with audiovisual stimuli. These studies primarily concentrated on rudimentary, non-linguistic audiovisual stimuli (sinusoidal tones and white discs) and showed a prolonged N1 response, and a greater *visual* modulation of the *auditory* N1 ERPs in CI users compared to NH listeners (Schierholz et al., 2015, 2017). Our previous study extended these results to more complex audiovisual syllables (Layer et al., 2022), using electrical neuroimaging (Michel et al., 2004, 2009; Michel and Murray, 2012) to perform topographic and ERP source analyses. Unlike traditional ERP data analysis, which is based on waveform morphology at specific electrode positions, electrical neuroimaging is reference-independent and takes into account the spatial characteristics and temporal dynamics of the global electric field to distinguish between the effects of response strength, latency, and distinct topographies (Murray et al., 2008; Michel et al., 2009). By using this topographic analysis approach, we previously showed a group-specific topographic pattern at N1 latency and an enhanced activation in the visual cortex at N1 latency for CI users when compared to NH listeners (Layer et al., 2022). These observations confirm a recent report about alterations in audiovisual processing and a multisensory benefit for CI users, if additional (congruent) visual information is provided (Radecke et al., 2022).

Based on previous ERP and behavioural results, one might conclude that multisensory processes, in particular integration of auditory and visual speech cues, remain intact in CI users despite the limited auditory signal provided by the CI. Nevertheless, it remains unclear whether the enhanced visual impact on auditory speech processing applies to all of the CI users, given that large inter-individual differences (e.g. with regards to the hearing threshold in the contralateral ear) have not been taken into account. Most of the aforementioned studies have included CI users with *bilateral hearing loss* (e.g. Finke et al., 2016a; Sandmann et al., 2015; Schierholz et al., 2015; Radecke et al., 2022; Layer et al., 2022), either provided with a CI on both ears (CI + CI on contralateral side) or on one ear (CI + hearing aid on contralateral side). These CI users will be referred to as CI-CHD users (CHD = ‘contralateral hearing device’) in the following. However, over the last years, the clinical margins for CI indication have been extended to *unilateral hearing loss*, enabling the implantation of single-sided deaf (SSD) patients (CI + NH on contralateral side; Arndt et al., 2011; Arndt et al., 2017; Buechner et al., 2010). This CI user group is particularly interesting, as the signal quality of the input is very different for the two ears, leading to maximally asymmetric auditory processing (Gordon et al., 2013; Kral et al., 2013). The variable hearing ability in the contralateral ear across different CI groups may at least partly account for the large variability in speech recognition ability observed in CI users (Lazard et al., 2012). To better understand the factors contributing to this variability and to extend previous findings on CI-CHD users and NH listeners (Layer et al., 2022), the current study systematically compared the timecourse of auditory and audiovisual speech processing as well as the lip-reading abilities between different groups of CI users, in particular CI-CHD users and CI-SSD users, and to NH listeners. The inclusion of the additional group of patients crucially extends our previous study because it not only evaluates the transferability our previous results to different patient groups but also provides deeper insights into the influence of individual factors - specifically the hearing ability of the second ear - on audiovisual speech processing in CI users. This is noteworthy because literature comparing CI-SSD to bimodal or bilateral CI users is scarce. However, the few existing studies reported differences in speech-in-noise performance (Williges et al., 2019) and in situations with multiple concurrent speakers (Bernstein et al., 2016) between CI-SSD users and bimodal or bilateral CI users, respectively. But, given this first evidence for purely auditory situations, we hypothesised that further differences would emerge for audiovisual stimulation, which has yet to be reported.

Given that CI-SSD users have an intact ear on the contralateral side, it is reasonable that this NH ear serves as the main communication channel despite the advantages given by the CI (Kitterick et al., 2015; Ludwig et al., 2021). Therefore, we hypothesised that CI-SSD users are less influenced by visual information, benefit less from audiovisual input and show poorer lip-reading skills than CI-CHD users. However, we expected a delay in cortical responses in the CI-SSD group, similar to the group of CI-CHD users, when compared to NH individuals, based on previous results from studies with purely auditory stimuli comparing the CI and the NH ear (Finke et al., 2016b; Bönitz et al., 2018; Weglage et al., 2022).

2. Material and methods

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the medical faculty of the University of Cologne (application number: 18 − 257). Prior to data collection, all participants gave written informed consent, and they were reimbursed.

2.1. Participants

In total, twelve post-lingually deafened CI-SSD patients were invited to participate in this study to extend the results from our previous study (Layer et al., 2022) by including an additional subgroup of CI-SSD users. Among these participants, one had to be excluded due to poor EEG data quality (high artefact load), resulting in a total of eleven CI-SSD patients (two right-implanted). Accordingly, we selected post-lingually deafened CI-CHD patients and NH listeners from our previous study (Layer et al., 2022; $n = 11$ each) such that they matched the CI-SSD patients as best as possible by gender, age, handedness, stimulated ear and years of education. The matched subset datasets from our previous study of CI-CHD users and NH listeners were reused for the current study and were extended by newly acquired data from an additional group of CI-SSD users. The CI-CHD users were implanted either unilaterally ($n = 2$; all left-implanted using a hearing aid on the contralateral ear) or bilaterally

($n = 9$; two right-implanted). All CI users had been using their device continuously for at least one year prior to the experiment. For the experiment, only the ear with a CI was stimulated and in the case of bilateral implantation, the 'better' ear (the ear showing the higher speech recognition scores in the Freiburg monosyllabic test) was used as stimulation side.

Thus, for final analyses, thirty-three volunteers were included, with eleven CI-SSD patients (7 female, mean age: 56.5 years ± 9.2 years, range: 39 – 70, 10 right-handed), eleven CI-CHD patients (7 female, mean age: 61.4 years ± 9.7 years, range: 39 – 75, 11 right-handed) and eleven NH listeners (7 female, mean age: 60.1 years ± 10.1 years, range: 34 – 70, 11 righthanded). Detailed information on the implant system and the demographic data are provided in Table 1. To check that cognitive abilities were age-appropriate, the DemTect Ear test battery was used (Brünecke et al., 2018). All participants scored within the normal, age-appropriate range (13 – 18 points). In addition, the German Freiburg monosyllabic speech test (Hahlbrock, 1970) with a sound intensity level of 65 dB SPL (see Table 4 for scores) was used to assess speech recognition abilities. To obtain a hearing threshold (HT) of the contralateral ear, we measured the aided HT in CI-CHD users in free-field and the unaided HT of the NH ear of CI-SSD users with headphones (see Table 1). All participants were native German speakers, had normal or corrected-to-normal vision (assessed by the Landolt test according to the DIN-norm; Wesemann et al., 2010) and none of the participants had a history of psychiatric disorder. Their handedness was assessed by the Edinburgh inventory (Oldfield, 1971).

2.2. Stimuli

The stimuli in this study were identical to those used in our previous study (Layer et al., 2022) and they were presented in three different conditions: visual-only (V), auditory-only (A) and audiovisual (AV). Additionally, there were trials with a black screen only ('nostim'), to which the participants were instructed to not react. The stimuli were delivered using the Presentation software (Neurobehavioral Systems, version 21.1) and a computer in combination with a duplicated monitor (69 inch). The stimuli consisted of the two syllables /ki/ and /ka/ which are included in the Oldenburg logatome speech corpus (OLLO; Wesker et al., 2005). They were cut from the available logatomes from one speaker (female speaker 1, V6 ′normal spelling style', no dialect). These two syllables in particular differed in their phonetic distinctive features (vowel place and height of articulation) in the vowel contrast (/a/ vs. /i/; Micco et al., 1995). These German vowels are different in terms of central frequencies of the first (F1) and second formant (F2) representing the highest contrast between German vowels (e.g. Obleser et al., 2003), making them easily distinguishable for CI users. Importantly, as we presented visual-only syllables as well, the chosen syllables not only highly differ in terms of auditory (phoneme) realisation, but also in their visual articulatory (viseme) realisation. A viseme is the visual equivalent of the phoneme: a static image of a person articulating a phoneme (Dong et al., 2003). The editing of the syllables was done with Audacity (version 3.0.2) by cutting and adjusting them to the same duration of 400 ms. The syllables were normalised (adjusted to the maximal amplitude) in Adobe Audition CS6 (version 5.0.2).

To create a visual articulation of the auditory syllables, we used the

Table 1
Demographic information on the CI participants; HT (hearing threshold; average over 500 Hz, 1 kHz, 2 kHz, 4 kHz); Stim. = stimulated; HL = hearing loss; m = male; f = female.

ID	Group	Sex	Age	Handedness	Fitting	HT (dB HL; contralateral ear)	Stim. ear	Etiology	Age at onset of HL (years)	CI use of the stim. ear (months)	CI manufacturer
1	CI-CHD	m	61	right	bilateral	32	left	unknown	41	15	MedEl
2	CI-CHD	f	75	right	bilateral	31	left	hereditary	57	30	Advanced Bionics
3	CI-CHD	f	39	right	bilateral	26	right	otosclerosis	24	17	Advanced Bionics
4	CI-CHD	f	70	right	bilateral	37	left	unknown	37	56	MedEl
5	CI-CHD	f	70	right	bilateral	37	left	meningitis	69	20	MedEl
6	CI-CHD	m	59	right	bimodal	85	left	unknown	49	33	Advanced Bionics
7	CI-CHD	f	63	right	bilateral	36	left	meningitis	20	106	Advanced Bionics
8	CI-CHD	f	64	right	bilateral	29	left	whooping cough	9	78	Cochlear
9	CI-CHD	m	53	right	bilateral	36	left	unknown	30	235	Cochlear
10	CI-CHD	f	58	right	bimodal	41	left	unknown	49	18	Advanced Bionics
11	CI-CHD	m	56	right	bilateral	35	right	hereditary	19	63	MedEl
12	CI-SSD	f	64	right	SSD	10	left	unknown	49	30	Cochlear
13	CI-SSD	f	40	right	SSD	10	right	sudden hearing loss	34	77	MedEl
14	CI-SSD	m	43	right	SSD	12	left	bike accident	42	12	Cochlear
15	CI-SSD	m	54	right	SSD	17	left	unknown	52	28	MedEl
16	CI-SSD	f	49	right	SSD	23	right	otosclerosis	39	19	MedEl
17	CI-SSD	m	59	left	SSD	17	left	sudden hearing loss	49	54	Cochlear
18	CI-SSD	f	57	right	SSD	12	left	sudden hearing loss	20	53	Cochlear
19	CI-SSD	m	62	right	SSD	13	left	sudden hearing loss	47	63	Cochlear
20	CI-SSD	f	62	right	SSD	15	left	otitis media	14	65	MedEl
21	CI-SSD	f	68	right	SSD	25	left	unknown	60	50	Cochlear
22	CI-SSD	f	52	right	SSD	22	left	hereditary	20	12	MedEl

MASSY (Modular Audiovisual Speech SYnthesizer; Fagel and Clemens, 2004), which is a computer-based video animation of a talking head. This talking head has been previously validated for CI users (Meister et al., 2016; Schreitmüller et al., 2018) and is an adequate tool to generate audiovisual and visual speech stimuli (Massaro and Light, 2004). To generate articulatory movements matching the auditory speech sounds, one has to provide files that transform the previously transcribed sounds into a probabilistic pronunciation model providing the segmentation and the timing of every single phoneme. This can be done by means of the web-based tool MAUS (Munich Automatic Segmentation; Schiel, 1999). To obtain a video file of the MASSY output, the screen recorder Bandicam (version 4.1.6) was used in order to save the finished video files. Finally, the stimuli were edited in Pinnacle Studio 22 (version 22.3.0.377), making video files of each syllable in each condition: 1) Audiovisual (AV): articulatory movements with corresponding auditory syllables, 2) Auditory-only (A): black screen (video track turned off) combined with auditory syllables, 3) Visual-only (V): articulatory movements without auditory syllables (audio track turned off). Each trial started with a static face (500 ms) and was followed by the video, which lasted for 800 ms (20 ms initiation of articulatory movements + 400 ms auditory syllable + 380 ms completion of articulatory movements). For further analyses, we focused on the moving face (starting 500 ms post-stimulus onset/after the static face), as the responses to static faces comparing NH listeners and CI users have been investigated previously (Stropahl et al., 2015).

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In general, all participants were assessed monaurally, meaning that in CI-SSD users the CI-ear was measured, in bimodal CI users the CI-ear was measured and in bilateral CI users the better CI-ear was measured. Regarding the *CI-SSD patients*, we followed the procedures of a previous study (Weglage et al., 2022) and positioned the processor inside an aqua case (Advanced Bionics; https://www.advancedbionics.com) to specifically stimulate the CI-ear without risking a cross-talking to the NH ear. Note that stimulation via a loudspeaker is not possible in this group, because an ear-plug is not enough to cover and mask the NH-ear, as it only reduces the intensity level by maximally 30 dB (Park et al., 2021). We refused the option of using noise to mask the NH ear, as this noise would have to be very loud to fully mask the information. This stimulation option would rather represent a speech-in-noise condition and would differ much more from the other two groups. An insert earphone (3M E-A-RTONE 3A) was put inside a hole of the aqua case where it was placed right over the microphone of the CI. A long coil cable was used to connect the processor with the implant. Regarding the *CI-CHD users*, the stimuli were presented via a loudspeaker (Audiometer-Box, type: LAB 501, Westra Electronic GmbH) which was placed in front of the participant. The hearing aid or the CI at the contralateral side was removed during the experiment and the ear was additionally covered with an ear-plug. For *NH participants*, the ear of the matched CI user was stimulated via an insert earphone (3M E-A-RTONE 3A), and the contralateral ear was closed with an ear-plug as well to avoid a cross-talking to the contralateral ear. The stimuli were calibrated to 65 dB SPL to ensure that the intensity level was equal for each stimulation technique. All participants rated the perceived loudness of the syllables with a seven-point loudness rating scale (as used in Sandmann et al., 2009, 2010), to ensure that the syllable intensity was perceived at a moderate level of 60− 70 dB (Allen et al., 1990). The stimuli (video files) are provided as supplementary material and can be downloaded.

2.3. Procedure

The procedure was identical to our previous study (see Layer et al., 2022). The additional CI-SSD users were seated comfortably in an electromagnetically shielded and dimly lit booth at a viewing distance of 175 cm to the screen. The participants were instructed to discriminate as fast and as accurately as possible between the syllables /ki/ and /ka/. The given response was registered using a mouse, with each of the two buttons assigned to one syllable. The sides were counterbalanced across the participants to prevent confounds caused by the used finger.

For each condition (AV, A, V, 'nostim'), 90 trials each were presented per syllable, resulting in a total number of 630 trials (90 repetitions x 3 conditions (AV, A, V) x 2 syllables (/ki/, /ka/) + 90 'nostim'-conditions). Each trial began with a 'nostim'-condition or a static face of the talking head (500 ms) followed by a visual-only, auditory-only or an audiovisual syllable. Afterwards, a fixation cross was shown until the participant pressed a button. In the case of a 'nostim'-trial, the participants were asked not to respond to. The trials were pseudo-randomised such that no trial of the same condition and syllable appeared twice in a row. The experiment lasted for 25 min excluding breaks, composed of five blocks of approximately 5 min each. A short break was given after each block. To ensure that the task was understood by the participants, we presented a short practice block consisting of five trials per condition before starting the recording. An illustration of the experimental paradigm can be found in Fig. 1A.

To obtain further behavioural measures apart from the ones registered in the EGG task (hit rates, response times), we asked the additionally measured CI-SSD users to rate the exertion of performing the task after each experimental block by using the 'Borg Rating of Perceived Exertion'-scale (Borg RPE-scale; Williams, 2017). Further, we measured the lip-reading abilities by means of a behavioural lip-reading test consisting of monosyllabic words from the German Freiburg test (Hahlbrock, 1970) which were visualised by various speakers and filmed (Stropahl et al., 2015). The participants were asked to watch the short videos of the muted monosyllabic word performances and to report which word was understood. This test was used in previous studies with CI patients (Stropahl et al., 2015; Stropahl and Debener, 2017), as well as in our previous study with CI-CHD users and NH listeners (Layer et al., 2022), whose scores we compared to CI-SSD users in the current study.

2.4. EEG recording

Similar to our previous study (Layer et al., 2022), the EEG data of the additionally measured CI-SSD users were continuously recorded by means of 64 AG/AgCl ActiCap slim electrodes using a BrainAmp system (BrainProducts, Gilching, Germany) and a customised electrode cap with an electrode layout (Easycap, Herrsching, Germany) according to the 10-10 system. To record an electrooculogram (EOG), two electrodes were placed below and beside the left eye (vertical and horizontal eye movements, respectively). The nose-tip was used as reference, and a midline electrode placed slightly anterior to Fz served as ground. Data recording was performed using a sampling rate of 1000 Hz. The online analog filter was set between 0.02 and 250 Hz. Electrode impedances were maintained below 10 k Ω during data acquisition.

2.5. Data analysis

The subset data taken from our previous study including the newly acquired data of the CI-SSD users were analysed in MATLAB 9.8.0.1323502 (R2020a; Mathworks, Natick, MA) and R (version 3.6.3; R Core Team (2020), Vienna, Austria). Topographic analyses were carried out in CARTOOL (version 3.91; Brunet et al., 2011). Source analyses were performed in Brainstorm (Tadel et al., 2011). The following R packages have been used: ggplot2 (version 2.3.3) for creating plots; dplyr (version 1.0.4), tidyverse (version 1.3.0) and tidyr (version 1.1.3) for data formatting; ggpubr (version 0.4.0) and rstatix (version 0.7.0) for statistical analyses.

2.5.1. Behavioural data

In a first step, we collapsed the syllables /ki/ and /ka/ for each condition (A, V, AV), as they did not show substantial differences between each other (mean RTs ± one standard deviation of the mean: CI-CHD: /ki/= 620 ms ± 88.3 ms, /ka/= 611 ms ± 88.0 ms; CI-SSD: /ki/=

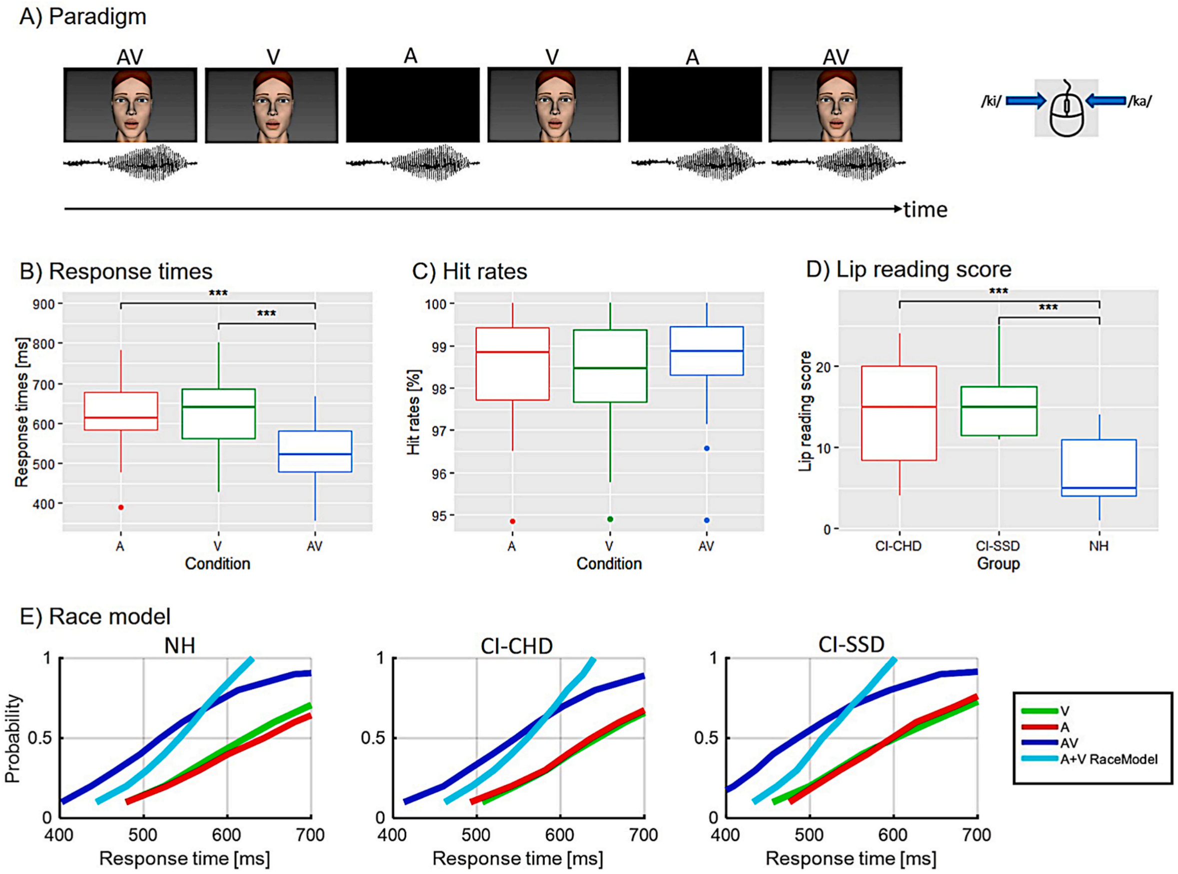

Fig. 1. Behavioural results. A) Overview of the paradigm (adapted from Layer et al., 2022). B) Mean response times for auditory (red), visual (green) and audiovisual (blue) syllables averaged over all groups, demonstrating that audiovisual syllables had shorter response times than auditory-only and visual-only RTs. C) Mean hit rates for auditory (red), visual (green) and audiovisual (blue) syllables averaged across all groups, with no differences between the three conditions. D) Cumulative distribution functions for CI-CHD, CI-SSD and NH. The race model is violated for all three groups because they show that the probability of faster response times is higher for audiovisual stimuli (blue line) than for those estimated by the race model (cyan line). Significant differences are indicated (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

574 ms ± 100.0 ms, /ka/= 566 ms ± 94.0; NH: /ki/= 607 ms ± 91.6 ms, /ka/= 587 ms ± 102.0 ms; all $p \geq 0.354$). Second, false alarms or missing responses were discarded from the dataset. Trials that exceeded the individual mean by more than three standard deviations for each condition were declared as outliers and were removed from the dataset. Then, RTs and hit rates were computed for each condition (A, V, AV) for each individual. To analyse the performance for each condition and group, a 3 x 3 mixed ANOVA was used separately for the RTs and the hit rates, with condition (AV, A, V) as the within-subjects factor and group (NH, CI-CHD, CI-SSD) as the between-subjects factor. In the case of violation of the sphericity assumption, a Greenhouse-Geisser correction was applied. Moreover, post-hoc t-tests were carried out and corrected for multiple comparisons using a Bonferroni correction, in the case of significant main effects or interactions ($p \leq .05$). As the hit rates were very high in our previous study (Layer et al., 2022), we did not expect CI-SSD users to deviate from this pattern. Concerning the RTs, we expected similar results for CI-SSD users as for CI-CHD users and NH listeners, with shorter RTs for AV conditions compared to unisensory (A, V) conditions.

In a next step, we analysed the origin of the redundant signals effect, which is the effect of achieving faster RTs for audiovisual stimuli in comparison to unimodal stimuli (A, V) (Miller, 1982). For this purpose, we reused a subset of our previously reported data of the CI-CHD users and NH listeners (Layer et al., 2022) and extended these by the additional group of CI-SSD users. There are two accounts explaining this issue: the race model (Raab, 1962) and the coactivation model (Miller, 1982). Briefly, the race model claims that due to statistical facilitation it is more probable that either of the stimuli (A and V) will result in shorter response times in comparison to one stimulus alone (A or V). Therefore, one can assume that RTs of redundant signals (AV) are significantly faster, and that no neural integration is required to observe a redundant signals effect (Raab, 1962). In contrast, the coactivation model (Miller, 1982) assumes an interaction between the unimodal stimuli which forms a new product before initiating a motor response, leading to faster RTs. A widely used method in multisensory research is to test for the race model inequality (RMI; Miller, 1982) to explain whether the redundant signals effect was caused by multisensory processes or by statistical facilitation. According to the RMI, the cumulative distribution function (CDF) of the RTs in the multisensory condition (AV) can never exceed the sum of the CDFs of the two unisensory (A, V) conditions:

$$P(RT_{\mathrm{AV}} \leq t) \leq P(RT_{\mathrm{A}} \leq t) + P(RT_{\mathrm{V}} \leq t), \quad \text{for all } t \leq 0,$$

where $P(RT_x \leq t)$ represents the likelihood of a condition $x \in \{\mathrm{AV}, \mathrm{A}, \mathrm{V}\}$ being less than an arbitrary value t. Violation of this model, for any given value of t, is an indication for multisensory processes (see also Ulrich et al. (2007) for details). By applying the RMITest software by Ulrich et al. (2007), the CDFs of the RT distributions for each condition (AV, A, V) and for the sum of the modality-specific conditions (A + V) were estimated. The individual RTs were rank ordered for each condition to obtain percentile values (Ratcliff, 1979). Next, for each group separately (NH, CI-CHD, CI-SSD), the CDFs for the redundant signals conditions (AV) and the modality-specific sum (A + V) were compared for the five fastest deciles (bin width: 10 %). We used one-tailed paired t-tests followed by a Bonferroni correction to account for multiple comparisons. Significance at any decile bin was treated as violation of the race model, suggesting multisensory interactions in the behavioural responses. Here, we expected a similar redundant signals effect for CI-SSD users, as CI-CHD users and NH listeners both showed a violation of the race model inequality in our previous study (Layer et al., 2022).

To assess differences between the CI user groups and the NH listeners in the lip-reading task and in the subjective rating of exertion, we performed one-way ANOVAs. Whenever a significant main effect of group was present, we performed follow-up tests with a Bonferroni correction to account for multiple comparisons. Concerning the lip-reading ability, we anticipated that CI-SSD users performed worse compared to CI-CHD users due to their intact contralateral ear, which may reduce the need to rely on lip movements in their everyday life. In terms of subjective exertion rating, we expected no difference between experimental groups because our previous study (Layer et al., 2022) found no difference, which was likely due to the easy task.

2.5.2. EEG pre-processing

The pre-processing of the EEG data was done with EEGLAB (version v2019.1; Delorme and Makeig, 2004), a software working within the MATLAB environment (Mathwork, Natick, MA). The raw data were down-sampled (500 Hz) and filtered with a FIR-filter, having a high pass cut-off frequency of 0.5 Hz with a maximum possible transition bandwidth of 1 Hz (cut-off frequency multiplied by two), and a low pass cut-off frequency of 40 Hz with a transition bandwidth of 2 Hz. For both filters, the Kaiser-window (Kaiser-$\beta = 5.653$, max. stopband attenuation $= -60$ dB, max. passband deviation $= 0.001$; Widmann et al., 2015) was used to maximise the energy concentration in the main lobe by averaging out noise in the spectrum and minimising information loss at the edges of the window. Electrodes in the proximity of the speech processor and transmitter coil were removed for CI users (mean: 2.8 electrodes; range: $1-4$). Afterwards, the datasets were epoched into 2 s dummy epoch segments, and pruned of unique, non-stereotype artefacts using an amplitude threshold criterion of four standard deviations. An independent component analysis (ICA) was computed (Bell and Sejnowski, 1995) and the resulting ICA weights were applied to the epoched original data ($1-40$ Hz, -200 to 1220 ms relative to the stimulus onset (including the static and moving face)). Independent components reflecting vertical and horizontal ocular movements, electrical heartbeat activity, as well as other sources of non-cerebral activity were rejected (Jung et al., 2000). Independent components exhibiting artefacts of the CI were identified based on the side of stimulation and the time course of the component activity, showing a pedestal artefact around 700 ms after the auditory stimulus onset (520 ms). The identified components were removed from the EEG data. In a next step, we interpolated the missing channels using a spherical spline interpolation (Perrin et al., 1989) which allows for a solid dipole source localisation of auditory ERPs in CI users (Debener et al., 2008; Sandmann et al., 2009). Only trials yielding correct responses (NH: 91.0 % ± 3.9 %; CI-CHD: 88.1 % ± 3.8 %; CI-SSD: 86.6 % ± 4.5 %) were kept for further ERP analyses.

2.5.3. EEG data analysis

We compared event-related potentials (ERPs) of all conditions (AV, A, V) between the two CI user groups and the NH participants. The additive model which is denoted by the equation $AV = A + V$ (Barth et al., 1995) was used to investigate multisensory interactions. The model is satisfied and suggests independent and linear processing if the multisensory (AV) responses equal the sum of the unisensory (A, V) responses. Whereas, if the model is not satisfied, non-linear interactions between the unisensory modalities are assumed (Barth et al., 1995). Similar to our previous study (Layer et al., 2022), we rearranged the equation to $A = AV - V$ such that we could compare the directly measured auditory ERP response (A) with the term [$AV - V$], denoting an ERP difference wave representing a visually-modulated auditory ERP response. Hence, [AV-V] is an estimate of an auditory response elicited in a multisensory context. In the case of a lack of interaction between the two unisensory (A, V) modalities, both A and AV-V should be identical. However, if the auditory (A) and the modulated auditory (AV-V) ERPs are *not* identical, this would point to non-linear multisensory interactions (Besle et al., 2004; Murray et al., 2005; Cappe et al., 2010; Foxe et al., 2000; Molholm et al., 2002). Such non-linear effects can be either super-additive ($A < AV - V$) or sub-additive ($A > AV - V$). But, since interpreting these effects is not straightforward, it is necessary to obtain reference-independent measurements of power or of source estimates (e.g. Cappe et al., 2010). Before creating the difference waves (AV-V), we randomly reduced the number of epochs based on the condition with the lowest number of epochs for each individual to guarantee that there was an equal contribution of each condition to the resulting difference wave. The difference waves were only created for the CI-SSD users in this study, and the difference waves for the NH listeners and CI-CHD users were reused from our previous study (Layer et al., 2022).

As in our previous study (Layer et al., 2022), we analysed our ERP data within an electrical neuroimaging framework (Murray et al., 2008; Michel et al., 2009; Michel and Murray, 2012), comprising topographic and ERP source analysis to compare auditory (A) and modulated (AV-V) ERPs within and between groups (NH, CI-CHD, CI-SSD). We investigated the global field power (GFP) and the global map dissimilarity (GMD) to quantify ERP differences in response strength and response topography, respectively (Murray et al., 2008). First, we looked at the GFP, at the time window of the N1 and the P2 (N1: $80-200$ ms; P2: $200-370$ ms), which were chosen based on visual inspection of the GFP computed for the grand average ERPs across conditions and groups. The GFP is the spatial standard deviation of all electrode values at a specific time point (Murray et al., 2008) and was first described by Lehmann and Skrandies (1980). The reason for choosing the GFP instead of selecting specific channels of interest is that this approach allows for a more objective peak detection. The GFP peak mean amplitudes and latencies were detected for each individual, condition (A, AV-V) and time window (N1, P2) and were statistically analysed by using a 3 x 2 mixed ANOVA with group (NH, CI-CHD, CI-SSD) as the between-subjects factor and condition (A, AV-V) as the within-subjects factor for each peak separately. Based on previous observations with CI-CHD users (Beynon et al., 2005; Finke et al., 2016a; Henkin et al., 2014; Sandmann et al., 2009; Layer et al., 2022) and CI-SSD users (Finke et al., 2016b; Bönitz et al., 2018; Weglage et al., 2022), we expected delayed N1 and reduced P2 responses for all CI user groups compared to NH controls.

Second, we analysed the GMD (Lehmann and Skrandies, 1980) to quantify topographic dissimilarities (and by extension, dissimilar configurations of neural sources; Vaughan Jr, 1982) between experimental conditions and groups, regardless of the signal strength (Murray et al., 2008). The GMD was analysed in CARTOOL by computing a 'topographic ANOVA' (TANOVA; Murray et al., 2008) to quantify differences in topographies between groups for each condition. Even though the name is misleading, this is no analysis of variance, but a non-parametric randomisation test. This randomisation test was executed with 5.000 permutations and by calculating sample-by-sample p-values. To control for multiple comparisons, an FDR correction was applied (FDR = false discovery rate; Benjamini and Hochberg, 1995). Since ERP topographies remain stable for a certain period of time before changing to another topography (called 'microstates'; Michel and Koenig, 2018) and to account for temporal autocorrelation, the minimal significant duration was adjusted to 15 consecutive time frames, corresponding to 30 ms.

2.5.4. Hierarchical clustering and single-subject fitting analysis

Whenever differences in topographies (GMD) for two groups or conditions are found, this is an indication for distinct neural generators contributing to these topographies (e.g. Vaughan Jr, 1982). However, it is also possible that a GMD is caused by a latency shift of the ERP, meaning that the same topographies are present but just shifted in time (Murray et al., 2008). To disentangle these two possible GMD causes, we performed a hierarchical topographic clustering analysis with group-averaged data (NH(A), NH(AV-A), CI-CHD(A), CI-CHD(AV-V), CI-SSD(A), CI-SSD(AV-V)) to identify template topographies within the time windows of interest (N1, P2). Again, we used CARTOOL for this analysis and chose the atomize and agglomerate hierarchical clustering (AAHC) which has been especially designed for ERP-data (detailed in Murray et al., 2008). This method includes the global explained variance of a cluster and prevents blind combinations (agglomerations) of short-duration clusters. Thus, this clustering method identifies the minimal number of topographies accounting for the greatest variance within a dataset (here NH(A), NH(AV-A), CI-CHD(A), CI-CHD(AV-V), CI-SSD(A), CI-SSD(AV-V)).

In a next step, the template maps detected by the AAHC were entered into a single-subject fitting (Murray et al., 2008) to identify the distribution of specific templates by calculating sample-wise spatial correlations for each individual and condition between each template topography and the observed voltage topographies. Each sample was matched to the template map with the largest spatial correlation. For statistical analyses, we focused on the *first onset of maps* (latency) and the *map presence* (number of samples in time frames) which are two of many other output options provided by CARTOOL. Particularly, we performed a mixed ANOVA with group (NH, CI-CHD, CI-SSD) as the between-subjects factor and condition (A, AV-V) and template map as within-subject factors, separately for each time window (N1, P2). In the case of significant three-way interactions, group-wise mixed ANOVAs (condition x template map) were computed. A Greenhouse-Geisser correction was applied whenever there was a violation of the sphericity assumption. Post-hoc t-tests were computed and corrected for multiple comparisons using a Bonferroni correction. We anticipated that the analysis of the first onset of maps would confirm a delayed N1 latency for both CI-CHD and CI-SSD users based on previous results. In terms of map presence at N1 latency range, we speculated that there would be a pattern between CI-CHD users and NH listeners for CI-SSD users, as they have both a CI and a NH ear. However, we are not aware of previous studies reporting similar results for CI-SSD users.

2.5.5. *Source analysis*

We performed an ERP source analysis for each group and condition by means of Brainstorm (Tadel et al., 2011) to find out whether topographic differences can be explained by fundamentally different configurations of neural generators. The tutorial provided by Stropahl et al. (2018) served as guideline for conducting the source analysis. As in our previous study (Layer et al., 2022) and in various studies with CI patients (Bottari et al., 2020; Stropahl et al., 2015; Stropahl and Debener, 2017), we selected the method of dynamic statistical parametric mapping (dSPM, Dale et al. (2000)). dSPM works more precisely in identifying deeper sources than standard norm methods, even though the spatial resolution stays relatively low (Lin et al., 2006). It takes the minimum-norm inverse maps with constrained dipole orientations to approximate the locations of electrical activity recorded on the scalp. This method can be successfully used to localise small cortical areas such as the auditory cortex (Stropahl et al., 2018). First, individual noise covariances were calculated from single-trial pre-stimulus onset baseline intervals (−50 to 0 ms) to estimate single-subject based noise standard deviations at each location (Hansen et al., 2010). As a head model, the boundary element method (BEM) which is implemented in OpenMEEG was used. The BEM gives three realistic layers and representative anatomical information (Gramfort et al., 2010). The final activity data is then displayed as absolute values with arbitrary units based on the normalisation within the dSPM algorithm. Consistent with the procedures of our previous study (Layer et al., 2022), we defined an *auditory* and a *visual* ROI by combining smaller regions within the Destrieux-atlas (Destrieux et al., 2010; Tadel et al., 2011; auditory: G_temp_sup-G_T_transv, S_temporal_transverse, G_temp_sup-Plan_tempo and Lat_Fis-post; visual: G_cuneus, S_calcarine, S_parieto_occipital). These ROIs were chosen in accordance with several previous studies (Stropahl et al., 2015; Stropahl and Debener, 2017; Giraud et al., 2001b, c; ; Prince et al., 2021; Layer et al., 2022). In specific, the chosen parts of the auditory ROI have been reported as both N1 (Näätänen and Picton, 1987; Godey et al., 2001; Woods et al., 1993; Bosnyak et al., 2004) and P2 (Crowley and Colrain, 2004 (for review)*;* Hari et al., 1987*;* Bosnyak et al., 2004; Ross and Tremblay, 2009) generators. The selected ROIs can be viewed in Fig. 4A.

Source activities for each ROI, condition and group were exported from Brainstorm for each participant. Afterwards, the peak means and latencies for each time window of interest (N1: 80 − 200 ms, P2: 200 − 370 ms) were extracted. A mixed-model ANOVA was performed separately for each time window with group (NH, CI-CHD, CI-SSD) as between-subject factor and condition (A, AV-V), ROI (auditory, visual) and hemisphere (left, right) as within-subjects factors. A Greenhouse-Geisser correction was applied in the case of violation of the sphericity assumption. In the case of significant interactions or main effects, post-hoc t-tests were computed and corrected for multiple comparisons using a Bonferroni correction. Similar to our hypotheses for the fitting data, we speculated that a pattern between the one of CI-CHD users and NH listeners would emerge for the recruitment of the visual cortex, which we observed for CI-CHD users in our previous study (Layer et al., 2022). In addition, in accordance with the fitting data and the GFP, we expected a delayed auditory cortex response for CI-SSD users as well. Finally, based on our previous study, we expected to find indications for multisensory processing, with different activity for AV-V compared to A for CI-SSD users, too.

3. Results

3.1. *Behavioural results*

Overall, all participants showed hit rates of ≥ 98 % in all conditions, and the mean RTs were between 504 ms and 638 ms (see Table 2). The 3 x 3 mixed ANOVA with condition (AV, A, V) as within-subject factor and group (CI-CHD, CI-SSD, NH) as between-subject factor revealed for RTs no main effect of group ($F_{2,30} = 1.06;\ p = .36, \eta p^2 = 0.058$) and no group × condition interaction, but a main effect of condition ($F_{1.31,39.3} = 100.63;\ p \leq .001, \eta p^2 = 0.31$). Follow-up post-hoc t-tests showed that RTs to redundant signals (AV) were significantly faster when compared to V ($t(32) = 12.4;\ p \leq .001$) or A ($t(32) = 20.3;\ p \leq .001$). There was no difference in RTs between the unisensory stimuli A and V ($t(32) = -0.84;\ p = 0.41$). These results are displayed in Fig. 1B.

For the hit rates, the 3 x 3 mixed ANOVA with condition (AV, A, V) as within-subject factor and group (CI-CHD, CI-SSD, NH) as between-subject factor showed no main effects or interactions (see Fig. 1C).

Concerning the race model, the one sample t-tests were significant in at least one decile for each group (see Table 3). This means that the likelihood of faster response times for redundant signals (AV) is higher than for those estimated by the race model (A + V). Fig. 1D displays the results of the race model. Overall, the violation of the race model in CI-CHD, CI-SSD users and NH listeners confirms the existence of multisensory integration in all tested groups.

For the other behavioural measures, we calculated one-way ANOVAs with subsequent t-tests to assess differences in *auditory word recognition ability* and *(visual) lip-reading abilities* between CI-CHD, CI-SSD users and

Table 2
Mean hit rates (in %) and mean response times (in ms).

Condition	Hit rates			Response times		
	NH	CI-CHD	CI-SSD	NH	CI-CHD	CI-SSD
A	99.0 ± 0.7	98.6 ± 1.1	98.1 ± 1.6	638 ± 84.1	623 ± 92.4	607 ± 79.4
V	98.5 ± 1.2	98.0 ± 1.3	98.5 ± 1.3	638 ± 98.4	623 ± 96.1	602 ± 87.7
AV	98.7 ± 1.0	98.3 ± 1.3	99.1 ± 0.8	526 ± 81.9	530 ± 89.4	504 ± 74.0

Table 3
Redundant signals and modality-specific sum in each decile. AV is the redundant signals condition. A + V is the modality-specific sum. Paired-samples one-tailed t-tests were conducted for each group (with Bonferroni correction for multiple comparisons). An asterisk indicates a statistically significant result ($p \le .05/5$).

Decile	NH			CI-CHD			CI-SSD		
	AV	A + V	p	AV	A + V	p	AV	A + V	p
.10	402	444	.000*	413	462	.000*	373	432	.000*
.20	437	480	.000*	460	494	.008*	409	461	.000*
.30	467	504	.000*	489	520	.014	435	484	.000*
.40	496	525	.003*	519	541	.056	456	450	.000*
.50	520	543	.011	547	560	.169	485	515	.000*

Table 4
Other behavioural measures for CI users and NH listeners. In the Freiburg monosyllabic word test and in the lip-reading test, a score of 100% means that all words have been repeated correctly. A higher value for the exertion rating means it was more effortful to perform the task (range: 6–20; 6 = no effort, 20 = highly effortful).

Group	Freiburg test (%)	Lip-reading test	Exertion rating
CI-CHD	70.9 ± 12.2	14.5 ± 6.7	12.5 ± 2.0
CI-SSD	71.4 ± 13.1	15.5 ± 4.4	12.2 ± 1.8
NH	98.2 ± 4.0	6.9 ± 4.7	11.9 ± 1.6

NH listeners. The ANOVAs showed a main effect of group for both the auditory word recognition ability ($F_{2,30} = 23.99$; $p < .001$, $\eta p^2 = 0.615$) and (visual) lip-reading abilities ($F_{2,30} = 8.6$; $p = .001$, $\eta p^2 = 0.364$). Follow-up t-tests revealed poorer speech recognition ability in the Freiburg monosyllabic test ($p \le .001$), but better lip-reading skills for all CI users when compared to NH listeners (CI-CHD vs. NH: $p = .002$, CI-SSD vs. NH: $p = .004$). There was no difference between the two CI-user groups (CI-CHD vs. CI-SSD: $p = 0.6$). Concerning the *subjective exertion* measured during the EEG task, the ANOVA did not show a difference between the CI-CHD, the CI-SSD users and NH listeners ($F_{2,30} = 0.25$; $p = 0.78$, $\eta p^2 = 0.016$). These results indicate that none of the tested groups perceived the task as more effortful than another group. The scores of these tests can be found in Table 4.

3.2. ERP results on the sensor level: GFP

In Fig. 2 the GFP of the grand averaged ERPs for the unisensory auditory (A) and the visually modulated auditory (AV-V) responses are shown for each group. Approximately between 120 and 140 ms, the first prominent peak is visible for all three groups. This peak fits into the time window of a N1 ERP. The next peak is around 240 ms and seems to be more prominent in NH listeners when compared to the two CI user groups. In the following, this peak is labelled as the P2 ERP. The GFP of the other conditions (V, AV) are also shown in the supplementary material (including the GMD between groups for each condition) to give an idea of the "raw," non-difference wave data. First, we calculated a 3 x 2 mixed ANOVA with group (NH, CI-CHD, CI-SSD) as between-subject variable and condition (A, AV-V) as within-subject factor for the N1 GFP peak mean amplitude and the GFP peak latency. For the *N1 peak amplitude*, no statistically significant main effects or interactions were found. However, the ANOVA with *N1 latency* revealed a significant main effect of group ($F_{2,30} = 4.76$; $p \le .05$, $\eta p^2 = 0.18$). Follow-up t-tests

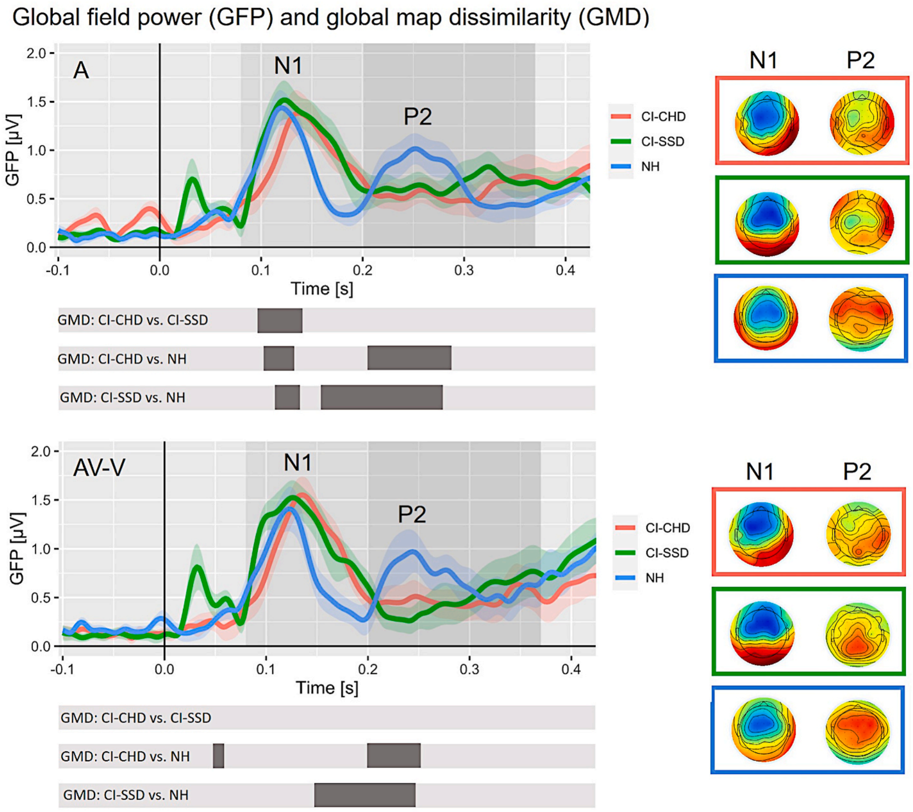

Fig. 2. ERP results on the sensor level. A) GFP of conditions A and AV-V for CI-CHD users (red), CI-SSD users (green) and NH listeners (blue), including standard error. It is important to note that the GFP only provides positive values because it represents the standard deviation across all electrodes separately for each time point. The ERP topographies at the GFP peaks (N1(A) = CI-CHD: 147 ms, CI-SSD: 136 ms, NH: 118 ms; N1(AV-V) = CI-CHD: 137 ms, CI-SSD: 135 ms, NH: 118 ms; P2(A) = CI-CHD: 305 ms, CI-SSD: 288 ms, NH: 256 ms; P2(AV-V) = CI-CHD: 284 ms, CI-SSD: 307 ms, NH: 245 ms) are given separately for each group (displayed on the right). The grey-shaded areas represent the N1 and P2 time windows for detecting peak and latency. The grey bars below represent the time window in which significant GMDs between the three groups were observed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

showed a prolonged N1 latency for both the CI-CHD ($t(21) = 3.14$; $p \leq .05$) and the CI-SSD users ($t(21) = 3.83$; $p \leq .05$) compared to NH individuals. There was no significant difference between the two CI groups ($t(21) = -0.03$; $p = .97$).

We performed the same 3 x 2 mixed ANOVA for the P2 GFP peak mean amplitude and latency. For both the P2 peak amplitude and latency, there was no significant main effects or interactions.

3.3. ERP results on the sensor level: GMD

The GMD was analysed sample-by-sample to identify if and when ERP topographies significantly differ between conditions and groups. We compared CI-CHD with NH listeners (CI-CHD vs. NH), CI-SSD with NH listeners (CI-SSD vs. NH) and both CI groups (CI-CHD vs. CI-SSD) *separately for each condition (A and AV-V)*. For the *auditory condition (A)*, the results revealed topographic differences for all group comparisons within the time window of the N1 (CI-CHD vs. NH: 90– 132 ms, CI-SSD vs. NH: 114 – 128 ms, CI-CHD vs. CI-SSD: 100 – 122 ms). Concerning the topographic differences within the P2 time window, there were no differences between the two groups of CI users, but we observed differences between the NH listeners and the two CI groups (CI-CHD vs. NH: 208 – 280 ms, CI-SSD vs. NH: 152 – 272 ms).

Regarding the GMD for the *modulated condition (AV-V)*, there was a difference between NH listeners and CI-CHD at the N1 time window (NH vs. CI-CHD: 104 – 126 ms). Within the P2 time window, again there were no differences between the two CI groups, however there were differences between the NH listeners and each CI group (CI-CHD vs. NH: 204 – 264 ms, CI-SSD vs. NH: 154 – 242 ms). In addition, the GMD duration at the P2 time window was shorter for AV-V compared to A. The exact durations displaying differences between the groups are illustrated in Fig. 2 (grey bars beneath the GFP plots).

3.4. ERP results on the sensor level: Hierarchical clustering and single-subject fitting results

To better understand the underlying topographic differences (i.e. GMD) between the three groups, we conducted a hierarchical topographic clustering analysis by using the group-averaged data (CI-CHD (A); CI-CHD(AV-V); CI-SSD(A); CI-SSD(AV-V); NH(A); NH(AV-V)) in order to find template topographies within the N1 and P2 time windows. For that purpose, we chose a segment ranging from −100 ms to 470 ms (50–235 time frames). Specifically, we employed the atomize and agglomerate hierarchical clustering (AAHC) to identify the minimal amount of topographies that can explain the variance in our data set as best as possible. This method detected 17 template maps in 18 clusters that explained 88.08 % of all data. To be precise, we detected two maps within the N1 time window (map A and Map B) and three prominent maps within the P2 time window (Map C, Map D, Map E). With these template maps, we performed a single-subject analysis (Murray et al., 2008) to determine how well each of the template maps spatially correlated with the data from each participant. As the *template Map B* matches the topography from a conventional N1 peak (Fig. 2; Finke et al., 2016a; Sandmann et al., 2015), this template map will be referred to as N1 topography hereafter. *Template Map C* looks like a typical P2 topography (Fig. 2; Finke et al., 2016a; Schierholz et al., 2021) and therefore we will refer to this template map as the P2 topography. The *template Map E* is particularly prominent in the two CI-user groups and will be referred to as P2-like topography due to its similarity to the P2 topography (Fig. 2).

Dissimilarities within the topography across groups and conditions (see section 'ERP results on the sensor level: GMD') can be explained by a latency shift of the ERPs and/or by distinct neural generator configurations. To shed light on the origin of these differences, we analysed the *first onset of maps* and the *map presence* for the N1 and the P2 time windows. These results are presented in the following two subsections.

3.4.1. N1 time window

On the *descriptive level*, the CI-CHD users showed a map A and a Map B (= N1 topography) which were both present in the auditory-only condition (A; number of samples map A: 18.3 ± 18.6; Map B: 30.5 ± 19.0). Interestingly, specifically in the modulated condition (AV-V), the Map B (= N1 topography) was clearly more frequent compared to map A (number of samples 39.9 ± 18.2 (Map B) vs. 9.27 ± 16.6 (map A)). By contrast, both the NH listeners and the CI-SSD users showed a greater presence of Map B (= N1 topography) in general, irrespective of condition (A: number of samples: NH 40.8 ± 10.8; CI-SSD 48.0 ± 6.71; AV-V: number of samples: NH 36.9 ± 12.5; CI-SSD 47.5 ± 8.26).

To obtain an explanation for a potential ERP latency shift, we statistically analysed the *first onset of maps* by using a mixed-model ANOVA with group (NH, CI-CHD; CI-SSD) as the between-subjects factor and condition (A, AV-V) and template map as the within-subject factors for the N1 time window. The three-way mixed ANOVA revealed a significant group × map interaction ($F_{2,29} = 13.4$; $p \leq .001$, $\eta p^2 = 0.39$). Follow-up t-tests showed that the onset of Map B (=N1 topography) was earlier in the NH listeners when compared with the CI-CHD ($t(20) = 3.82$; $p \leq .01$) and the CI-SSD ($t(21) = 6.75$; $p \leq .001$). There was no group difference in the onset of the N1 topography between CI-CHD and CI-SSD ($t(20) = -0.54$; $p = .6$). The results suggest that the N1 is generated later in CI users compared to NH individuals, regardless of the hearing threshold of the contralateral ear.

Second, we statistically analysed the number of time frames of the maps that showed the highest spatial correlations to the single-subject data, i.e. the *map presence*. This variable can provide an explanation for potentially distinct underlying neural generators between the three groups (CI-CHD, CI-SSD, NH) and the two conditions (A, AV-V). As above, we calculated a mixed-model ANOVA with group (NH, CI-CHD, CI-SSD) as the between-subjects factor and condition (A, AV-V) and template map as the within-subjects factors for the N1 time window.

For the N1 template maps, the ANOVA results showed a group x map × condition interaction ($F_{2,30} = 7.12$; $p \leq .005, \eta p^2 = 0.04$). Post-hoc t-tests revealed for the CI-CHD users, but not for the CI-SSD users or NH listeners, that the presence of Map B (=N1 topography) was significantly *enhanced* for the modulated (AV-V) compared to the auditory-only (A) condition ($t(10) = -2.85$; $p \leq .05$). These results are illustrated in Fig. 3A. Given that template Map B corresponds to a conventional N1 topography, the results suggest that CI-CHD users in specific generate a N1 ERP map for the modulated response (AV-V) more frequently compared to the unisensory (A) condition. This visual modulation effect at the N1 latency was not observable for the NH listeners and the CI-SSD users.

Taken together, our results for the N1 on the *first onset of maps* and the *map presence* suggest that the observed topographic group differences at N1 latency can be explained by the following two reasons: 1) there are generally delayed cortical N1 ERPs in CI users, regardless of the condition (auditory-only or modulated response) and regardless of whether these patients have unilateral or bilateral hearing loss, and 2) there is a distinct pattern of ERP topographies specifically for the CI-CHD users compared to NH listeners and CI-SSD users. The visual modulation effect in the N1 topography was only observed for CI-CHD users, which suggests that this CI group in particular has a strong visual impact on auditory speech processing. By contrast, the visual impact in the CI-SSD users seems to be less pronounced and appears to be comparable to the NH listeners.

3.4.2. P2 time window

Similar to the analysis on the N1 time window, we analysed the *first onset of maps* by using a mixed-model ANOVA with group (NH, CI-CHD; CI-SSD) as the between-subjects factor and condition (A, AV-V) and template map as the within-subject factors for the P2 time window. The results did not reveal any significant main effects or interactions.

In a second step, we analysed the *map presence* for the P2 time window. As above, we calculated a mixed-model ANOVA with group

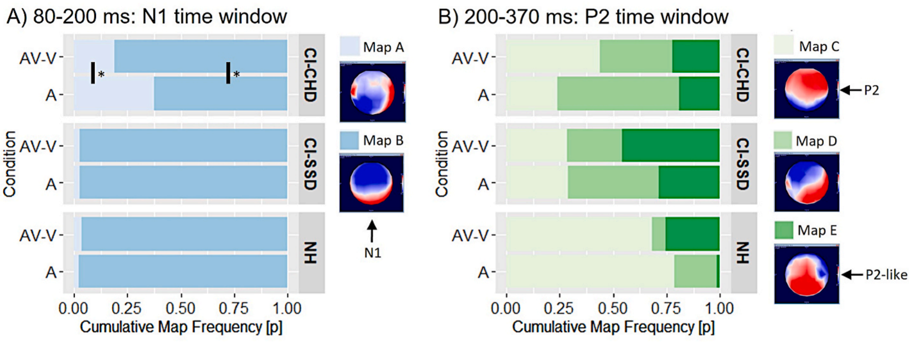

Fig. 3. Results from the hierarchical clustering and the single-subject fitting. A) Cumulative map frequency of the N1 maps: the CI-CHD users, but not the NH listeners or CI-SSD users, show a condition effect, with more frequent N1 map presence for AV-V compared to A. The corresponding map topographies are displayed on the right side, with Map B being referred to as the N1 topography. B) Cumulative map frequency of the P2 maps: there is a group effects (independent of the condition): NH listeners reveal a more frequent presence of a P2 topography (Map C) compared to CI-SSD users, and CI-SSD users show a more frequent presence of a P2-like topography (Map E) compared to NH listeners. CI-CHD users show a more frequent presence of Map D compared to NH listeners. Additionally, there is a condition effect (independent of the group): The presence of the P2-like topography (Map E) is enhanced for AV-V compared to A. This suggests a visual modulation of auditory speech processing at P2 latency in all groups. Significant differences are indicated (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

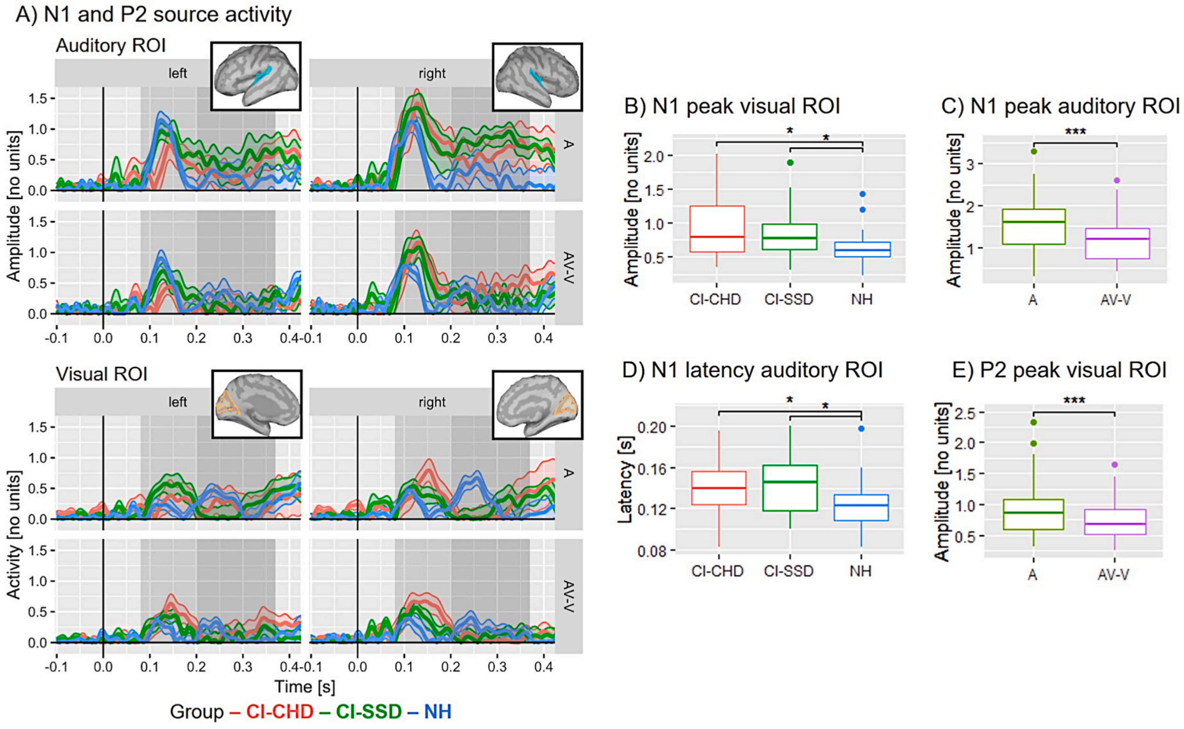

Fig. 4. ERP results on the source level. A) N1 and P2 source activity for CI users (red), CI-SSD users (green) and NH listeners (blue) separately for each ROI and each hemisphere with standard error (standard error shading was capped at zero). The source activity is displayed as absolute values with arbitrary units based on the normalisation within Brainstorm's dSPM algorithm. The grey shaded areas mark the N1 (light grey) and the P2 (dark grey) time windows. The boxes depict the location of the defined ROIs, with auditory ROIs in blue and visual ROIs in yellow. B) Group effect of the N1 peak mean in the visual cortex: both CI-CHD and CI-SSD users show more activity in the visual cortex compared to NH listeners, regardless of condition. C) Condition effect of the N1 peak mean in the auditory cortex: there is a significantly reduced auditory-cortex activation for AV-V compared to A, indicating multisensory interactions in all groups. D) N1 latency effect in the auditory cortex: Both CI and CI-SSD users show a prolonged N1 latency compared to NH listeners in the auditory cortex, regardless of the condition. This suggests a delayed auditory-cortex activation in CI users, independent of the hearing threshold in the contralateral ear. E) P2 condition effect in the visual cortex: there is a significantly reduced visual-cortex activation for AV-V compared to A, pointing towards multisensory interactions in all groups. Significant differences are indicated (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(NH, CI-CHD, CI-SSD) as the between-subjects factor and condition (A, AV-V) and template map as the within-subjects factors for the P2 time window. The three-way mixed ANOVA showed a significant group x map ($F_{4,60} = 3.47$; $p \leq .05, \eta p^2 = 0.12$) and a condition x map ($F_{2,60} = 3.41$; $p \leq .05$, $\eta p^2 = 0.03$) interaction. For the group × condition interaction, follow-up t-tests revealed for the NH listeners a significantly enhanced presence of Map C (= P2 topography) compared to CI-SSD users ($t(21) = -3.18$; $p \leq .01$). Vice versa, CI-SSD users showed a significantly enhanced presence of Map E (= P2-like topography) compared to NH listeners ($t(21) = 3.65$; $p \leq .01$), regardless of the condition. Finally, for Map D, there was a significant difference between CI-CHD users and NH individuals ($t(21) = 3.46$; $p \leq .01$), with CI-CHD users showing a more dominant presence of this map compared to NH controls. These results are shown in Fig. 3B. Following the condition × map interaction, follow-up t-tests revealed significant differences between A and AV-V only for Map E ($t(32) = -2.5$; $p \leq .01$). This result suggests that a P2-like topography (Map E) is generated more often for modulated responses (AV-V) compared to unmodulated responses (A), which is shown in Fig. 3B.

In sum, our results about the *first onset of maps* and the *map presence* at *P2 latency* suggest group-specific topographic differences at P2 latency, with a stronger presence of a conventional P2 topography (Map C) in NH listeners compared to CI-SSD users and a stronger presence of the P2-like topography (Map E) in CI-SSD users compared to NH listeners. Together with the observation that Map D is more present in CI-CHD users than in NH listeners, these results confirm our GMD results, showing a significant group difference between NH listeners and the two CI-user groups for both conditions (A, AV-V) at P2 latency (Fig. 2). Finally, all groups show a P2-like topography (Map E) that is more frequent in the modulated than in the auditory-only condition, which points to alterations in the cortical processing at P2 latency due to the additional visual information in the speech signal.

3.5. *Results from ERP source analysis*

We conducted a source analysis to further analyse the differences between the three groups, focusing on the auditory and visual cortex activity in both hemispheres. Single-subject source activities for each ROI, condition and group were exported from Brainstorm and were statistically analysed. The source waveforms for the N1 and the P2 are illustrated in Fig. 4A, showing the response in the auditory cortex (N1 peak latency mean: CI-CHD = 141 ms ± 27 ms; CI-SSD = 143 ms ± 28 ms; NH = 122 ms ± 22 ms) and in the visual cortex (N1 peak latency mean: CI-CHD = 143 ms ± 29 ms; CI-SSD = 136 ms ± 28 ms; NH = 136 ms ± 35 ms) for all groups. The peak mean amplitudes and latencies were the dependent variables for the following ANOVA. We performed a mixed-model ANOVA with group (NH, CI-CHD, CI-SSD) as the between-subjects factor and condition (A, AV-V) and hemisphere (left, right) as the within-subject factors for each time window of interest (N1, P2) and each ROI (auditory, visual) separately.

Concerning the N1 *peak mean* in the *visual cortex*, the mixed-model ANOVA showed a significant main effect of group ($F_{2,30} = 4.39$; $p \leq .05, \eta p^2 = 0.15$). Post-hoc t-tests confirmed a significant difference between the NH listeners and both CI groups (NH vs. CI-CHD: $t(21) = 3.01$; $p \leq .05$; NH vs. CI-SSD: $t(21) = 3.18$; $p \leq .05$), but no difference between the two CI groups (CI-CHD vs. CI-SSD: $t(21) = -0.24$; $p = 0.81$). Thus, both CI user groups showed more recruitment of the visual cortex compared to NH listeners, regardless of hemisphere and condition (see Fig. 4B).

For the N1 *peak mean* in the *auditory cortex*, the mixed-model ANOVA revealed a significant main effect of hemisphere ($F_{1,29} = 9.46$; $p \leq .005$, $\eta p^2 = 0.11$) and a significant main effect of condition ($F_{1,29} = 34.25$; $p \leq .001, \eta p^2 = 0.11$). Resolving the main effect of hemisphere, follow-up t-tests showed a greater amplitude for the right hemisphere compared to the left hemisphere ($t(63) = -3.66$; $p \leq .001$), regardless of group and condition. Following the main effect of condition, the subsequent t-tests revealed reduced amplitudes for AV-V compared to A ($t(64) = 5.95$; $p \leq .001$), regardless of hemisphere and group, which points to multisensory interaction processes (see Fig. 4C).

For the N1 *peak latency* in the *auditory cortex*, the mixed-model ANOVA identified a significant main effect of group ($F_{2,29} = 4.31$; $p \leq .05, \eta p^2 = 0.13$) and a significant main effect of hemisphere ($F_{1,29} = 5.68$; $p \leq .05, \eta p^2 = 0.02$). Following the main effect of hemisphere, the post-hoc *t*-test revealed a significant difference between the left and the right auditory cortex ($t(63) = 2.20$; $p \leq .05$) with the right hemisphere showing faster latencies compared to the left hemisphere. Resolving the main effect of group, follow-up t-tests revealed a significantly shorter latency of the auditory-cortex response in the NH listeners compared to both CI groups (NH vs. CI-CHD: $t(21) = 5.64$; $p \leq .001$; NH vs. CI-SSD: $t(21) = 6.01$; $p \leq .001$), but no difference between the two CI groups (CI-CHD vs. CI-SSD: $t(21) = -0.20$; $p = 0.80$). Hence, both CI user groups showed a delayed auditory-cortex response compared to NH listeners, regardless of hemisphere and condition (see Fig. 4C). For the N1 *peak latency* in the *visual cortex*, the mixed-model ANOVA did not show any significant main effects or interactions.

Concerning the P2 *peak mean* in the *auditory cortex*, the mixed-model ANOVA found a significant main effect of condition ($F_{1,29} = 11.25$; $p \leq .01, \eta p^2 = 0.04$). Resolving this main effect, the post-hoc t-tests revealed a significant difference between A and AV-V ($t(64) = 2.9$; $p \leq .005$), with A showing greater amplitudes than AV-V, regardless of group and hemisphere. This points to multisensory interaction processes in the auditory cortex at P2 latency.

For the P2 *peak mean* in the *visual cortex*, the mixed-model ANOVA found a significant main effect of condition ($F_{1,30} = 17.06$; $p \leq .001$, $\eta p^2 = 0.06$) as well. Follow-up t-tests revealed a significant difference between A and AV-V ($t(65) = 3.92$; $p \leq .001$), with A showing greater amplitudes than AV-V, regardless of group and hemisphere. This points to multisensory interaction processes in the visual cortex at P2 latency as well (see Fig. 4E).

Regarding the P2 *peak latency* in the *auditory and visual cortices*, the mixed-model ANOVA found neither significant main effects nor significant interactions.

3.6. *Correlations*

We performed correlations for each CI user group (CI-SSD and CI-CHD), using the Pearson's correlation and the Benjamini-Hochberg (BH) procedure to control for multiple comparisons (Benjamini and Hochberg, 1995). First, we wanted to check whether lip-reading abilities are related to the CI experience and the age at onset of hearing loss (Stropahl et al., 2015; Stropahl and Debener, 2017; Layer et al., 2022). The results revealed a trend for a positive relationship between lip-reading abilities and CI experience (CI-CHD: $r = 0.51$; $p = 0.038$; p corrected = 0.076; CI-SSD: $r = 0.47$; $p = 0.12$; p corrected = 0.147) and a negative relationship between lip-reading abilities and the age of onset of hearing loss for both CI user groups (CI-CHD: $r = -0.84$; $p = 0.001$; *p corrected* = 0.005; CI-SSD: $r = -0.69$; $p = 0.01$; *p corrected* = 0.027). Thus, for both CI user groups it holds that the earlier the onset of hearing impairments, the more pronounced are the lip-reading abilities. Moreover, we aimed to reproduce the relationship between CI experience and the activation in the visual cortex (Giraud et al., 2001c; Layer et al., 2022). The results did not reach a significance level ($CI - CHD : r = 0.51$; $p = 0.1$; $p\ corrected = 0.16$; $CI - SSD : r = 0.34$; $p = 0.29$; $p\ corrected = 0.29$).

4. Discussion

In this follow-up study, we used behavioural and EEG measures to investigate audiovisual interactions in CI users with unilateral (CI-SSD) and bilateral (CI-CHD) hearing loss and in a group of NH controls. This study was conducted to extend the results from our previous study comparing CI-CHD users with NH listeners (Layer et al., 2022), by including a third group of participants; namely the CI-SSD users. A subset of our previously reported data was reused and compared to the additional group of CI-SSD users. The inclusion of the additional group of patients significantly extends our previous study because it not only examines the transferability of our previous findings to different CI patient groups, but also provides valuable insights into the influence of individual factors - specifically the hearing ability of the second ear - on audiovisual speech processing in CI users.

At the behavioural level, we confirmed multisensory interactions for all three groups, as evidenced by the shortened response times for the audiovisual condition compared to each of the two unisensory conditions (Fig. 1B) and by the violation of the race model (Fig. 1E). This was in line with the ERP analyses, confirming a multisensory effect for all groups by exhibiting a reduced activation in the auditory and visual cortex for the modulated (AV-V) response compared to the auditory-only (A) response at both the N1 and P2 latencies (Fig. 4C and E, respectively). In addition to this multisensory effect across all groups, we found group-specific differences. First, specifically the group of CI-CHD users, showed a change of N1 voltage topographies when additional visual information accompanied the auditory information (Fig. 3A), which suggests a particularly strong visual impact on auditory speech processing in CI users with bilateral hearing loss. Second, both groups of CI users revealed a delayed auditory-cortex activation (Fig. 4D), enhanced lip-reading abilities (Fig. 1D) and stronger visual-cortex activation (Fig. 4B) when compared to the NH controls. Thus, the current results extend the results of our previous study (Layer et al., 2022) by showing distinct multisensory processes not only between NH listeners and CI users in general, but even between CI users with unilateral (CI-SSD) and bilateral (CI-CHD) hearing loss.

4.1. *Behavioural multisensory integration in all groups*

The behavioural results revealed that both the NH listeners and the two CI user groups had faster reaction times for audiovisual syllables than for unisensory (auditory-alone, visual-alone) syllables (Fig. 1; Table 2). No difference was found between the auditory and visual conditions. Hence, all groups exhibited a clear redundant signals effect for audiovisual syllables, implying that the benefit of cross-modal input is comparable between the CI user groups and NH listeners on a behavioural level (Laurienti et al., 2004; Schierholz et al., 2015; Layer et al., 2022), at least when considering syllables that are combined with a talking head. The violation of the race model for each group (CI-CHD, CI-SSD, NH) suggests that multisensory integration was the cause for the observed redundant signals effect in both CI user groups and NH listeners. However, the behavioural responses of the CI users were not slower compared to the NH listeners, even though the signal provided by the CI is known to be limited in comparison to a natural hearing experience (Drennan and Rubinstein, 2008). The observation of comparable response times in CI users can be explained by the fact that there were only two syllables, and that the difficulty of the task was correspondingly low. Compatible with this, all groups were equally able to perform the task, and the subjective rating of the listening effort showed no difference between the groups.

One would assume that the CI users might be better and faster at identifying the purely visual syllables due to results from previous studies with congenitally deaf individuals and CI users, showing visual enhancements, in particular visually induced activation in the auditory cortex (Bottari et al., 2014; Finney et al., 2003; Hauthal et al., 2014; Bavelier and Neville, 2002; Heimler et al., 2014; Sandmann et al., 2012). This cross-modal activation seems to be driven by auditory deprivation and might form the neural basis for specific superior visual abilities (Lomber et al., 2010). Importantly, auditory impairment is not only experienced in CI users before receiving a CI, but also after the implantation when only a limited auditory input is provided by the CI. Thus, it is not surprising that CI users reveal compensatory visual strategies, such as enhanced lip-reading abilities, in order to overcome the limited CI signal (Rouger et al., 2007; Schreitmüller et al., 2018; Stropahl et al., 2015; Stropahl and Debener, 2017). Our results extend previous observations of enhanced visual abilities in CI users by showing that not only CI-CHD users, but surprisingly also CI-SSD users demonstrate a better lip-reading ability when compared to NH listeners. Importantly, the lip-reading ability was comparable between the two patient groups, and both groups showed a positive correlation with the age of the onset of hearing loss, indicating that an earlier onset of hearing loss triggers improved behavioural visual abilities. Our results demonstrate that this visual improvement develops across different groups of CI patients, independent of the hearing abilities of the contralateral ear.

However, behavioural visual improvements in CI users seem to be stimulus- and task-specific, as indicated by our finding that the two CI user groups showed comparable behavioural results to NH listeners in the speeded response task. Our finding is consistent with previous studies, using a speeded response task with simple tones and white discs as auditory and visual stimuli, respectively (Schierholz et al., 2015, 2017). It seems that in our study the task with the basic stimuli and the two syllables was too easy, leading to ceiling effects in all groups. This estimation is in line with our observation that the perceived exertion effort was comparable between all three groups. Importantly, behavioural group differences have well been reported in a previous study using more complex stimuli presented in the context of a difficult recognition paradigm, showing an enhanced audiovisual gain in CI users when compared to NH listeners (Radecke et al., 2022). This is consistent with the view that behavioural advantages due to additional visual information in CI users are task- and stimulus-selective, and that they become evident under specific circumstances, for instance in conditions with semantic information (Moody-Antonio et al., 2005; Rouger et al., 2008; Tremblay et al., 2010; Radecke et al., 2022). Thus, future studies should use linguistically complex stimuli, such as words or sentences presented in auditory, visual and audiovisual conditions, in order to better understand the behavioural advantages for visual and audiovisual speech conditions in CI users compared to NH individuals.

4.2. *Electrophysiological correlates of multisensory speech perception*

Similar to the behavioural data, we also discovered commonalities among groups at the ERP level. Nonetheless, group differences were found as well, which will be discussed in the following sections.

4.2.1. *Group similarities in multisensory speech processing*

Similar to the behavioural results, we found evidence for multisensory effects in the ERP responses. The topographic clustering analysis with subsequent single-subject fitting confirmed multisensory interactions for both CI user groups and NH individuals by revealing an increase in *P2-like topographies* for the modulated ERPs (AV-V) compared to the purely auditory condition (A). This observation points to a visual modulation of the auditory ERPs in the two CI user groups as well as in the NH individuals.

These findings are supported by the source analysis. Specifically, we investigated the visual impact on the auditory cortical response by comparing the ERPs of the auditory condition (A) with the visually modulated ERPs (AV-V). A difference between these two conditions can be seen as evidence for non-linear multisensory interactions (Besle et al., 2004; Murray et al., 2005; Cappe et al., 2010; Foxe et al., 2000; Molholm et al., 2002). As previous studies have shown, a difference between two conditions can either be superadditive ($A < AV - V$; e.g. Schierholz et al., 2015) or subadditive ($A > AV - V$; e.g. Cappe et al., 2010) (Stevenson et al., 2014). Our source analyses confirmed the multisensory interactions in all groups, both within the N1 and the P2 time windows by demonstrating a subadditive effect, indicated by a reduced activation in the auditory cortex for the modulated (AV-V) compared to the auditory-only (A) condition. A similar subadditive effect was even observed for the visual cortex at P2 latency in all groups. In sum, these findings are highly consistent with the results from other ERP studies (e.g. Cappe et al., 2010) as well as fMRI studies (e.g. Martuzzi et al., 2007), showing multisensory interactions in both the auditory and visual cortex and confirming the behavioural results of multisensory integration for all groups.

4.2.2. *Group differences in multisensory speech processing*

As measured by global field power (GFP), the signal strength of cortical responses did not differ between the two CI user groups and the NH listeners. Nevertheless, for the response topography, as quantified by the global map dissimilarity (GMD), we detected various differences between CI-CHD, CI-SSD and NH listeners for both the auditory-only condition (A) and the modulated response (AV-V). Thus, group differences were not caused by signal strength but rather by differences in their electric field topographies and by extension the configuration of active brain networks. To ascertain whether distinct topographies were caused by a simple latency shift of the ERP responses and/or by variable configurations of the neural sources, we conducted various analyses, in particular hierarchical clustering, single-subject fitting and source analysis.

Within the N1 time window, hierarchical clustering and single-subject fitting showed specifically for the CI-CHD users – but not for CI-SSD users and not for NH listeners – a greater presence of N1 topographies (Map B) for modulated responses (AV-V) compared to purely auditory responses (A). The difference in N1 topography between CI-CHD users and NH listeners was already reported in our previous study (Layer et al., 2022), which was now expanded by including a group of CI-SSD users. Interestingly, the NH listeners and CI-SSD users showed no differences in map presence between auditory and modulated responses, indicating that these two groups use similar neural processes to evaluate the audiovisual speech stimuli. An increasing presence of a conventional N1 topography (Map B) specifically for the modulated condition indicates alterations in audiovisual processing and a multisensory benefit for CI-CHD users, when additional visual information is present. This modulation in CI-CHD users reflects most likely a strategy that they develop to compensate for the limited CI input. Interestingly, this modulation was not detected in CI-SSD users, which leads to the assumption that CI-CHD have a higher benefit from additional visual input compared to CI-SSD users. This group-specific effect may be due to the fact that CI-SSD users have a NH ear on the contralateral side which might serve as the main communication channel. Therefore, it is not surprising that CI-SSD users and NH listeners show comparable topographic results, at least within the N1 latency range. Previous research comparing different groups of CI users is limited. Nevertheless, first evidence of differences in speech-in-noise performance between CI-SSD users and bimodal CI users (CI on one ear and hearing aid on the contralateral ear) was reported (Williges et al., 2019). On the other hand, differences between CI-SSD users and bilateral CI users (both ears fitted with CIs) were observed in situations with multiple concurrent speakers (Bernstein et al., 2016). As a result, we expected group differences to emerge not only for auditory stimulation but also for audiovisual stimulation. However, as far as we are aware, this has not been investigated yet. Our results therefore indeed confirm first indications of different processing strategies among different CI user groups.

Given that our results are restricted to the processing of syllables, we propose that further studies should use more complex speech stimuli in order to refine and deepen the current findings about different groups of CI users. Similar to the current analyses, future studies should apply electrical neuroimaging (Michel et al., 2009), including topographic and ERP source analysis, given that it is a powerful approach to investigate multisensory interactions (Stevenson et al., 2014). It is likely that the testing of CI-CHD in more complex speech conditions, in particular with semantic information, results in even more enhanced cortical audiovisual interactions (Radecke et al., 2022), as can be assumed based on previous behavioural results (Moody-Antonio et al., 2005; Rouger et al., 2008; Tremblay et al., 2010). We speculate that in these demanding stimulus conditions, an increase in audiovisual interactions may become even detectable in the group CI-SSD users.

Apart from this modulation effect, which was specific for CI-CHD users, we found generally delayed cortical responses for both CI user groups compared to NH listeners, which was consistently reflected in various analyses. On the sensor level, ERP data revealed that both CI-CHD users and CI-SSD users had a prolonged N1 latency compared to NH listeners for both the modulated and the auditory-only responses. By comparing the first onset of Map B (N1 topography) between the three groups of participants, hierarchical clustering and single-subject fitting analyses confirmed the delayed onset of the N1 topography in the two groups of CI users. Similarly, the source analysis revealed a delayed N1 response in the auditory cortex for both CI-CHD and CI-SSD users compared to NH listeners. In fact, since the signal does not have to pass through the middle and inner ear due to direct stimulation of auditory nerve fibres, one might assume that the time until the electrical signal reaches the auditory nerve with a CI is faster than in NH listeners. Interestingly, Schierholz et al. (2017) discovered delayed cortical responses not only in patients with a CI, but also in patients with an auditory brainstem implant (ABI; direct stimulation of the cochlear nucleus) and an auditory midbrain implant (AMI; direct stimulation of the inferior colliculus). Despite the fact that central auditory implants bypass more structures than CIs, ABI and AMI patients showed even more delayed cortical and poorer behavioural responses when compared to CI patients, appearing to be specifically related to the insufficient input provided by central auditory implants (Schierholz et al., 2017). Analogously, delayed N1 ERP responses in CI users are likely to reflect difficulties in processing speech sounds with the CI compared to natural hearing. In line with this, previous research with NH listeners has shown that difficult acoustic listening conditions, such as speech in background noise, cause a delay in the N1 response (Billings et al., 2011; Finke et al., 2016a). Furthermore, our findings of slowed cortical N1 ERPs in CI users are consistent with the findings of several other studies which used auditory stimuli of varying acoustic complexity, and which showed delayed N1 latency and poorer auditory discrimination ability in CI-CHD users compared to NH listeners (Beynon et al., 2005; Finke et al., 2016a; Sandmann et al., 2009, 2015; Senkowski et al., 2014). This is also an observation that has been reported in studies with CI-SSD users comparing the cortical responses from the CI ear and the NH ear (Finke et al., 2016b; Weglage et al., 2022).

To sum up, the results on the N1 ERPs revealed several group differences. First, the hierarchical clustering and single-subject fitting analyses showed a *condition effect* specifically for the group of CI-CHD users, showing distinct patterns of N1 topography between the modulated auditory response (AV-V) and the auditory-only response (A; Fig. 3A). However, for both the CI-SSD users and the NH listeners, such a modulation was not given, which leads to the conclusion that these two groups do not benefit from additional visual input to the same extent as CI-CHD users. CI-CHD users seem to have a particularly strong visual impact on auditory speech processing, allowing these individuals to compensate the limited CI input. By contrast, CI-SSD users appear to be less dependent on additional visual input, probably due to the fact that they can rely on the contralateral ear, which is normal-hearing.

Apart from the CI-CHD-specific condition effect, however, our results revealed a *map dissimilarity at N1 latency* between the three groups, at least for the auditory condition (Fig. 2A). The results from the topographic and source analyses suggest that these group differences can at least partially be explained by a delayed N1 auditory-cortex response in both CI-CHD and CI-SSD users when compared to NH listeners. However, as discussed in the following section (4.2.3), the results from the source analyses indicate that this map dissimilarity at N1 latency is also caused by a different configuration of neural sources. Both CI user groups showed an additional activation in the visual cortex compared to NH listeners (see section 4.2.3 for more details).

Within the P2 time window, the hierarchical clustering and single-subject fitting analyses showed a condition effect (independent of group; Fig. 3B) and some group effects (independent of condition; Fig. 3B). The *condition* effect, which revealed an enhanced map presence of the P2-like topography (Map E) for the modulated (AV-V) compared to the auditory response (A), indicates a visual modulation of the auditory ERPs in all groups of participants. Regarding the *group* effects, we found a greater map presence of the P2 topography (Map C) for NH individuals compared to CI-SSD users, and a greater map presence of a P2-like topography (Map E) for CI-SSD users compared to NH listeners. This difference is in line with the results from the GMD observations, pointing to a difference in response topography at the P2 time window (Fig. 2). At the same latency window, we also found a difference between CI-CHD users and NH listeners for the Map D, showing a greater presence of this topography in CI-CHD users than NH listeners. This difference was also confirmed by the GMD analysis, showing a difference in response topography at the P2 time window (Fig. 2). Importantly, no significant differences between CI-CHD users and CI-SSD users were detected in the topographic analysis at P2 latency, which corresponds to the lack of differences in the GMD analysis. These results however are not easy to interpret. One may speculate that the two CI user groups do not differ statistically at P2 latency but exhibit distinct topographic patterns when compared to NH listeners. Therefore, a source analysis is unlikely to yield clear results revealing group-specific cortical activation patterns. Indeed, the source analysis revealed no group differences in auditory or visual cortex activation. Nevertheless, the source analysis provided evidence for audiovisual interactions by identifying reduced amplitudes for the modulated condition (AV-V) compared to the purely auditory condition (A), independent of the groups (see section 4.1). Taken together, we conclude that CI users and NH listeners recruit the auditory and visual cortices similarly during auditory and audiovisual speech processing, at least at the P2 latency range. Future research is required to determine if group-specific differences within the P2 time window emerge with other stimuli/tasks and whether they appear beyond the visual and auditory sensory systems, as in frontal or other temporal areas (Campbell and Sharma, 2013; Giraud et al., 2001a).

4.2.3. *Cross-modal plasticity in the visual cortex*

The results from the source analysis within the N1 time window revealed a greater recruitment of the visual cortex for both the CI-CHD users and CI-SSD users when compared to NH listeners. This cross-modal activation of the visual cortex is in line with previous research findings from CI-CHD users, reporting that cortical alterations are not limited to the auditory cortex (Campbell and Sharma, 2013, 2016; Chen et al., 2016; Giraud et al., 2001a,b) but seem to extend to the visual and even inferior frontal areas (Rouger et al., 2012). As far as we are aware, this is the first study to show that auditory-induced activation in the visual cortex is not restricted to CI-CHD users, as shown in our previous study (Layer et al., 2022) but is also present in CI-SSD users.

It has been suggested that the additional recruitment of the visual cortex in CI users is a way to compensate the limited auditory input delivered through the CI (Doucet et al., 2006; Giraud et al., 2001c; Strelnikov et al., 2010, 2013). In the PET (positron emission tomography) study of Giraud and colleagues (Giraud et al., 2001c), a greater auditory activation in the visual cortex was reported for unilaterally-implanted CI users (with bilateral hearing loss) in comparison to NH controls for meaningful sounds. The authors found an association between this visual recruitment with longer CI experience and pronounced lip-reading abilities (Giraud et al., 2001c). By now, cross-modal recruitment of the visual cortex for processing auditory stimuli has been observed in CI users for syllables, words, environmental sounds, pure tones, and reversed words (Chen et al., 2016; Giraud et al., 2001b; Giraud et al., 2001c). This visual cortex activation when processing auditory stimuli may represent an enhanced synergy of the auditory and visual modalities in CI users. This might be beneficial for speech comprehension recovery following cochlear implantation, when CI users must learn to match novel auditory speech inputs with corresponding visual speech cues (Strelnikov et al., 2013). Consistent with this view, our previous study showed a positive correlation between CI experience and visual-cortex activation, indicating that CI users increasingly recruit the visual cortex with increasing duration of CI usage (Layer et al., 2022).

The present study extends previous findings by showing visual recruitment for auditory (and audiovisual) syllables not only in CI-CHD users but also in CI-SSD users. This observation in CI-SSD users may appear surprising because these individuals have at least one ear on the contralateral side on which to rely. However, in natural conditions with bilateral stimulation, the CI-SSD users' auditory performance is still impaired compared to normal hearing patients (Dorman et al., 2015; Ludwig et al., 2021), particularly in difficult listening conditions, which may explain why these individuals develop compensatory strategies, as indicated by enhanced lip-reading skills and cross-modal recruitment of the visual cortex. Taken together, our results suggest that auditory-induced activation of the visual cortex is independent of the hearing abilities on the contralateral ear when being stimulated over the CI ear. However, future studies are required to systematically compare the stimulation of the CI ear alone, the contralateral ear alone and both ears together. The measured cortical activation differences would provide a clearer picture of how much of the large variability in speech recognition ability in different CI users can be attributed to the contralateral ear. Further, we suggest that future studies should further split the CI groups into bimodal (CI – HA), bilateral (CI–CI) and SSD (CI–NH) CI users and use more ecologically valid stimuli such as complex speech stimuli, and different task conditions (e.g. passive vs. active) in order to deliver a portrait of the characteristics for each group in terms of audiovisual speech processing and cortical reorganisation. This could allow for developing methods for accelerating and improving auditory rehabilitation after implantation that are specific for each CI user group.

5. Limitations

An important limitation of this study is the small sample size of n = 11 per group. A small sample size is common in the scarce literature on CI-SSD users, because this patient group was not implanted a few years back due to the intact NH ear. Only after proving the benefits of an implantation (improved hearing abilities compared to other techniques such as bone-anchored hearing aids (BAHA) or contralateral routing of signal (CROS) (Arndt et al., 2011, 2017); better speech intelligibility, sound localisation and quality of life (Kitterick et al., 2015)), CI-SSD users were increasingly fitted with a CI. Consequently, results with small sample sizes always must be interpreted with caution. Future studies, however, should aim to increase the number of participants in order to improve statistical power and apply more extensive statistical correction methods, as suggested by Cramer et al. (2016).

One might ask the question whether the presented results are transferrable to other audiovisual stimuli or whether these are restricted to language-specific stimuli. We assume that the significant audiovisual benefit observed in our CI users was strongly driven by the linguistic property of the presented stimuli, and we hypothesise that this audiovisual benefit may even be more pronounced for more difficult linguistic stimuli (words or sentences). Nevertheless, when solely focusing on the additional recruitment of the visual cortex, as observed in the present and our recent results (Layer et al., 2022), previous studies have suggested that this effect is not restricted to purely linguistic tasks. This effect has been shown for syllables, words and environmental sounds (Giraud et al., 2001c). Another study (Chen et al., 2016) extended these results to pure tones and reversed words, showing that intelligibility is not necessary for eliciting auditory-induced recruitment of the visual cortex. However, these previous studies do not provide answers concerning processing differences and similarities between CI user groups, which is the novelty of this study. We hypothesise that further and more pronounced differences between CI-CHD users and CI-SSD users will become evident for more difficult linguistic stimuli (words/sentences vs. syllables) and more difficult task conditions (semantic processing vs. discrimination of syllables). Importantly, future studies should use the same experimental settings (i.e. the same paradigm) for different types of stimuli. They should compare cortical response patterns between non-linguistic stimuli (e.g. basic and environmental sounds) and linguistic stimuli (e.g., syllables and words), to see if our findings are transferable to both non-linguistic and more difficult linguistic stimulus conditions within the same patients.

6. Conclusion

The present study applied electrical neuroimaging, including topographic and source analysis, to investigate whether the cortical processing of audiovisual syllables is different between CI-CHD users and CI-SSD users. These two CI user groups were also compared to NH listeners. This study expands on our previous study that compared CI-CHD users to NH listeners by reusing these data to include an additional group of CI users. Our findings showed a clear multisensory effect in both CI user groups and NH listeners, as evidenced by faster behavioural response times and reduced auditory-cortex activation at N1 and P2 latencies. Furthermore, we discovered a condition effect for the N1 ERP topography in the group of CI-CHD users only, demonstrating a distinct pattern of N1 topography between the auditory-only (A) and the modulated auditory response (AV-V). This finding indicates a strong visual influence on auditory speech processing especially in CI-CHD users, allowing these patients to compensate for the limited CI input. Finally, we discovered that both CI user groups showed a delay in the auditory-cortex response at N1 latency, indicating difficulties in cortical processing of the CI's limited signal. Nonetheless, we found that both CI user groups showed pronounced lip-reading abilities and an additional recruitment of the visual cortex compared to NH listeners. This finding extends previous results by demonstrating that this cross-modal visual activation is also present in CI-SSD users, who have an intact NH ear on the contralateral side. One may speculate that these cortical alterations allow the CI users to combine multisensory information, to refine expectations and to sharpen perception. We conclude that an auditory-induced activation in the visual cortex is independent of the hearing threshold and supply on the contralateral ear when being stimulated via the CI ear. This auditory-induced activation in the visual cortex is an important and insightful similarity between the two CI user groups. Overall, these results confirm existing differences in multisensory processing both when comparing NH listeners and CI users and when comparing different groups of CI users. This emphasises the importance of developing individual rehabilitation methods tailored to different groups of CI users.

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CRediT authorship contribution statement

Natalie Layer: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Anna Weglage:** Software, Validation, Formal analysis, Investigation, Writing – review & editing. **Verena Müller:** Conceptualization, Writing – review & editing. **Hartmut Meister:** Conceptualization, Software, Resources, Writing – review & editing. **Ruth Lang-Roth:** Conceptualization, Writing – review & editing. **Martin Walger:** Conceptualization, Writing – review & editing. **Micah M. Murray:** Software, Formal analysis, Validation, Writing – review & editing. **Pascale Sandmann:** Conceptualization, Methodology, Validation, Resources, Writing – original draft, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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.

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Appendix A. Peer Review Overview and Supplementary data

A Peer Review Overview and (sometimes) Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.crneur.2022.100059.

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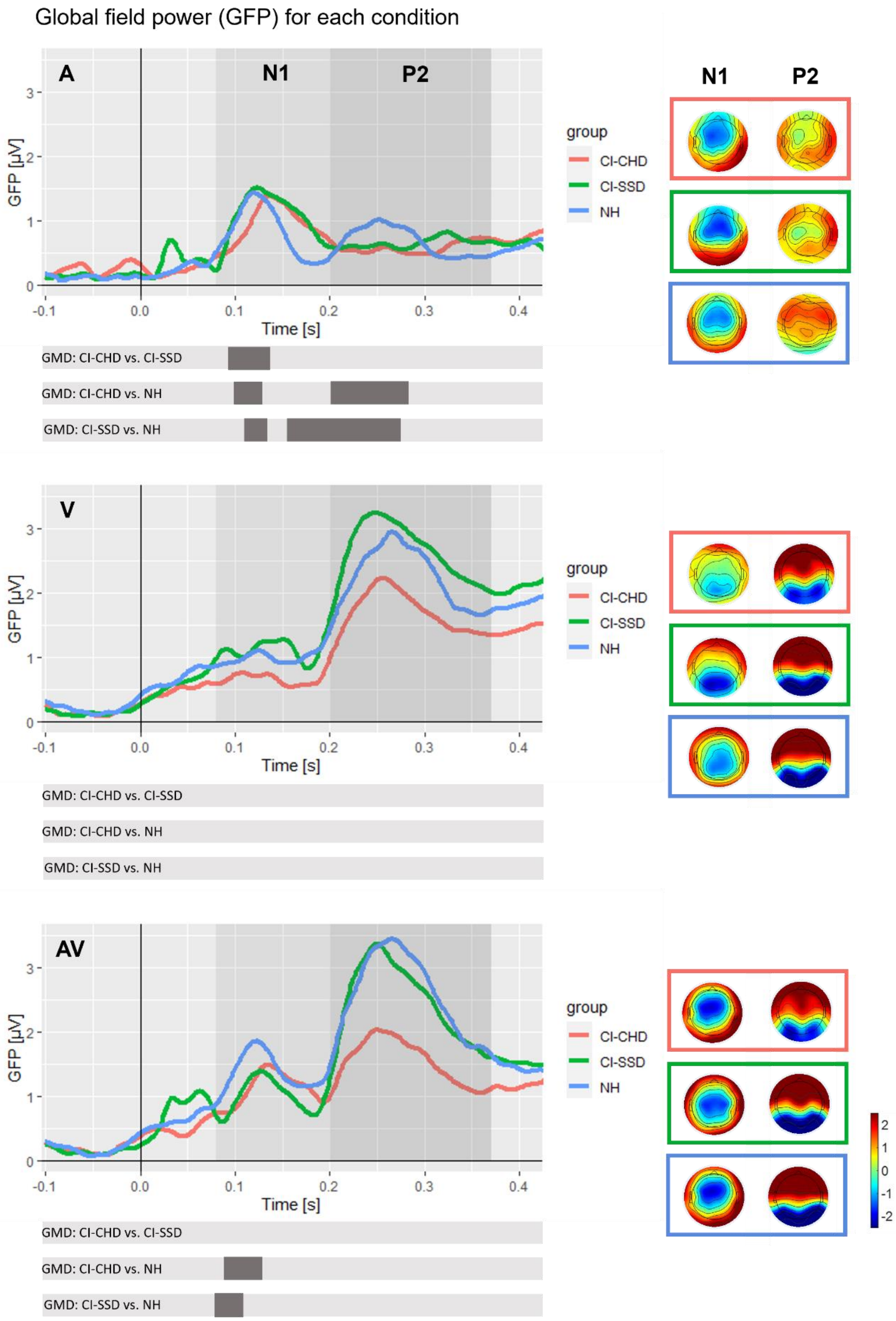
Supplementary Material

We added a supplementary figure to illustrate the “raw” data for each condition, as we displayed only the condition A and the difference wave (AV-V) in the manuscript:



Global field power (GFP) for each condition

GFP of the conditions A, V, and AV for CI-CHD users (red), CI-SSD users (green) and NH listeners (blue). It is important to note that the GFP only provides positive values because it represents the standard deviation across all electrodes separately for each time point. The ERP topographies at the GFP peaks (N1(A) = CI-CHD: 147 ms, CI-SSD: 136 ms, NH: 118 ms; N1(V) = CI-CHD: 149 ms, CI-SSD: 134 ms, NH: 153 ms; N1(AV) = CI-CHD: 147 ms, CI-SSD: 144 ms, NH: 127 ms ; P2(A) = CI-CHD: 305 ms, CI-SSD: 288 ms, NH: 256 ms; P2(V) = CI-CHD: 259 ms, CI-SSD: 265 ms, NH: 268 ms; P2(AV) = CI-CHD: 253 ms, CI-SSD: 250 ms, NH: 264 ms) are given separately for each group (displayed on the right).

4

CHANGES IN VISUALLY AND AUDITORY ATTENDED AUDIOVISUAL SPEECH PROCESSING IN COCHLEAR IMPLANT USERS: A LONGITUDINAL ERP STUDY

This chapter is based on the following publication:

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Author contributions:
Anna Weglage: Conceptualisation; literature review; creation, editing and calibration of stimuli; programming of the experiment; pilot measurements; participant recruitment; data acquisition; data analysis; interpretation and presentation of results to research group; discussion of findings and further procedures; writing initial manuscript draft; incorporating suggestions of co-authors; submission to journal; presentation of results at national conferences. **Natalie Layer**: Assistance in data acquisition; assistance in data analysis; group discussions; proofreading of manuscript. **Verena Müller**: Initial assistance in participant enrolment; proofreading of manuscript. **Hartmut Meister**: Funding acquisition; conceptualisation; provision of software for stimuli generation; discussion; suggestions; proofreading of manuscript. **Ruth Lang-Roth**: Conceptualisation; proof-reading of manuscript. **Martin Walger**: Conceptualisation; proof-reading of manuscript. **Pascale Sandmann**: Supervisor of Anna Weglage; central role in project conceptualisation; funding acquisition; suggestions; discussions; assistance in writing manuscript and proofreading of manuscript.

SYNOPSIS

OBJECTIVES Postlingually deafened individuals show altered cortical processing due to the auditory deprivation and also due to the limited auditory input after cochlear implantation. Especially in the time before implantation, they heavily rely on their other senses like vision and touch (Pavani and Bottari, 2012). It has also been shown that they develop enhanced multisensory interactions (Schierholz et al., 2015). This study aims to systematically examine the deprivation- and CI-induced alteration of the cortical processing of audiovisual speech stimuli and to study the (top-down) attention effect on (bottom-up) sensory cortical processing by directing the focus to one modality at a time. Methods from electrical neuroimaging (Michel, 2009) are used to explore the processing of the audiovisual words.

METHODS This prospective longitudinal study included postlingually deafened individuals that were supplied with a CI in the course of the study and a NH control group. Participants were measured with a 64 channel EEG at three timepoints, one before implantation and two after implantation (five weeks and six months after the initial fitting of the speech processor; same timing for the NH control group). The task was to identify three different german words presented by a computer animation of a talking head in an audiovisual word-identification task with congruent and incongruent stimuli, while focusing the attention on either the visual (lip movement) or the auditory speech signal. Additionally, a behavioural McGurk task (McGurk and MacDonald, 1976) was performed, a lip reading task with natural speakers, and the task difficulty was assessed after each experimental block.

ANALYSIS Behavioural results were analysed by using the task efficiency (performance divided by hit rates), as well as the performance in the lip reading and McGurk task. The global field power (GFP) was analysed on the sensor level for the time period following the onset of the words. Amplitudes and latencies of the GFP peaks were compared between the groups (CI, NH), conditions (attend A, attend V) and time points (before implantation, five weeks after implantation, six months after implantation). Afterwards, a hierarchical clustering identified frequent topographic maps that were used for a single-subject analysis. For the analysis of different frequency ranges, event-related spectral perturbation (ERSPs) were calculated and the power was compared between the groups, conditions and time points in two time-frequency bands following the word onset. Ultimately, a source analysis including a connectivity measure was performed. The peaks and latencies of the activity in the visual and auditory cortex were statistically compared between groups, conditions and time points. For the connectivity an envelope correlation was calculated between the cortices.

RESULTS The behavioural results show different patterns for the two groups. While the NH listeners are more efficient in the auditory attended conditions and more often report the auditory percept in the McGurk task, the CI group is better in the lip reading task and more often reports the fusion percept in the McGurk task. Both groups are more efficient in the auditory than visually attended conditions and show the worst efficiency in the visually attended incongruent condition. Regarding the listening effort, all participants report more effort for the visually attended conditions and the CI group reported more effort for the auditory attended condition solely at the second time point (five weeks after implantation). On the sensor level, a smaller peak amplitude was found for the peak at the N1 latency in the CI group when compared to the NH group only at the first time point. While this reduced peak converges to the results of the NH group, the topography remains more occipitally pronounced for the CI group, especially in the visually attended condition. Further, a greater theta power was found for the NH group in both conditions (attend A, attend V). In the beta frequency, the NH groups revealed a condition difference, while the CI group did not. Finally, at the source level, a greater activation of the auditory cortex was found for the NH group when compared to the CI group in both conditions. For the auditory attended condition the CI group develops a stronger intra-modal connectivity between the left and right auditory cortex with CI use.

DISCUSSION In sum, the results suggest effects of auditory deprivation on audiovisual speech processing, which partially reverse after CI implantation. Although the CI users show distinct audiovisual speech processing even after six months of CI use when compared to NH listeners, effects of (top-down) direction of attention on the (bottom-up) audiovisual processing are observable in both groups. Nevertheless, only the NH listeners show enhanced allocation of cognitive resources when attending the visual part of the audiovisual words as compared to when attending the auditory part. This supports the observation of poorer lip reading abilities and a reduced visual influence on auditory signals in NH listeners compared to CI users, who are more accustomed to using the lip movement as a support for understanding auditory input in their everyday lives.

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Changes in visually and auditory attended audiovisual speech processing in cochlear implant users: A longitudinal ERP study

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ABSTRACT

Limited auditory input, whether caused by hearing loss or by electrical stimulation through a cochlear implant (CI), can be compensated by the remaining senses. Specifically for CI users, previous studies reported not only improved visual skills, but also altered cortical processing of unisensory visual and auditory stimuli. However, in multisensory scenarios, it is still unclear how auditory deprivation (before implantation) and electrical hearing experience (after implantation) affect cortical audiovisual speech processing.

Here, we present a prospective longitudinal electroencephalography (EEG) study which systematically examined the deprivation- and CI-induced alterations of cortical processing of audiovisual words by comparing event-related potentials (ERPs) in postlingually deafened CI users before and after implantation (five weeks and six months of CI use). A group of matched normal-hearing (NH) listeners served as controls. The participants performed a word-identification task with congruent and incongruent audiovisual words, focusing their attention on either the visual (lip movement) or the auditory speech signal. This allowed us to study the (top-down) attention effect on the (bottom-up) sensory cortical processing of audiovisual speech.

When compared to the NH listeners, the CI candidates (before implantation) and the CI users (after implantation) exhibited enhanced lipreading abilities and an altered cortical response at the N1 latency range (90–150 ms) that was characterized by a decreased theta oscillation power (4–8 Hz) and a smaller amplitude in the auditory cortex. After implantation, however, the auditory-cortex response gradually increased and developed a stronger intra-modal connectivity. Nevertheless, task efficiency and activation in the visual cortex was significantly modulated in both groups by focusing attention on the visual as compared to the auditory speech signal, with the NH listeners additionally showing an attention-dependent decrease in beta oscillation power (13–30 Hz).

In sum, these results suggest remarkable deprivation effects on audiovisual speech processing in the auditory cortex, which partially reverse after implantation. Although even experienced CI users still show distinct audiovisual speech processing compared to NH listeners, pronounced effects of (top-down) direction of attention on (bottom-up) audiovisual processing can be observed in both groups. However, NH listeners but not CI users appear to show enhanced allocation of cognitive resources in visually as compared to auditory attended audiovisual speech conditions, which supports our behavioural observations of poorer lipreading abilities and reduced visual influence on audition in NH listeners as compared to CI users.

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1. Introduction

Individuals with severe to profound hearing loss can compensate for the limited auditory input by increasingly using the visual system (e.g., Bottari et al., 2011; Loke and Song 1991; Neville and Lawson, 1987a, 1987b; Bavelier et al., 2006). In particular, the visual system helps with orientation, environmental change-detection and speech recognition through lipreading. Visual compensation remains important even after implantation of a cochlear implant (CI), which is a neuroprosthesis that can help to regain the hearing abilities of individuals with sensorineural hearing loss. However, electrical hearing with a CI is impaired when compared to natural acoustic hearing, given that only limited spectral and temporal information is transmitted by the CI (Drennan and Rubinstein, 2008). Therefore, the central auditory system has to learn to interpret the electrical input as meaningful sounds after implantation (Giraud et al., 2001; Sandmann et al., 2015). Over a period of six months, CI users typically reach a satisfactory level of speech recognition in conditions without background noise (Fetterman and Domico, 2002; Hey et al., 2016; Holden et al., 2013; Krueger et al., 2008). However, in more difficult listening conditions, such as speech conditions with background noise, the speech recognition remains limited (Wilson and Dorman, 2008), so that CI users continue to strongly rely on the visual input and they use lipreading to master their everyday lives.

Several previous studies have focused on visual compensation in (congenitally) deaf individuals and (postlingually deafened) CI users, showing not only superior lipreading abilities before and after implantation (Rouger et al., 2007; Stropahl et al., 2015; Anderson et al., 2019) but also enhanced visual capabilities like larger visual fields (Buckley et al., 2010; Codina et al., 2011; Stevens and Neville, 2006) and faster reaction times in visual detection tasks (Bottari et al., 2010; Loke and Song, 1991). This perspective is also called the *sensory compensation hypothesis*. Another perspective in the literature is referred to as the *perceptual deficit hypothesis* which states that a deficit of one modality can have detrimental effects on the organisation and development of other sensory systems (e.g., Myklebust, 1964). Regarding multisensory conditions, in particular audiovisual speech conditions, CI users show enhanced visual influence on auditory perception (Desai et al., 2008) and stronger audiovisual interactions (Stevenson and James, 2009). These latter observations go along with the principle of "inverse effectiveness" (Stein and Meredith, 1993) which states that the gain in audiovisual conditions is enhanced when the responses to unisensory stimuli are difficult. As a result, the limited auditory speech percept through a CI increases the benefit of a simultaneously presented visual speech signal, thus improving the overall speech recognition ability in audiovisual conditions (van de Rijt et al., 2019).

Several previous studies on audiovisual speech perception have used the McGurk paradigm, which includes congruent and incongruent audiovisual syllable conditions, and which offers to examine the effect of (visual) lip movements on the perceived (auditory) vocalisation (McGurk and MacDonald, 1976). In incongruent conditions, normal-hearing (NH) listeners typically either report the auditory syllable, or they experience a fusion percept caused by visual influence on auditory syllable perception. A similar pattern of findings has been observed in CI users with *good* speech recognition ability (Tremblay et al., 2010). By contrast, CI users with *poor* speech recognition ability seem to primarily report the visually presented syllables, which indicates that poor CI performers rely more on visual than auditory information in audiovisual speech conditions (Tremblay et al., 2010). These observations have been confirmed by studies with children, showing that an older age at implantation in most cases not only leads to a poorer CI outcome but also to visual dominance and reduced ability to fuse audio-visual stimuli (Gilley et al., 2010; Schorr et al., 2005). Although these previous results have provided important insights into audiovisual syllable perception in CI users, it remains poorly understood which specific effects the (top-down) direction of attention has on (bottom-up) cortical audiovisual speech processing in CI users. Further, given the limited number of longitudinal studies with CI users, it is not yet well understood whether these top-down effects of attention are specifically influenced by auditory deprivation and cochlear implantation, respectively.

There is increasing evidence for changes in (bottom-up) sensory processing in the auditory and visual cortex of CI users, which appear to be induced by auditory deprivation and CI experience (Giraud et al., 2001; Strelnikov et al., 2013; Chen et al., 2017). For instance, several studies showed that electrical (auditory) stimulation over the first months of CI use result in increasing cortical activation, not only in the auditory (Giraud et al., 2001; Green et al., 2005; Sandmann et al., 2015) but also in the visual cortex (Giraud et al., 2001). These observations indicate that CI experience induces pronounced functional changes in the auditory and visual cortices, which enable an increase in speech recognition ability with the implant. However, intra-modal changes in the visual cortex, as revealed by *visual* cortical alterations in response to *visual* stimuli, seem to be mainly induced by auditory deprivation and not by cochlear implantation. This is suggested by a recent electroencephalography (EEG) study of our group which focused on visual cortical processing of purely visually presented articulated words (Weglage et al., submitted). The results of this study have shown reduced cortical visual responses in postlingually deafened individuals (before implantation) that hardly changed over the first six months of CI usage. However, the reduced visual cortical responses as recorded before implantation correlated with the speech recognition ability after 6 months of CI use, suggesting a connection between the deprivation-induced cortical (visual) reorganisation and the CI (auditory) outcome. Finally, other EEG studies with CI users indicated experience-related cortical alterations in the processing of simple and more complex audiovisual stimuli, suggesting strong visual modulation of the auditory-cortex response (Schierholz et al., 2015; Layer et al., 2022a) and different cortical processing patterns in CI users when compared to NH listeners (Radecke et al., 2022).

EEG is an interesting tool for studying cortical plasticity not only in deaf individuals (Bottari et al., 2011; Hauthal et al., 2014) but also in CI users (Sandmann et al., 2009; Sandmann et al., 2015; Sharma et al., 2002; Viola et al., 2012). Event-related potentials (ERPs) derived from EEG allow the tracking of the single steps in cortical processing, since the temporal resolution is high (Biasiucci et al., 2019; Michel and Murray, 2012). For auditory conditions, several studies with CI users reported a decreased N1 ERP amplitude (negative potential around 100 ms after stimulus onset; Bosnyak et al., 2004; Finke et al., 2016; Sandmann et al., 2009; Weglage et al., 2022), which reflects neural activation in response to auditory changes and which seems to be primarily generated in the primary and secondary auditory cortex (Näätänen and Picton, 1987; Ross and Tremblay, 2009; Tremblay et al., 2014; Vaughan Jr and Ritter, 1970). Regarding visual conditions, previous findings about CI users have pointed to a reduced P1 ERP amplitude (positive potential around 100 ms; Sandmann et al., 2012), which seems to have generators lying in the primary and secondary visual cortex (Di Russo et al., 2001; Noachtar et al., 1993). However, in more ecologically valid stimulus conditions, including audiovisual speech stimuli, previous EEG and neuroimaging studies have reported the recruitment of both the auditory and the visual cortex in hearing-impaired individuals (Layer et al., 2023; Rosemann and Thiel, 2018).

Time-frequency analysis is a type of EEG analysis that complements the traditional ERP methodology by providing a more differentiated insight into cortical processes that are related to specific frequency ranges. For instance, neural activity in the *alpha* frequency range (8–12 Hz) is modulated by different attention levels (Berger 1929; Adrian and Matthews 1934), with increased attention associated with a decrease in alpha power (Foxe and Snyder, 2011). Activity in the *beta* frequency range (13–30 Hz), on the other hand, seems to reflect rather cognitive and emotional processes. In particular, weaker beta band responses over posterior scalp regions seem to be related to higher memory load (Pesonen et al., 2007, 2006). Furthermore, *theta* oscillations (4–8 Hz) have been mostly associated with storage and retrieval of information from long-term memory (e.g., Burgess and Ali, 2002; Klimesch et al., 2001; Klimesch, 1999), as well as with working memory processes (e.g., Bastiaansen et al., 2002; Jensen and Tesche, 2002; Tesche and Karhu, 2000; Kahana et al., 1999). Regarding CI users, the aforementioned frequency bands have not yet been systematically evaluated in relation to audiovisual speech processing in the literature. Therefore, our study aimed to compare the CI and NH groups based on their oscillatory activity in the different frequency ranges when stimulated with audiovisual words.

Here, we present a prospective longitudinal EEG study which used electrical neuroimaging, including topographic and source analysis (Michel, 2009), to systematically examine the cortical audiovisual speech processing in NH listeners and in postlingually deafened CI users before and after cochlear implantation. In contrast to previous EEG studies which presented simple audiovisual stimuli, such as tones/white circles (Schierholz et al., 2015) and syllables (Layer et al., 2022a), the CI users in the present study were tested with more complex stimuli, in particular words that were articulated by a talking head (Fagel and Clemens, 2004; Schreitmüller et al., 2018). This computer animation allowed us to test our participants in highly controlled, reproducible, and precisely timed audio-visual speech conditions. Importantly, these audiovisual stimuli were presented in two tasks, whereby the CI users directed their attention to either the auditory or the visual signal. This allowed to systematically study the effect of top-down attention effects on the processing of physically identical audiovisual speech stimuli, which is an aspect that has not yet been investigated in CI users. Specifically, we compared the cortical processing of the auditory and visually attended words within and between CI users and NH listeners at different time points, one before cochlear implantation and two afterwards. This allowed to address the question of whether the top-down attentional effects on cortical audiovisual processing are influenced by auditory deprivation and cochlear implantation, respectively.

Based on previous studies, which however only used unisensory auditory stimuli (Giraud et al., 2001; Sandmann et al., 2015), we expected for the CI group a CI-related increase in the cortical response to audiovisual speech stimuli. We also expected group differences between CI users and NH listeners in the cortical processing of auditory and visually attended audiovisual speech stimuli. Given that the CI users typically have supranormal lipreading ability (Rouger et al., 2007; Layer et al., 2022b) and the auditory input in these individuals is missing (before implantation) or limited (after implantation), we expected that CI candidates/CI users rely more on the visual modality, whereas the NH listeners rely more on the auditory modality.

2. Materials and methods

2.1. Participants

In total, 37 adult volunteers (20 females, 17 males) participated in this study. Twenty of them suffered from severe to profound hearing loss with postlingual onset, and they were supplied with a cochlear implant (CI) in the time course of the study. The age ranged from 36 to 74 (57.19 ± 14.71 years). The first experimental sessions took place prior to implantation (29.65 ± 34.22 days), the second measurement occurred approximately five weeks (5.71 ± 0.47 weeks) after the initial fitting of the sound processor and the third session approximately six months (5.71 ± 0.47 months) after the initial fitting of the sound processor. Three of the hearing-impaired participants were excluded from the analysis, due to dropouts during the study for personal reasons. In addition to the CI users, a group of age and gender matched normal-hearing (NH) controls was tested at three timepoints in time intervals of approximately five weeks and six months. All participants had normal or corrected-to-normal vision according to the Landolt test (Landolt C; Wesemann et al., 2010) and none had a history of psychiatric illness. All participants were fluent in the German language and none of them used sign language to communicate. Among the 17 CI users, two individuals were unaided, thirteen individuals used a hearing aid on the contralateral side, and two individuals were also implanted on the contralateral side (see Table 1). The speech recognition ability was tested after six months of CI experience, using the German Freiburg monosyllabic word test with the CI ear only.

Since it is difficult to estimate the exact time point for ‘onset of hearing loss’ and therefore to derive the ‘duration of deafness’, we used a pragmatic definition for this parameter. The ‘age at onset of profound hearing loss’ means the age where the hearing loss was too severe to be treated with conventional hearing aids. The ‘duration on deafness’ was calculated as the time between the ‘onset of profound hearing loss’ and the date of the experiment.

To verify age-appropriate cognitive abilities, the DemTect Ear test battery was used (Brünecke et al., 2018). It is an adjusted version of the conventional DemTect (Kalbe et al., 2004) especially evolved for patients with hearing disabilities. Hence, it enables to test cognitive skills independently of hearing and prevents disadvantages caused by hearing loss. The test battery consists of various subtests including a word list, a number transcoding task, a word fluency task, a digit span reverse and a delayed recall of the word list. In this way, attention, memory and word fluency skills are tested. All participants achieved scores within the age-appropriate normal range (13–18 points).

All participants gave written informed consent. The study was approved by the Ethics Commission of Cologne University’s Faculty of Medicine (application number 18–197) and was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki, 2013).

2.2. Additional behavioural tasks

In addition to the EEG paradigm (see next Section 2.3), two behavioural tasks were performed to test for the lipreading ability and the ability to process incongruent stimuli. We measured the lipreading ability by means of a behavioural lipreading test with three natural speakers (see Stropahl et al., 2015) who articulated 21 different monosyllabic words from the German Freiburg monosyllabic word test (Hahlbrock, 1970). Participants were asked to report the word they understood after each muted video. Moreover, we performed a behavioural McGurk paradigm with only audiovisual stimuli. The syllables /pa/, /ka/ and /ta/ were presented in congruent trials, as well as in incongruent trials (visual /pa/ and auditory /ka/). After each video, participants were asked to report the syllable they perceived. The words and syllables of the two behavioural tests were presented on a computer screen in front of the participants.

2.3. EEG paradigm: stimuli and procedure

The stimuli consisted of audiovisual videos produced by ‘The Modular Audiovisual Speech Synthesizer’ (MASSY; Fagel and Clemens, 2004), a computer-based video animation of a talking head, articulating three different words in German (‘Tagung’ [ˈtaːɡʊŋ] (conference), ‘Torwart’ [ˈtoːɐ̯vart] (goalkeeper), ‘Treffen’ [ˈtrɛfn̩] (meeting)) (Fig. 1). The stimuli started with a blank screen for 500 ms, which was followed by the respective video (1660 ms), the latter of which showed a static face for 500 ms and then the respective word. The trials ended with a fixation cross for no longer than 1500 ms. The fixation cross disappeared by a button press.

Participants were seated in front of a screen in a dimly lit and sound shielded room. The stimuli were presented using the Presentation software (Neurobehavioral Systems, version 21.1) on a 68 cm screen at a viewing distance of 160 cm. The videos were presented in a pseudorandomised order, and they were separated into three blocks. In each block, the participants were instructed to press an assigned button for one word (target word), and the other button for the other two words (non-targets). The assignment of the words (target, non-target) was

Table 1
Demographic information of the CI participants (AB = Advanced Bionics; AS/AN = auditory synaptopathy/auditory neuropathy; HA = hearing aid; HL = hearing loss; PTA = pure tone average).

Age [years]	Gender	CI side	Etiology	Duration HL [years]	PTA [dB HL] (CI ear, pre implantation)	other ear	CI manufacturer	Monosyllabic word test [%]
44	f	right	progredient	12	94	HA	Cochlear	75
56	m	left	hereditary	43	111.5	CI	MedEl	75
64	m	left	sudden deafness	31	84.25	HA	AB	80
70	f	right	hereditary	4	118	HA	MedEl	75
68	m	left	sudden deafness	19	77.25	HA	Cochlear	60
46	f	right	AS/AN	16	71.75	HA	Cochlear	80
75	m	right	unknown	4	107.25	HA	MedEl	65
39	f	left	unknown	32	100.75	HA	Cochlear	75
63	m	left	progredient	53	84	HA	MedEl	30
36	m	right	progredient	32	91.25	HA	Cochlear	45
74	f	left	unknown	12	96.25	CI	AB	75
57	f	right	sudden deafness	1	135	–	AB	65
66	m	left	unknown	21	98	HA	AB	60
56	f	left	sudden deafness	6	94.25	HA	MedEl	80
59	f	right	hereditary	59	107.75	HA	Cochlear	70
54	f	right	unknown	49	122.75	–	Cochlear	10
59	m	left	unknown	26	104.5	HA	Cochlear	45

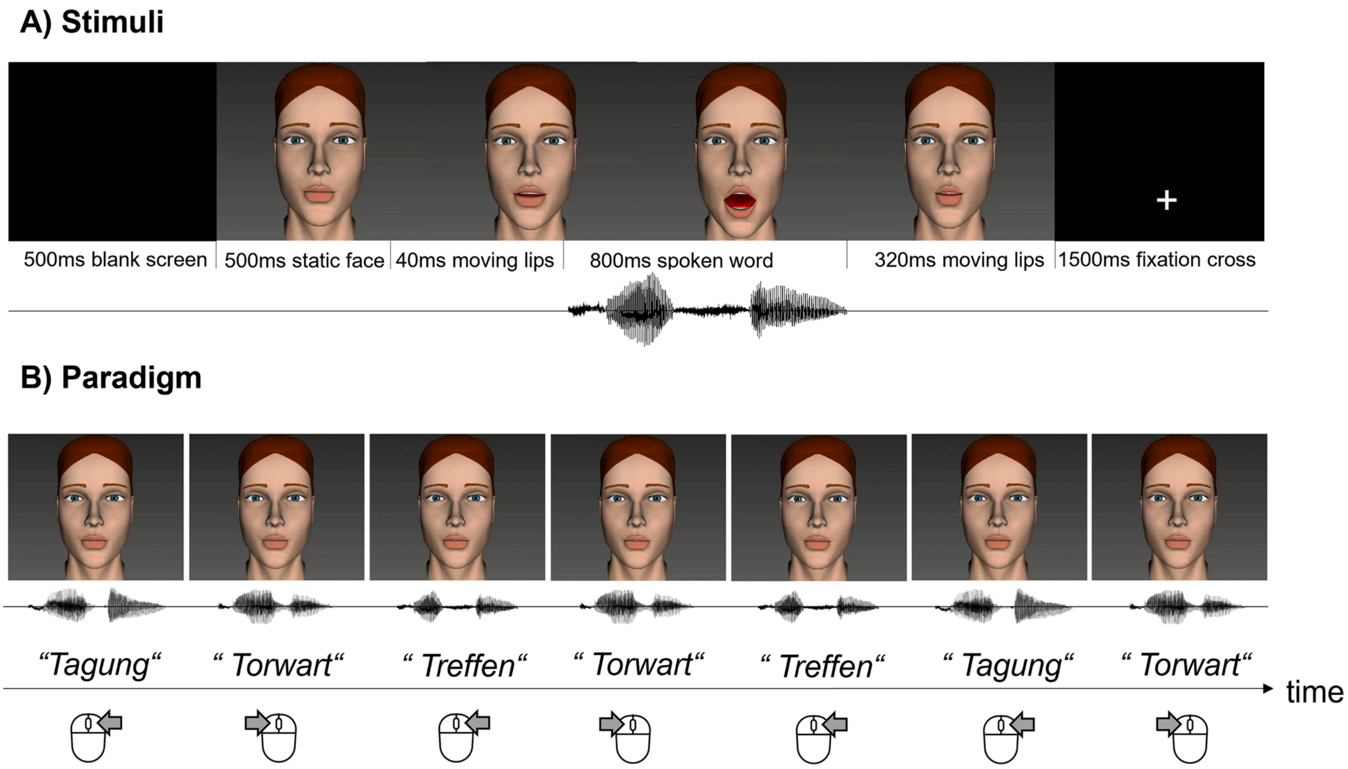


Fig. 1. The EEG task. (A) Depiction of one audiovisual stimulus. All stimuli started with a blank screen and a static face for 500 ms each. The static face was the same for all three presented words. Note that the lip movement of the word started 40 ms earlier than the auditory word. All stimuli ended with a fixation cross that disappeared by a button press. (B) The procedure of the word-identification task. The three different words were presented in a pseudorandomised order. The participants were asked to press one assigned button for the target word ("Torwart" in this example) and another button for the two nontargets ("Treffen" and "Tagung" in this example). The assignment of the words (target, non-target) was alternated between the different blocks. The participants were instructed to focus their attention on either the auditory or the visual speech signal.

alternated between the different blocks. Each word was the target in one block. Additionally, the task was separated into two different task conditions. In one run, consisting of three blocks (i.e., 81 targets, 162 non-targets), participants were instructed to attend to the lip movement, whereas in the other run they were instructed to attend to the auditory speech signal. Since the first time point occurred prior to cochlear implantation, the participants were only tested with the visually attended condition but not with the auditory attended condition. Given the severe to profound hearing loss at this time point, the CI candidates would not have been able to perform the auditory task. Consequently, the NH group also only executed the visually attended condition at the first timepoint. To ensure that the task was performed correctly, we included incongruent so-called catch trials (24 in each condition), which consisted of a lip movement that did not match the auditory presented word. Furthermore, the listening effort was prompted after each experimental block at the two time points after implantation (time point two: five weeks CI use, time point three: six months CI use). Specifically, the participants were asked to report the subjectively perceived listening effort by means of the "Borg Rating of Perceived Exertion"-scale (Borg RPE-scale; Williams, 2017).

2.4. Data recording and processing

EEG data was continuously recorded by 61 Ag/AgCl slim active electrodes (EasyCap) placed across the head according to the extended 10/20 system. Two additional electrodes were placed next to and under the left eye to record electro-oculograms. A reference electrode was placed at the tip of the nose, and the ground electrode was placed in front of AFz. Two BrainAmp DC amplifiers (Brainproducts, http://www.brainproducts.de) were used in the AC coupled mode with a time constant of 10 s, and a sampling rate was 1000 Hz to record the data. Electrode impedances were kept below 10 kΩ during the measurement.

2.4.1. Behavioural data

Similar to a previous study (Prodi et al., 2010), we calculated the ratio between the performance (hit rate) and the reaction times, which we refer to here as task efficiency. This ratio was calculated for all four conditions in the EEG task (attend visual: congruent, incongruent; attend auditory: congruent, incongruent), for both groups (CI/NH) and all three measurement time points separately. Importantly, this measure of task efficiency matches the accuracy with the time that is needed to achieve it (Prodi et al., 2010).

2.4.2. EEG preprocessing

Prior to the EEG data analysis, all trials with missing or false responses were removed from the dataset. The incongruent catch trials were not included in the further analysis, due to an insufficient number of trials for the EEG data analysis. Thus, only the correct congruent audiovisual trials were included into the EEG preprocessing.

The imported data was analysed with EEGLAB (Delorme and Makeig, 2004) in the MATLAB environment (R2020a; Mathworks). The data were downsampled to 500 Hz and filtered offline using a FIR-filter. The high pass cut-off frequency was 0.1 Hz with a maximum possible transition bandwidth of 0.2 Hz (two times cut-off frequency), and the low pass cut-off frequency was 40 Hz with a transition bandwidth of 2 Hz. In both cases, the Kaiser-window (beta = 5.653, maximal stopband attenuation = −60 dB, maximal passband deviation = 0.001) approach was used (Widmann et al., 2015), where the energy concentration in the main lobe is maximised and the noise in the spectrum is averaged out, which reduces information loss at the edges of the window (Widmann et al., 2015). In a second step, an independent component analysis (ICA) was computed on additionally bandpass-filtered (1 Hz – 40 Hz) dummy-segments of two seconds of duration, to identify components assigned to the electrical CI artefact, ocular artefacts and other sources of non-cerebral activity. These components were then removed, and remaining artefact-containing trials were subsequently rejected from the dataset using an amplitude threshold criterion of four standard deviations (Jung et al., 2000). Afterwards, the EEG data was segmented into epochs from −100 to 1000 ms relative to the onset of the lip movement, and a baseline correction was applied (−100 to 0 ms).

Subsequently, the global field power (GFP) was used to compare the different groups, conditions and time points. The GFP equals the root mean square (RMS) across the average-referenced electrode values at one point in time, which provides the spatial standard deviation of all electrodes at this time point (Murray et al., 2008). The GFP, which was first introduced by Lehmann and Skrandies (1980), is advantageous compared to selected regions of interest, because it avoids biases that can be caused by wrong channel selections. In this study, we chose two time windows in which the GFP peaks were analysed with regards to the amplitude and latency. The first time window included the time period of 50–190 ms after lip movement onset, and the second time window included the time period of 200–400 ms after the lip movement onset.

2.4.3. Topographic analysis

To explore for topographic differences between groups and conditions, we analysed the global map dissimilarity (GMD; Lehmann and Skrandies, 1980) using the software CARTOOL (Brunet et al., 2011). The GMD quantifies topographic differences and configurations of neural sources (Vaughan Jr, 1982) independently of the signal strength (Murray et al., 2008). We computed a so-called 'topographic ANOVA' (TANOVA; Murray et al., 2008), which is a non-parametric randomisation test, by using 5000 permutations and by computing sample-by-sample p-values. To control for multiple comparisons, an FDR-correction was applied (Benjamini and Hochberg, 1995). Since previous observations suggest that ERP topographies stay stable for a certain time period before changing to another topography (Michel and Koenig, 2018), the minimal significant duration was set to 10 consecutive time frames (corresponding to 20 ms).

2.4.4. Hierarchichal clustering and single-subject fitting analysis

A difference in the GMD can be explained by two different reasons. First, it can originate from a latency shift of the ERP, causing similar topographic maps that are shifted in time. Second, it can be caused by different configurations of the underlying neural generators between the compared groups/conditions. In order to distinguish between these two reasons for topographic differences, a hierarchical topographic clustering was performed by calculating template topographies based on the group-averaged data (separately for attend visual and attend auditory) in the two time windows of interest (following the lip movement: 50–190 ms and 200–400 ms). Following the recommendations by Murray et al. (2008), we performed this analysis in CARTOOL (Brunet et al., 2011), using the atomize and agglomerate hierarchical clustering (AAHC). This type of topographic clustering finds the minimal number of topographies (template maps), explaining the greatest variance in a given dataset by including the global explained variance of a cluster and hindering blind combinations (or agglomerations) of clusters with short durations. This is done because ERP topographies do not show random variations across time but stay stable for some time (microstates; Michel and Koenig, 2018).

In a second step, the identified template maps were submitted to a single-subject fitting (Murray et al., 2008). In this procedure, a sample-wise correlation for each subject and condition is computed between each template map and the observed voltage topographies of each participant in order to quantify how specific the templates are distributed on a single-subject's level. Each time point is matched to the template map with the highest spatial correlation. We statistically analysed two different outcome measures, in particular the *first onset of maps* (latency) and the *map presence* (number of time frames) assigned to a specific template topography.

2.4.5. Time-frequency analysis

To examine the results in different frequency ranges, we calculated event-related spectral perturbations (ERSP) for each participant at each channel using a sinusoidal wavelet-based analysis implemented in EEGLAB (Delorme and Makeig, 2004). The number of cycles increased with frequency (start point 3-cycle wavelet with sliding Hanning-tapered window, 30 frequency steps from 1 to 30 Hz). Power changes across frequencies were baseline-corrected by subtracting the mean baseline power spectrum (−100 to 0 ms). The ERSPs were averaged for an occipital ROI (PO3, POz, PO4, O1, Oz, O2) and a central ROI (FCz, Cz, C1, C2, CPz). For statistical evaluation, two time-frequency-windows were defined, matching the time windows of the prior analysis. The first time-frequency window starts directly after the lip movement onset (50–190 ms), the second starts afterwards

(200–800 ms).

2.4.6. *Source analysis*

The Brainstorm software (Tadel et al., 2011) was used to compute cortical source activities (Stropahl et al., 2018). The software applies dynamic statistical parametric mapping (dSPM; Dale et al., 2000) to the data, which uses the minimum-norm inverse maps with constrained dipole orientations to estimate the electrical activity of the neurons based on the scalp-recorded measures. It localises deeper sources more accurately than other methods (e.g., the standard minimum norm), but the spatial resolution is still blurred (Lin et al., 2006). Individual noise covariance matrices and thereby individual noise standard deviations at each location were calculated using the single-trial pre-stimulus baseline interval (−100 to 0 ms; Hansen et al., 2010). The boundary element method (BEM) was used as a head model. It is implemented in Open MEEG and provides three realistic layers and representative anatomical information (Gramfort et al., 2010; Stenroos et al., 2014). Given that we were primarily interested in the cortical activation in both the visual and auditory cortex, we defined a visual and an auditory region of interest (ROI) based on the implemented Destrieux-Atlas (Destrieux et al., 2010). Similar to previous studies (Prince et al., 2021; Layer et al., 2022a), we used a visual ROI consisting of the *left and right pole_occipital* to approximate the primary visual cortex, and we used an auditory ROI consisting of the *left and right Lat_fis-post* to approximate Brodmann areas 41 and 42. Source activities were evaluated in these ROIs using the peak activation magnitude and latency for each participant in the two time windows (first time window: 50–190 ms, second time window: 200–400 ms). The activation data have absolute values and arbitrary units calculated by the normalisation within the dSPM algorithm.

2.4.7. *Connectivity analysis*

For the computation of connectivity values between the used ROIs, a pre-implemented procedure in Brainstorm was used (envelope correlation). This was done by computing a correlation on the instantaneous amplitude, also called envelope, of the analytic signal derived from the original data. This analytic signal is the result of a Morlet wavelet transformation. To reduce volume conduction and cross-talk effects, the pairs of envelopes were orthogonalized prior to the connectivity computation (Hipp et al., 2012). The connectivity measure was calculated for the time-window after the lip movement (50–400 ms).

2.4.8. *Statistical analysis*

To statistically evaluate the behavioural and ERP/ERSP data, the software R (Version 3.6.3, R Core Team 202, Vienna, Austria) was used. The ERP data were separately examined on the sensor level (GFP, GMD) and the source level (visual and auditory cortex). In a first step, we analysed the data in a longitudinal approach, computing the analysis of variance (ANOVA) for the two conditions (attend visual, anted auditory) separately due to the different number of data sets (three measurement time points for attend visual, two measurement time points for attend auditory). Specifically, we computed mixed ANOVAs with the between-subject factor "group" (CI/NH) and the within-subject factor "time point" (before implantation/five weeks CI use/six months CI use). In a second step, we examined the effect of direction (visual/auditory) of attention on the behavioural and ERP/ERSP results, using 2 × 2 × 2 mixed ANOVAs with the within-subjects factors condition (attend visual, attend auditory) and time point (second and third time point). Significant interactions and main effects ($p \leq 0.05$) were followed-up by paired *t*-test, and they were corrected for multiple comparisons by the Holm-Bonferroni approach (Holm, 1979). In case of a violation of sphericity, a Greenhouse-Geisser correction was applied.

3. Results

3.1. *Behavioural data*

Fig. 2 shows the behavioural results of the EEG paradigm, more precisely the task efficiency as calculated by dividing the performance by the reaction times. In addition, the reported subjective listening effort, as well as the results of the two additional behavioural tasks (McGurk paradigm, lipreading task) are illustrated in Fig. 2. Moreover, Fig. 2D shows a scatterplot, representing the correlation between the lipreading ability and the task efficiency specifically for the incongruent stimuli (i.e. catch trials) in the visually attended condition.

Regarding the *task efficiency* in the context of the longitudinal analysis, we computed two mixed ANOVAs (one for the attend visual condition and one for the attend auditory condition) with the between-subjects factor group (CI, NH) and the within-subjects factors condition (congruent, incongruent) and time point (attend visual: before implantation, five weeks CI use, six months CI use; attend auditory: five weeks CI use, six months CI use; note that the participants were not tested in the auditory attended conditions at the first measurement time point, because they had severe to profound hearing loss before cochlear implantation). Regarding the analysis of *visually attended* blocks (congruent and incongruent conditions), the 2 × 2 × 3 ANOVA showed a main effect of condition ($F_{1,31} = 155.10$ $p \leq 0.01$, $\eta^2 = 0.43$), which was caused by better efficiency for the congruent compared to the incongruent condition in both groups at all time points. Regarding the *auditory attended* blocks (congruent and incongruent conditions), the 2 × 2 × 2 ANOVA showed a main effect of group ($F_{1,31} = 11.64$, $p \leq 0.01$, $\eta^2 = 0.08$), which was caused by a better efficiency for the NH group compared to the CI group in both conditions at all time points.

In order to analyse the effect of (visual/auditory) attention on *task efficiency*, we computed a 2 × 4 × 2 ANOVA, including the between-subject factor group (NH, CI) and the within-subjects factors condition (attend visual and attend auditory in congruent and incongruent conditions, respectively) and time point (five weeks CI use, six months CI use). This analysis revealed a main effect of condition ($F_{3,31} = 78.17$, $p \leq 0.01$, $\eta^2 = 0.48$), which was due to a higher efficiency for the auditory attended conditions as compared to the visually attended conditions.

For the *listening effort*, a 2 × 2 × 2 mixed-ANOVA was computed, with the within-subjects factor group (CI, NH), and the within-subjects factors condition (attend visual, attend auditory) and time point (five weeks CI use, six months CI use). The results showed a three-way interaction ($F_{1,31} = 3.36$, $p = 0.05$, $\eta^2 = 0.09$), which could be explained by a greater listening effort in the auditory attended condition for the CI users compared to the NH listeners specifically at the time five weeks of CI use (second time point). Additionally, the listening effort was greater in the attend visual condition as compared to the attend auditory condition in both groups and at both time points. Interestingly, the listening effort in the attend auditory condition correlated with the monosyllabic word test specifically in the CI group at the second time point ($R = -0.68$, $p \leq 0.01$): The better the speech recognition ability (in auditory-only conditions), the easier to attend to the auditory signal of the audio-visual word.

Regarding the *lip-reading task* (additional behavioural task), the 2 × 3 mixed-ANOVA with the factor group (CI, NH) and the within-subject factor time point (before implantation, five weeks CI use, six months CI use) revealed a main effect of group ($F_{1,31} = 4.88$, $p = 0.03$, $\eta^2 = 0.12$), where the CI group showed better lipreading ability than the NH group at all time points. A subsequent correlation analysis showed for both groups a positive relationship between the lipreading ability and the task efficiency in the incongruent visually attended condition (CI group: $R = 0.64$, $p \leq 0.01$; NH group: $R = 0.57$, $p = 0.02$; see Fig. 2D).

For the *behavioural McGurk paradigm* (additional behavioural task), two mixed ANOVAs were computed. One for the congruent syllables, more precisely a 2 × 3 mixed-ANOVA with the within-subjects factor group (CI, NH) and the between-subjects factor time point (before

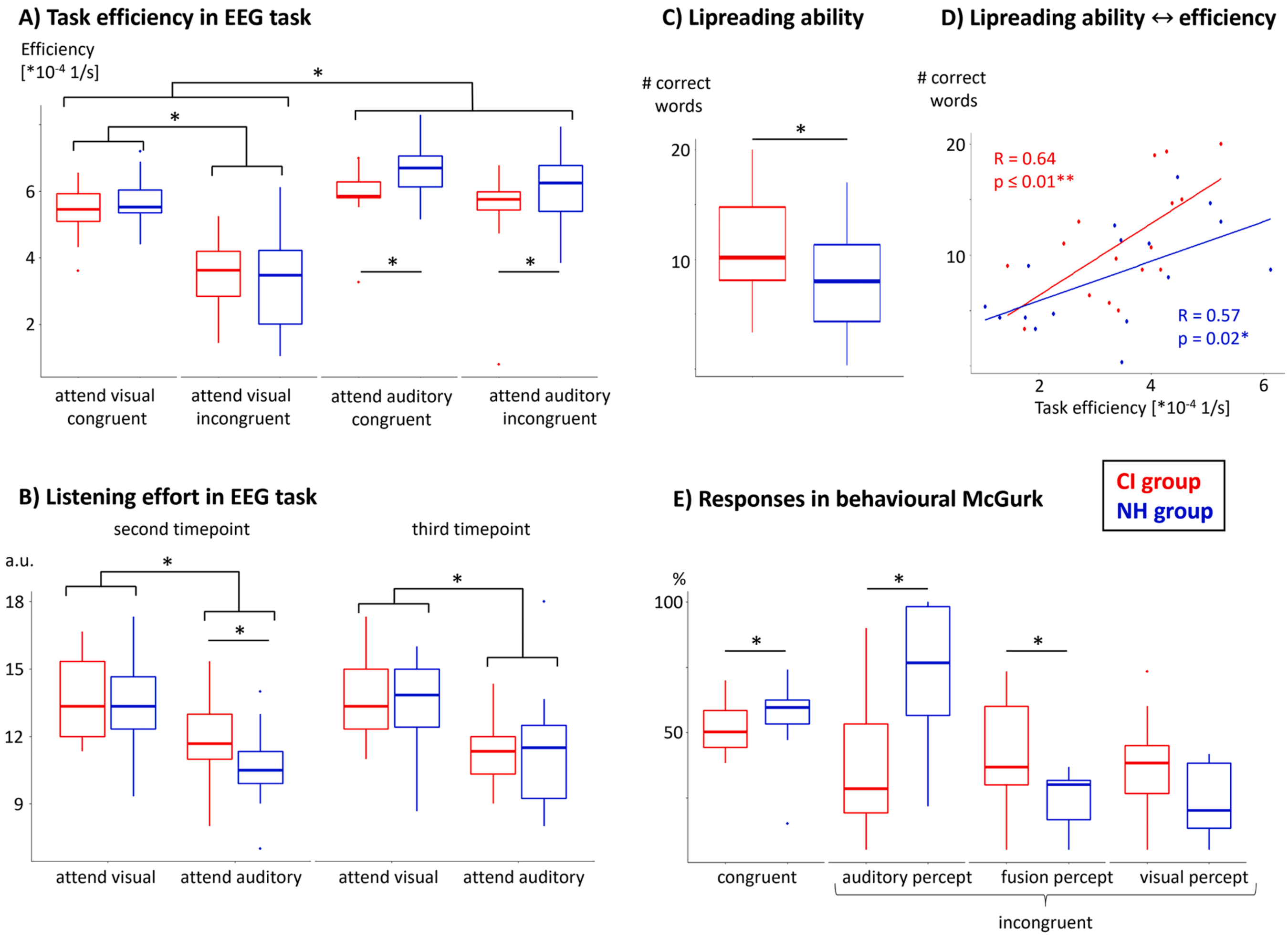


Fig. 2. The behavioural results. A) Task efficiency in the EEG task, which reflects the ratio between the measures of performance and response times, is given for all four conditions. The results are averaged over all time points since no effect of the factor time point was found. B) Listening effort rated after each block for the EEG task. Note that this measure was not recorded at the first time point/before implantation, since the CI candidates could hardly hear at this point. C) Lipreading ability measured by the additional behavioural task with natural speakers and words from the German monosyllabic word test. The results are averaged over all time points since no effect of the factor time point was found. D) Positive correlation for both groups between the lipreading ability (additional behavioural task) and the task efficiency (EEG paradigm) for the incongruent stimuli (i.e. catch trials) in the visually attended condition. E) Responses in the additional behavioural McGurk paradigm including congruent and incongruent audiovisual syllables. Asterisks indicate significant effects ($p < 0.05$).

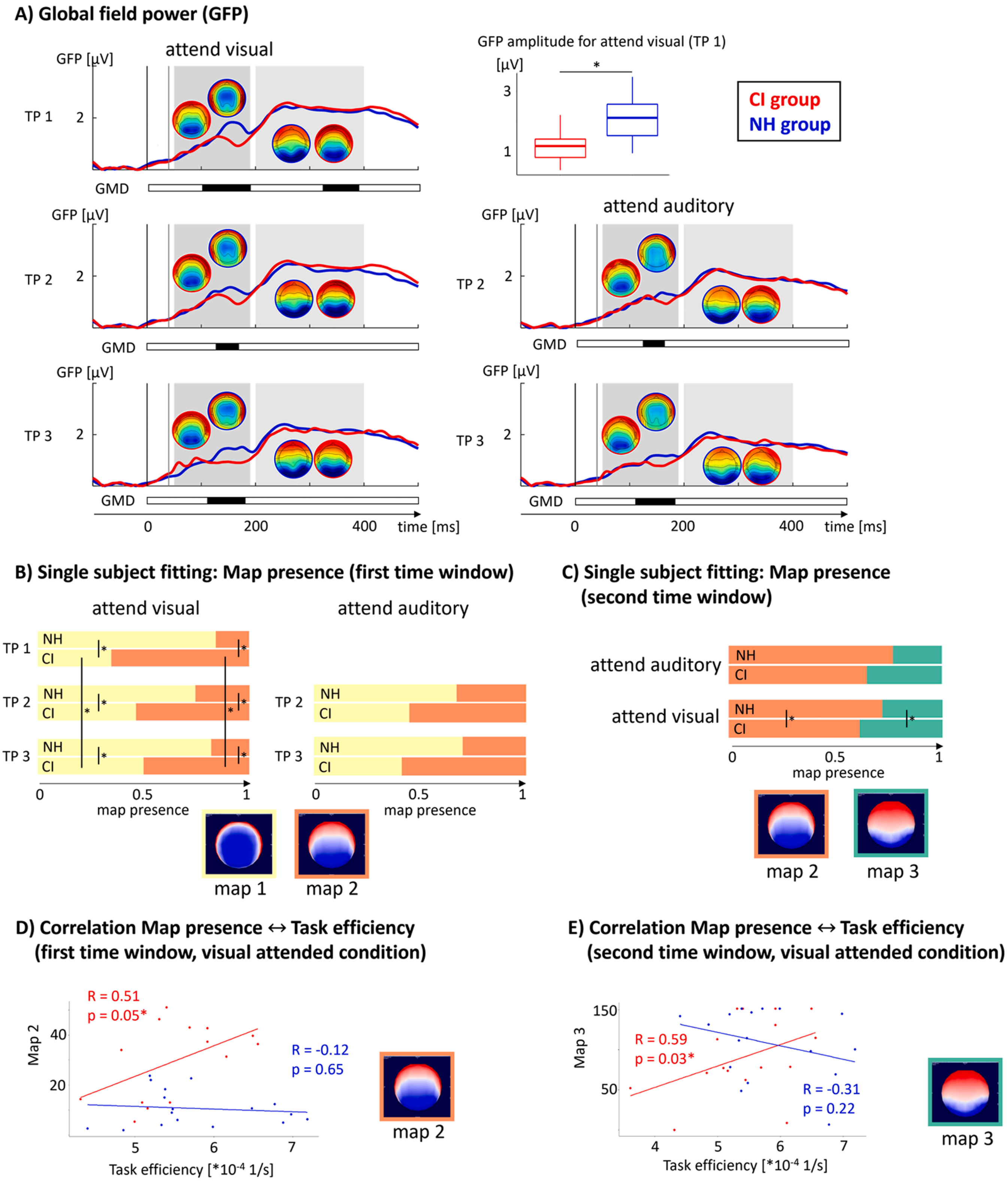
implantation, five weeks CI use, six months CI use), and one for the incongruent syllables with the additional within-subjects factor percept (auditory percept, fusion percept, visual percept). The 2 × 3 mixed ANOVA for the congruent syllables showed a main effect of group ($F_{1,31} = 8.03, p \leq 0.01, \eta^2 = 0.04$) with a better performance in the NH group compared to the CI group. The 2 × 3 × 3 mixed ANOVA for the incongruent syllables showed a two-way interaction between group and percept ($F_{2,31} = 30.70, p \leq 0.01, \eta^2 = 0.21$). Post-hoc tests revealed that the NH group reported more auditory syllables than the CI group, whereas the CI group was more likely to report the fusion percept than the NH group. All these group differences in the McGurk paradigm were present regardless of the time point.

In summary, our behavioural results support the sensory compensation hypothesis, since the auditory deprived patients showed enhanced visual abilities, especially in the lip-reading task and a higher influence of the visual modality in the McGurk task. Contrarily, as expected, the group of NH listeners showed enhanced auditory abilities as shown in a greater task efficiency and more auditory dominance in the incongruent McGurk syllables.

3.2. Sensor level: GFP and GMD

Fig. 3A displays the global field power (GFP) of both conditions at all time points for both groups separately. Two peaks are identifiable after the onset of the lip movement. The first peak appears at approximately 150 ms after lip movement onset (i.e., 110 ms after auditory onset), which corresponds to the time window of an auditory N1. This peak is followed by a second peak at approximately 250 ms after lip movement onset (i.e., 210 ms after auditory onset), which corresponds to the time window of an auditory P2. The topographic plots reveal differences between the two groups, especially for the first peak, with a more occipitally oriented map (map 2) for the CI group and a more centrally oriented map (map 1) for the NH group at all time points.

For the analysis of the GFP peak and the GFP peak latency in the context of the longitudinal analysis, we computed separate mixed ANOVAs, with group (NH, CI) as between-subject factor and time point (attend visual: before implantation, five weeks CI use, six months CI use; attend auditory: five weeks CI use, six months CI use) as within-subject factors. Note that due to the different number of time points (three for attend visual, two for attend auditory), these ANOVAs were separately performed for the visually attended and the auditory attended condition. We did not find significant effects in the attend auditory condition,



(caption on next page)

Fig. 3. Results of the sensor level analysis. A) GFP plots for both conditions at all time points, respectively. The GFP for the CI group is drawn in red, the GFP for the NH group is drawn in blue. The two time windows for GFP peak analysis are marked by grey boxes. Topographies for both time windows are depicted per group at all of the three time points (TP1 = before implantation; TP 2 = five weeks CI use; TP 3 = six months CI use). Note that in the first time window, the CI group showed an occipitally oriented map (map 2), whereas the NH listeners showed a more centrally oriented map (map 1). Significant time windows for the global map dissimilarity (GMD; indicating significant map differences between groups) are shown with the black areas in the bars underneath each GFP plot. The boxplot depicts the significantly reduced GFP amplitude for CI candidates compared to NH listeners in the first time window and at the first time point in the "attend visual condition". B) Cumulative map frequency for two template maps (map 1 and 2) in the first time window. Note that for the attend visual condition, the CI group showed an increase in map frequency of the centrally oriented map (map 1) from the first to the third time point. In addition to this within-group effect, a between-group difference was observed at all time points in the attend visual condition, with higher map frequency for the centrally oriented map (map 1) in the NH group compared to the CI group. D) Cumulative map frequency for two template maps (map 2 and 3) in the second time window. A between-group difference was observed for the attend visual condition, with a higher frequency of the more occipitally oriented map (map 3) in the NH group compared to the CI group. D) First time window: Positive correlation between the map presence and the task efficiency in the attend visual condition. This relationship was found specifically for the CI group but not for the NH group. The results are averaged over all time points. E) Second time window: Positive correlation between the map presence and the task efficiency in the attend visual condition. This relationship was found specifically for the CI group but not for the NH group. The results are averaged over all time points (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

neither for the first nor for the second time window. By contrast, for the attend visual condition, we found a significant interaction between group and time point ($F_{2,62} = 6.14$, $p \leq 0.01$, $\eta^2 = 0.05$). Post-hoc tests revealed a larger GFP amplitude for the NH group compared to the CI group specifically at the first time point (i.e., before implantation). The corresponding boxplot in Fig. 3A shows this result. Unlike the first time window, the ANOVAs computed on the GFP measures from the second time window did not reveal any significant results.

In order to analyse the effect of (visual/auditory) attention on GFP peak and GFP latency, we calculated additional 2 × 2 × 2 mixed ANOVAs with the between-subject factor group (NH, CI) and the within-subjects factors time point (five weeks CI use, six months CI use) and condition (attend visual, attend auditory). We found a main effect of condition for both the first and the second GFP peak amplitude (first: $F_{1,31} = 17.72$, $p \leq 0.01$, $\eta^2 = 0.07$; second: $F_{1,31} = 13.65$, $p \leq 0.01$, $\eta^2 = 0.02$), and the GFP latency of the second peak ($F_{1,31} = 5.19$, $p = 0.03$, $\eta^2 = 0.02$). Specifically, the visually attended condition resulted in GFP peaks with enhanced amplitude (both time windows) and prolonged latency (second time window) when compared to the auditory attended condition, regardless of group and time point.

Regarding the global map dissimilarity (GMD), sample-by-sample p-values were computed to quantify differences in ERP topographies between groups. This was done separately for each condition (attend visual, attend auditory) and each time point (attend visual: before implantation, five weeks CI use, six months CI use; attend auditory: five weeks CI use, six months CI use). The results revealed significant group differences in all conditions and at all time points, especially in the time range of the first time window (bars beneath GFP plots in Fig. 3A). The exact values of the significantly different GMD values can be seen in Table 2.

3.3. Sensor level: topography

To explore the origin of the underlying topographic differences between the groups and conditions, a hierarchical topography clustering analysis was performed. This method identifies template topographies in the time windows of interest, using the atomize and agglomerate hierarchical clustering (AAHC) to find the minimal number of topographies that explain the greatest variance in the dataset. Our analysis identified 4 template maps in 13 clusters that collectively explained 94.44% of the concatenated data. More precisely, two maps for the first time window (map 1 and 2) and two maps for the second time window (map 2 and 3) were observed. These template maps were submitted to a single-subject fitting (Murray et al., 2008) in order to quantify the presence and the first onset of these template maps on a single-subject level. We analysed the *map presence* (number of time frames where a corresponding template map is best correlated to the single subject data) to explore whether the topographic differences can be explained by group-specific patterns of ERP maps (for the analysis of the *first onset* of template maps see below). This would point to a distinct pattern of underlying neural generators between the two groups.

Table 2
Time windows in which the GMD values are significantly different between groups.

	Attend visual	Attend auditory
Time point 1: before implantation	100–188 ms + 316–390 ms	–
Time point 2: five weeks of CI use	132–166 ms	134–166 ms
Time point 3: six months of CI use	114–182 ms	108–184 ms

In the context of the longitudinal analysis, we computed separate mixed-ANOVAs for the two conditions (attend visual, attend auditory) and the two time windows (first, second), respectively. This was done using the between-subjects factor group (NH, CI) and the within-subjects factors time point (attend visual: before implantation, five weeks CI use, six months CI use; attend auditory: five weeks CI use, six months CI use) and template map (first time window: map 1 and map 2; second time window: map 2 and 3). For the *first time window*, we found a significant threefold interaction between the factors template map, time point and group for the *attend visual condition* ($F_{2,} = 2.63$, $p = 0.05$, $\eta^2 = 0.03$). Post-hoc *t*-tests revealed for the CI group in general (i.e., regardless of time point) a significantly reduced presence of the centrally oriented map 1 when compared to the NH group. However, the presence of this centrally oriented map 1 grew with increasing CI use, thereby approaching but not reaching the map 1 presence of the NH group. For the *second time window*, we again observed for the *attend visual condition* a significant interaction between the factors group and template map ($F_{1,31} = 5.49$, $p = 0.02$, $\eta^2 = 0.03$), which was caused by a higher presence of the centrally oriented map 2 for the NH group compared to the CI group. This group difference in the presence of map 2 was evident regardless of the time point. Regarding the *attend auditory condition*, the group(2) x time point(2) x template map(2) ANOVAs computed on the presence of maps did not reveal any significant results, neither for the first nor for the second time window.

In order to analyse the effect of (visual/auditory) attention on the template maps, we computed mixed ANOVAs with the between-subject factor group (NH, CI) and the within-subject factors time point (five weeks CI use, six months CI use), condition (attend visual, attend auditory), and template map (first time window: map 1 and map 2; second time window: map 2 and 3). The results revealed for the *first time window* an interaction between condition and map ($F_{1,31} = 7.95$, $p \leq 0.01$, $\eta^2 = 0.01$). This interaction effect was caused by the centrally oriented map (map 1) that was more present in the attend auditory condition as compared to the attend visual condition, regardless of group and time point. No significant effects were found for the *second time window*.

In a final step, we analysed the *first onset* of template map to explore whether the topographic differences between groups can be explained by latency shifts. In the context of the longitudinal analysis, we computed separate mixed-ANOVAs for the two conditions (attend visual, attend auditory) and the two time windows (first, second), respectively. This was done using the between-subjects factor group (NH, CI) and the within-subjects factors time point (attend visual: before implantation, five weeks CI use, six months CI use; attend auditory: five weeks CI use, six months CI use) and template map (first time window: map 1 and map 2; second time window: map 2 and 3). We found for the *first time window* an interaction between group and template map ($F_{1,31} = 12.68, p \leq 0.01, \eta^2 = 0.08$), revealing a delayed onset of the centrally oriented map 1 for the CI group when compared to the NH group in the *attend visual condition*, but not in the attend auditory condition. No significant results were found for the second time window. In addition, the analysis of the attention effect on the first onset of template map, as performed by a group (2) x time point (2) x condition (2) x template map (2) ANOVA, showed neither a significant main effect nor a significant interaction.

To sum up, our results for the GFP and GMD, including the single-subject topographic analysis, revealed different processing patterns for NH listeners and postlingually deafened individuals before and after implantation, with greater visual influence in the CI group at all time points. With increasing time of CI use, the deafened individuals approach the processing pattern of NH listeners, although the enhanced visual influence persists even in more experienced CI users.

3.4. Sensor level: time-frequency

Fig. 4 shows the results of the time-frequency event-related spectral perturbations (ERSPs) separately for both groups, both conditions and both ROIs averaged over the same two time points that were used in the GFP analysis. Several subplots show a power increase in the theta frequency range (4–8 Hz) directly after the onset of the lip movement and after the auditory onset (first time window: 50–190 ms). This theta-power increase is generally more pronounced in the NH group compared to the CI group, and it is stronger in the visually attended than the auditory attended condition. At a later time range (second time window: 200–800 ms), all of the subplots show a pronounced decrease in power over a broad frequency range (4–30 Hz), encompassing frequencies between the theta and beta band.

Regarding the *first time-frequency window* (50–190 ms; 4–8 Hz), we computed a 2 × 3 × 2 mixed ANOVA for the attend visual and a 2 × 2 × 2 ANOVA for the attend auditory condition. Specifically, these ANOVAs were separately calculated for three frequency ranges (theta: 4–8 Hz; alpha: 8–12 Hz; beta: 13–30 Hz) by using the between-subjects factor group (NH, CI) and the within-subjects factors time point (attend visual: before implantation, five weeks CI use, six months CI use; attend auditory: five weeks CI use, six months CI use) and ROI (occipital, central). The results revealed a main effect of group for both conditions (attend visual: $F_{1,31} = 14.89, p \leq 0.01, \eta^2 = 0.23$; attend auditory: $F_{1,31}, = 5.62$,

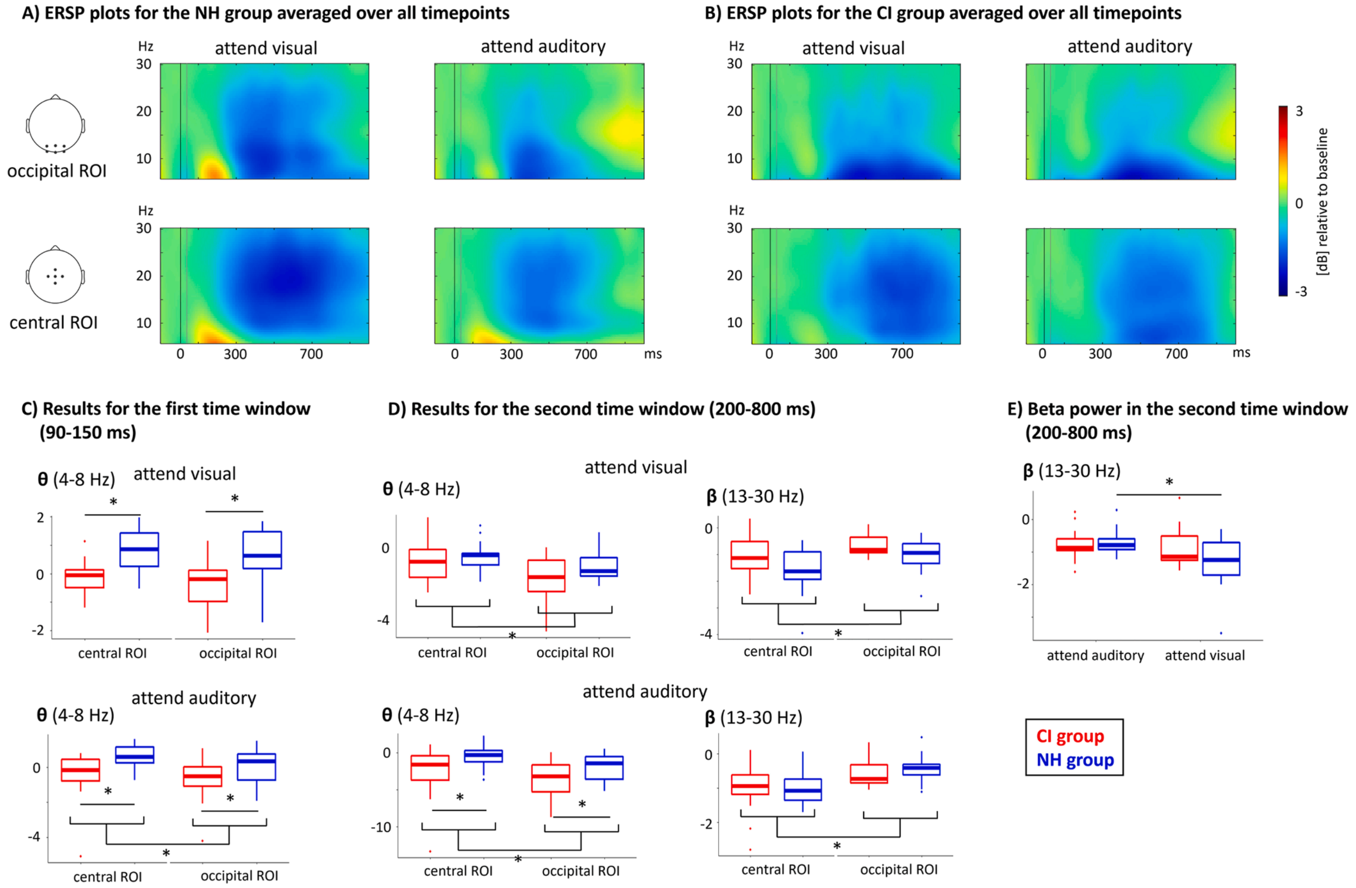


Fig. 4. Time frequency plots. A) ERSP plots for the NH group for both conditions in two ROIs. Note that the plots are averaged over all time points. The black line represents the onset of the lip movement (0 ms) and the grey line represents the onset of the auditory word (40 ms). B) ERSP plots for the CI group for both conditions in two ROIs. Note that the plots are averaged over all time points. The black line represents the onset of the lip movement (0 ms) and the grey line represents the onset of the auditory word (40 ms). C) Statistical results for the first time window (50–190 ms) in the theta frequency range for both conditions, showing a decreased theta power in the CI group than the NH group regardless of the ROI. D) Statistical results for the second time window (200–800 ms) in the theta and beta frequency range for both conditions. When compared to the NH group, the CI group showed a decreased power in the theta range for the attend auditory condition, regardless of time point and ROI. However, both groups revealed higher power in the theta range for the central ROI and higher power in the beta range for the occipital ROI. E) Statistical results for the attention effect in the second time window (200–800 ms). The NH group showed a decreased beta power for the visually attended condition when compared to the auditory attended condition, while the CI group did not show this condition difference.

$p = 0.02$, $\eta^2 = 0.10$), and a main effect of ROI for the attend auditory condition ($F_{1,31} = 24.33$, $p \leq 0.01$, $\eta^2 = 0.03$). The post-hoc *t*-tests revealed for the CI users a decreased theta power than the NH group, regardless of the ROI, the condition, and the time point. Moreover, the oscillatory activity in the theta range was increased in the central ROI when compared to the occipital ROI in the attend auditory condition, regardless of group and time point. The subsequent comparison of the two attention conditions by means of an additional 2 × 2 × 2 mixed ANOVA showed an interaction between ROI (central, occipital) and condition (attend visual, attend auditory) ($F_{1,31,} = 6.47$, $p = 0.02$, $\eta^2 = 0.01$), which was due to more theta power in the occipital ROI for the attend visual condition compared to the attend auditory condition in both groups.

Regarding the *second time-frequency window* (200–400 ms; 4–30 Hz), the statistical analysis was performed separately for three frequency ranges (theta: 4–8 Hz; alpha: 8–12 Hz; beta: 13–30 Hz). Specifically, we computed a 2 × 3 × 2 mixed ANOVA for the attend visual and a 2 × 2 × 3 ANOVA for the attend auditory condition, with the between-subjects factor group (NH, CI) and the within-subjects factors time point (attend visual: before implantation, five weeks CI use, six months CI use; attend auditory: five weeks CI use, six months CI use) and ROI (occipital, central). For the *theta range* (4–8 Hz), the ANOVAs computed on both conditions showed a main effect of ROI (attend visual: $F_{1,30} = 42.01$, $p \leq 0.01$, $\eta^2 = 0.11$; attend auditory: $F_{1,30} = 9.59$, $p \leq 0.01$, $\eta^2 = 0.04$), with higher oscillatory activity in the central ROI compared to the occipital ROI. However, the ANOVA computed on the attend auditory condition additionally showed a main effect of group ($F_{1,30} = 5.50$, $p = 0.03$, $\eta^2 = 0.08$), which was caused by higher oscillatory activity for the NH group compared to the CI group. For the *alpha frequency range* (8–12 Hz), the ANOVA for the attend visual condition revealed a significant interaction between the factors group and time point ($F_{2,60} = 4.57$, $p \leq 0.01$, $\eta^2 = 0.02$), although the post-hoc tests did not confirm significant effects. For the *beta range* (13–30 Hz), both ANOVAs revealed a main effect of ROI (attend visual: $F_{1,30} = 41.40$, $p \leq 0.01$, $\eta^2 = 0.10$; attend auditory: $F_{1,30} = 26.14$, $p \leq 0.01$, $\eta^2 = 0.15$), which was due to higher oscillatory activity in the occipital ROI compared to the central ROI in both conditions. The additional group (2) x time point (2) x condition (2) x ROI (2) ANOVA computed to study the effect of attention on oscillatory power

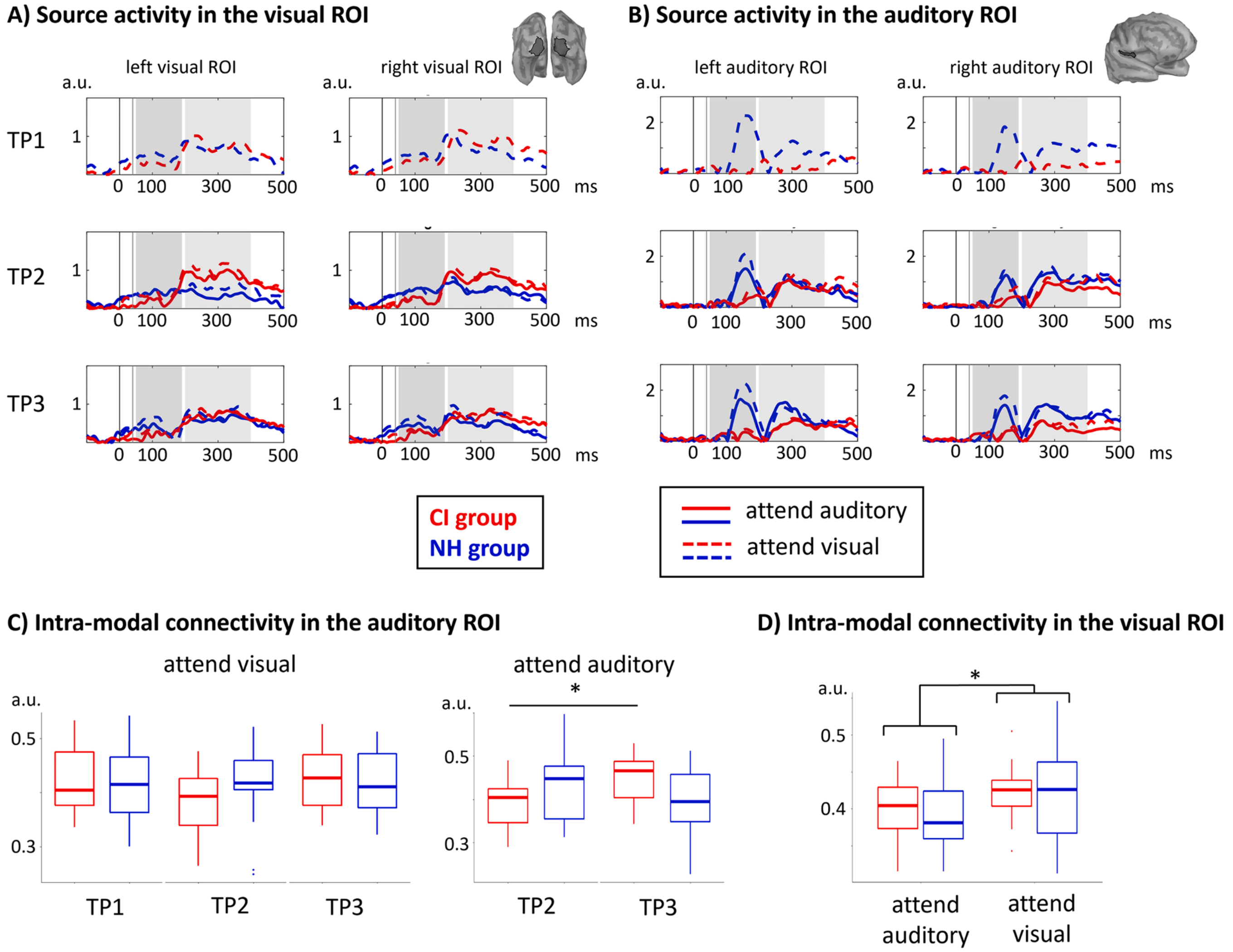


Fig. 5. Source activity for two ROIs and both conditions (attend visual, attend auditory) at all time points (TP1 = before implantation; TP 2 = five weeks of CI use; TP 3 = six months of CI use). A) Source activity in the visual ROI. Grey areas indicate the two time windows for peak detection. B) Source activity in the auditory ROI. Grey areas indicate the two time windows for peak detection. Greater activation for the NH group as compared to the CI group at all timepoints in the first time window. C) Mean intra-modal connectivity, as indicated by envelope correlation (50–400 ms after lip movement onset), for the auditory cortex. The results revealed specifically for the attend auditory condition and specifically for the CI users an increase in connectivity between the two auditory cortices, suggesting an effect of CI experience on functional connectivity. D) Mean intra-modal connectivity, as indicated by envelope correlation (50–400 ms after lip movement onset), for the visual cortex. The results revealed an increased connectivity between the left and right visual cortex for the attend visual condition compared to the attend auditory condition.

revealed an interaction between group and condition ($F_{1,31} = 5.42$, $p \leq 0.01$, $\eta^2 = 0.03$) in the beta frequency range (13–30 Hz). This interaction effect was driven by the NH group who showed enhanced beta power in the auditory than visually attended condition, regardless of the ROI. Furthermore, we found a correlation for the CI group between the beta power in the visually attended condition and the speech recognition ability in the monosyllabic word test ($R=-0.62$, $p \leq 0.01$). Greater beta power, reflecting reduced cognitive load, was related to a poorer speech recognition ability.

Taken together, we found two main effects in the time-frequency analysis. First, a decreased theta power right after the onset of the lip movement for the CI group when compared to the NH group. Second, a condition difference solely in the NH group for the beta power at the later time window, revealing decreased beta power for the visually attended when compared to the auditory attended condition.

3.5. *Source level: activation in visual and auditory cortex*

To further explore the observed group differences and to evaluate the audiovisual speech processing in the auditory and visually attended condition, a source analysis was conducted. Based on previous research, we focused on the auditory and visual cortex activity in both hemispheres. Fig. 5 displays the activation in the visual and auditory cortex, with one peak in the first time window (corresponding to the N1 latency range; 50–190 ms) and one in the second time window (corresponding to the P2 latency range; 200–400 ms). These peaks show an increase over time in the CI group, and they are more pronounced in the auditory than the visual cortex.

The analysis of the *peak amplitudes* in the *auditory cortex* revealed for the attend visual condition a main effect of group in the *first time window* ($F_{1,31} = 19.87$, $p \leq 0.01$, $\eta^2 = 0.28$), which was caused by greater activation for the NH group compared to the CI group. Further, this ANOVA showed a significant interaction between the factors group and time point ($F_{2,62} = 5.16$, $p \leq 0.01$, $\eta^2 = 0.04$), indicating that CI users have greater activation for the time points after implantation compared to the time point before implantation. Similar to the attend visual condition, the ANOVA computed on the attend auditory condition revealed a main effect of group ($F_{1,31} = 4.87$, $p = 0.04$, $\eta^2 = 0.09$), which was caused by greater activation for the NH group compared to the CI group. For the *second time window*, we found a significant effect only for the peak amplitude in the visually attended condition. Specifically, there was an interaction between the factors group and time point ($F_{2,62} = 4.16$, $p = 0.02$, $\eta^2 = 0.04$), which was caused specifically by the CI users who showed an enhanced auditory-cortex activation at the time points after implantation compared to the time point before implantation. No significant effects were found in the group (2) x time point (2) x condition (2) ANOVAs computed to study the effect of attention on the peak amplitudes in the auditory cortex.

Regarding the ANOVAs computed on the *peak latency* in the *auditory cortex,* the mixed ANOVAs computed separately for the visually (2 × 2 × 3 ANOVA) and auditory (2 × 2 × 2 ANOVA) attended conditions revealed for the *first time window* a main effect of group (attend visual: $F_{1,31} = 25.01$, $p \leq 0.01$, $\eta^2 = 0.17$; attend auditory: $F_{1,31} = 5.30$, $p = 0.03$, $\eta^2 = 0.05$), which was due to a prolonged latency for the CI group compared to the NH group. However, in the *second time window*, no significant results were found for the peak latencies. The group (2) x time point (2) x condition (2) ANOVAs, which were computed to study the attention effect on the peak latency, revealed for the first time window a main effect of condition ($F_{1,31} = 17.14$, $p \leq 0.01$, $\eta^2 = 0.03$), which was caused by a prolonged latency for the auditory than visually attended condition.

The longitudinal analysis of the *peak amplitudes and peak latencies* in the *visual cortex*, including group (2) x time point (3) mixed ANOVAs for the visually attended condition and group (2) x time point (2) ANOVAs for the auditory attended condition, did not reveal any significant effects. However, the group (2) x time point (2) x condition (2) ANOVAs computed to study the effect of attention showed a main effect of condition for the peak amplitudes in both time windows (peak in the first time window: $F_{1,31} = 4.72$, $p = 0.04$, $\eta^2 = 0.16$, peak in the second time window: $F_{1,31} = 7.60$, $p = 0.01$, $\eta^2 = 0.02$). This condition effect was caused by an increased amplitude in the visually than auditory attended condition, regardless of group and time point.

3.6. *Source level: connectivity analysis*

In a first step, we analysed the *intra-modal* functional connectivity for each cortex (auditory, visual) between the left and right hemisphere (Fig. 5C and D). This was done by mixed ANOVAs computed separately for the visually and auditory attended conditions and which included the between-subjects factor group (NH, CI) and the within-subject factor time point (attend visual: before implantation, five weeks CI use, six months CI use; attend auditory: five weeks CI use, six months CI use). In a second step, we analysed the *cross-modal* functional connectivity between the visual and auditory cortex within each hemisphere. This was done by mixed ANOVAs computed separately for the visually (2 × 3 ANOVA) and auditory (2 × 2) attended condition, with the between-subjects factor group (NH, CI) and the within-subject factor time point (attend visual: before implantation, five weeks CI use, six months CI use; attend auditory: five weeks CI use, six months CI use). For the analysis of the *intra-modal functional* connectivity, we found a significant interaction between the factors group and time point for the attend auditory condition in the *auditory cortex* ($F_{1,31} = 8.92$, $p = 0.02$, $\eta^2 = 0.11$). Post-hoc *t*-test revealed specifically for the CI users a greater intra-modal connectivity between the left and right auditory cortex at the third time point (six months after implantation) when compared to the second time point (five weeks after implantation). By contrast, there were no significant effects concerning the intra-modal connectivity between the left and right *visual cortex* in both conditions (attend visual, attend auditory). Also, there were no significant effects concerning the *cross-modal connectivity* between the visual and auditory cortex.

The analysis of the attention effect on intra-modal and cross-modal functional connectivity, as computed by 2 (group) x 2 (time point) x 2 (condition) ANOVAs, showed a main effect of condition for the *intra-modal connectivity* in the *visual cortex* ($F_{1,31} = 6.18$, $p = 0.02$, $\eta^2 = 0.04$). Specifically, the connectivity between the left and right visual cortex was enhanced for the visually than auditory attended condition, regardless of group and time point. However, no significant effects of attention were found for the intra-modal functional connectivity in the *auditory cortex*, nor for the *cross-modal connectivity* between the visual and auditory cortex.

Overall, our results on the source level showed a decreased activation of the auditory cortex in the CI group when compared to the NH group, which however increased with the time of CI use. At the same time, the intra-modal connectivity between the left and right auditory cortex enhanced with CI use. Despite this group-specific pattern, both groups showed a greater intra-modal connectivity between the left and right visual cortex for the visually attended than the auditory attended condition.

4. Discussion

The current prospective longitudinal study compared speech processing in audiovisual conditions between NH listeners and post-lingually deafened individuals before and after cochlear implantation. The results revealed (top-down) attention effects on the (bottom-up) sensory cortical processing of audiovisual speech in both groups and at all time points. Importantly, in the auditory attended condition both groups showed an enhanced task efficiency, a more centrally distributed N1 ERP map, and reduced functional connectivity between the left and right visual cortex when compared to the visually attended condition. The NH group additionally revealed decreased beta power in the visually attended condition, indicating that they require more memory load to process the audiovisual speech stimulus when focusing on the visual lip movement than when focusing on the auditory speech signal. Finally, we observed deprivation- and CI-induced alterations on cortical audiovisual speech processing, as manifested by changes in the N1 ERP topography, the amplitude of auditory-cortex activation and the theta oscillation power (4–8 Hz).

4.1. CI users show not only enhanced visual influence on audition but also reduced task efficiency in auditory but not visually attended audiovisual conditions

The behavioural measures of the EEG task revealed that both the NH group and the CI group showed a higher task efficiency for the congruent than the incongruent stimuli in the visually attended condition. Hence, both groups seem to be disturbed by the presence of an incongruent auditory signal that does not match the lip movement. Other studies have also reported distraction effects, albeit caused by an incongruent visual signal, but these effects were more pronounced in poor CI performers and elderly listeners with an age-related hearing loss when compared to NH listeners (Puschmann et al., 2014; Champoux et al., 2009). Regarding the auditory attended condition, we found no effects of the audiovisual congruency, but the CI group showed in general significantly decreased task efficiency compared to the NH group. This observation indicates that the CI users, perceiving only a limited auditory CI signal, require more time to complete the task successfully. This result matches previous studies that found delayed reaction times and decreased hit rates in CI users compared to NH listeners in both auditory and audiovisual conditions (e.g. Finke et al., 2016; Stropahl and Debener, 2017). Although the CI users showed a decreased task efficiency at both timepoints after implantation, the self-reported listening effort was significantly enhanced only in the auditory attended condition, specifically at five weeks of CI experience. As a result, while the CI group did not achieve the same level of performance as the NH group, the listening effort in the context of audiovisual speech decreased with CI use. Our observation of a significant relationship between the listening effort and the speech recognition ability at five weeks of CI experience underlines this point by showing that a better speech recognition ability in a purely auditory test negatively correlates with the effort to attend the auditory signal in audio-visual speech conditions.

Consistent with previous results in deaf individuals (Bottari et al., 2014; Finney et al., 2003; Hauthal et al., 2014), we found an enhanced lipreading ability in the postlingually deafened CI group when compared to NH listeners, both before implantation and at both timepoints after implantation (Rouger et al., 2007; Layer et al., 2022a). These findings support the view that hearing-impaired individuals rely more heavily on visual cues than NH listeners, and that this visual compensation persists after cochlear implantation (Desai et al., 2008; Moberly et al., 2023). Importantly, our correlation analyses revealed that not only in CI users but also in NH listeners the lipreading ability, as tested with a natural speaker, correlates positively with the task efficiency in the visually attended condition with incongruent trials. This leads to the conclusion that the visual representation of the used talking head model is reasonably precise and that good lipreading skills are useful in difficult listening situations (limited auditory input in the CI group) and even when the incongruent auditory signal is clear (NH group).

Syllable perception with a CI is even more difficult than word perception, especially when the syllables include the same vowel and only differ in the consonant. This is evident in the results of the behavioural McGurk task (McGurk and MacDonald, 1976; MacDonald and McGurk, 1978), which indicate that visual speech can profoundly alter speech perception when the simultaneously presented auditory counterpart is incongruent. In our case, an auditory /ka/ was dubbed with a synchronous visual /pa/, resulting in a perceived /ta/ in some of our participants. Especially the CI group reported this so-called fusion percept, which is neither the visual nor the auditory presented syllable, but a mixture of those. Since the auditory signal of a CI is limited in spectral and temporal information, the visual lip movement has a greater impact on the syllable perception in this group compared to the NH listeners, who mostly reported the auditory percept in the incongruent conditions (Rouger et al., 2008; Tremblay et al., 2010). Regarding the conditions with congruent syllables, the NH listeners showed better performance compared to the CI users, indicating that even in congruent audiovisual syllable conditions, the performance is limited with a CI (Tremblay et al., 2010).

Our behavioural results support the view that postlingually deafened individuals rely more on visual cues for speech perception, even after cochlear implantation. Moreover, even if the auditory function is (partially) restored with a CI, the task efficiency in attended auditory conditions remains reduced relative to NH listeners, and the listening effort is increased. With longer CI experience, however, the subjectively perceived listening effort decreases. Taken together, our behavioural results indicate that there are remarkable effects of auditory deprivation that persist even after implantation. The limited CI signal can explain the observation of a persistent strong visual impact on auditory speech perception, allowing the CI users to improve their speech recognition ability in audiovisual speech conditions (Rouger et al., 2007).

4.2. CI users show alterations in cortical audiovisual processing, regardless of whether they focus on the visual or on the auditory speech signal

For the first time point (before implantation), the analysis of the global field power (GFP) revealed for the visually attended condition an enhanced peak amplitude in the first time window (90–150 ms) for the NH group compared to the CI candidates. This indicates that the strength of the cortical response to audiovisual stimuli is weaker in postlingually deafened individuals compared to NH listeners. This observation, however, was expected because the CI candidates had a severe to profound hearing loss, so the acoustic input was very weak, if present at all, at the first time point. Nevertheless, after implantation, the GFP response increased and thus approached the GFP of NH listeners in the visually attended condition. Although this improvement after implantation can be explained by the (partially) restored auditory input from the CI, the cortical audiovisual speech processing remained different between the CI users and NH listeners, as indicated by the global map dissimilary (GMD), showing topographic differences in the time range of 90–150 ms after word onset (first time window). Importantly, this GMD group difference was observed for both attention conditions at a similar latency range, implying that CI users show alterations in cortical audiovisual processing, regardless of whether they focus on the visual or on the auditory speech signal.

In principle, GMD group differences can be caused either by a latency shift of the CI users' topographies and/or by distinct source configurations that cause different ERP topographies on the CI users' scalp (Murray et al., 2008). In order to differentiate between these two causes, we analysed the single-subject ERP topographies by means of a fitting analysis (Murray et al., 2008), which revealed a group effect specifically for the visually attended but not for the auditory attended condition. This group effect was shown by a group-specific pattern of "map presence", as indicated by a higher presence of the centrally pronounced map 1 in NH listeners than in CI users, for the time points both before and after implantation. Map 1 shows similarities to the typical topography of an auditory N1 ERP (Näätänen and Picton, 1987). Therefore, the group effect suggests a more auditory focused processing in the NH group compared to the CI group, even when the individuals are instructed to focus their attention to the visual lip movement in an audiovisual speech context.

For the visually attended condition, the pattern of map presence was different between the two groups at all three time points. Nevertheless, the CI users approached the results of NH listeners by showing a gradual increase in the presence of the centrally pronounced map 1. At the same time, the CI users developed an increased activation in the auditory cortex, as indicated by the source analysis. This increased strength of the cortical ERP source in the auditory cortex may explain the shift in voltage distribution across the scalp from an occipitally to a centrally oriented topography. Thus, it seems that over the first six months of CI experience, the CI users develop towards a more auditory focused processing. However, the fact that the group difference remained significant at the third timepoint suggests that the cortical processing of audiovisual words in visually attended conditions is still different after six months of CI use compared to NH listeners. It also suggests that the CI group is better able to "ignore" the auditory words and to focus on the visual lip movement.

In contrast to the visually attended condition, the topographic analysis for the auditory attended condition did not reveal a significant group difference, neither regarding the "map presence" nor the "first onset of maps". At least on the descriptive level, the CI users showed a lower presence of the centrally oriented map than the NH listeners. This observation is supported by the source analysis, which revealed significantly reduced auditory-cortex activation in the CI users than in NH listeners at both time points after implantation. Nevertheless, CI users developed an increased intra-modal connectivity between the left and right auditory cortex, suggesting an ongoing change in audiovisual processing with increasing CI experience.

In sum, these findings indicate that the observed GMD difference between the two groups, as observed for both the auditory and visually attended conditions, is not simply due to an ERP latency shift of the CI users' topographies. Rather, this group difference can be explained by the reduced strength of the cortical ERP source located in the CI users' auditory cortex, accounting for the presence of a less centrally oriented topography when compared to NH listeners. Similarly, previous studies using different unisensory auditory stimuli, for instance simple tones or more complex speech sounds, have reported reduced activation in the auditory cortex of CI users when compared to NH listeners (Sandmann et al., 2015; Glennon et al., 2020). Further studies about CI users have observed enhanced visually modulated responses in the auditory cortex (Schierholz et al., 2015; Layer et al., 2022a) and different ERP topographies in audiovisual conditions with environmental sounds when compared to NH listeners (Radecke et al., 2022). Our finding that CI users show distinct cortical audiovisual speech processing are consistent with these previous results. In fact, our results even extend these previous findings by demonstrating that these group differences in cortical audiovisual speech processing exist regardless of whether the attention is directed to the auditory or the visual speech signal.

Functional differences in audiovisual condition as found in the present study may also affect the connectivity between auditory and visual cortices, which is referred to as cross-modal connectivity. Several previous studies have focused on the connectivity between the auditory and visual cortex (Fullerton et al., 2023; Stropahl and Debener, 2017) and found increased connectivity for the CI users compared to NH listeners. Our results do not replicate these previous findings, which however could be explained by differences in stimulus conditions. While previous studies focused on purely auditory or visual stimulation, our stimuli were audiovisual, by themselves activating the auditory and visual cortices. This makes a direct comparison between the current and previous results difficult. Besides, Rosemann and Thiel (2019) found a relationship between the resting-state functional connectivity and the perceived listening effort, rather than the hearing loss itself, in mild to moderate age-related hearing loss. In sum, these previous results suggest complex interplays between the cross-modal functional connectivity and other factors, in particular hearing loss, listening effort and stimulus condition. Nevertheless, we found a stronger intra-modal connectivity between the left and right auditory cortex for the CI group at the third time point compared to the second time point. Other studies have reported a decreased intra-modal connectivity for CI users compared to NH listeners (Chen et al., 2017), which has been explained with the degraded auditory input via the CI, causing less temporal consistency. Accordingly, our results of increased intra-modal connectivity in the auditory cortex after six months of CI use could be interpreted as an alteration in perception of auditory input with increasing CI experience.

4.3. *Theta and beta oscillation differences between CI users and NH listeners for audiovisual word processing*

Frequency-related information can provide additional insight into neural processes, as different frequency ranges have been shown to represent different layers of processing. Activity in the beta frequency range (13–30 Hz), for instance, has been shown to reflect cognitive and emotional processes. A *decrease* in the beta power, especially in the parietal and parieto-occipital areas, was found in conditions with *increased* modality-independent memory load (Pesonen et al., 2006, 2007). Our results in the beta frequency range did not show any group differences in neither of the conditions (attend auditory, attend visual), but a main effect of ROI was found in the second time window (200–600 ms), with greater beta power in the occipital ROI as compared to the central ROI in both groups and at all timepoints. In addition to this ROI effect, we found that the beta power was affected by the direction of attention, as indicated by a decreased beta power for the visually attended as compared to the auditory attended condition. Specifically, this effect was found in the NH group in the second time window (200–800 ms), whereas the CI users at this latency range showed comparable beta power between the visually and auditory attended conditions. Given the link between *decreased* beta power and *increased* memory load, our observation suggests that the NH listeners, but not the CI users, have an increased memory load when attending the visual lip movement (Pesonen et al., 2006, 2007). CI users, however, do not seem to need additional cognitive resources when they attend the visual lip movement. This can be explained by the fact that CI users are more accustomed to using the visual cues in their everyday lives, which allows them to compensate for the limited CI signal.

In addition to the beta frequency range, we also found ROI and group effects in the theta frequency range from 4 to 8 Hz. The theta frequency band has been found to correlate with storage and retrieval of information from long-term memory (e.g., Burgess and Ali, 2002; Klimesch et al., 2001; Klimesch, 1999), as well as working memory processes (e.g., Bastiaansen et al., 2002; Jensen and Tesche, 2002; Tesche and Karhu, 2000; Kahana et al., 1999). Since there is an overlap between the language system and the declarative and working memory systems, theta oscillations can also be associated with language processing. Some studies found a relation between theta power increase and successful memory encoding and retrieval (e.g., Burgess and Ali, 2002; Klimesch et al., 2001; Klimesch, 1999). Our results revealed for the auditory attended condition an effect of ROI in the first time window immediately following the onset of the lip movement (50–190 ms). In particular, both groups showed enhanced theta power in the central as compared to the occipital ROI. This effect of ROI supports the view of a relationship between the theta power and language processing. Indeed, Bastiaansen et al. (2008) found that semantic representations are stored in functional networks in which the semantic properties of the items are reflected by the topography. Additionally, they stated that oscillatory brain dynamics especially in the theta frequency range are functionally related to the retrieval of lexical semantic information.

Regarding the theta power in the second time window (200–800 ms), our results revealed a main effect of ROI, with greater theta power in the central than occipital ROI for both groups, both conditions and all time points. Moreover, again a greater theta power was found for the NH group as compared to the CI group. Although this effect was similarly found in the first time window, it was only observed in the *auditory* but not *visually attended condition* in the second time window. Since the CI only provides a limited auditory signal, the incoming sensory information may not match the representations from the long-term memory, and an additional explicit processing of the degraded sensory signal may be required (Rönnberg et al., 2013). This view is consistent with our observation that CI users report greater listening effort and they achieve lower task efficiency, specifically in the auditory attended condition, when compared to NH listeners.

Our results also revealed decreased theta power for the CI group compared to the NH group in both the visually and the auditory attended conditions. This *group* difference was found for the first time window immediately following the onset of the lip movement (50–190 ms) and was present in both ROIs and at all time points. Given the link between *decreased* theta power and *less successful* memory encoding/retrieval, our observation of reduced theta power in CI users suggests a worse encoding/retrieval of the presented audiovisual words when compared to the NH group (e.g., Burgess and Ali, 2002; Klimesch et al., 2001; Klimesch, 1999).

Overall, the time frequency analysis revealed group differences in the cortical processing of audiovisual words, as indicated by distinct oscillation power in the theta (4–8 Hz) and beta (13–30 Hz) frequency ranges. The reduced theta power in the CI group (in all conditions and at all timepoints) indicates a less successful memory encoding/retrieval as compared to the NH listeners, which may be related to the limited CI signal. In the visually attended condition, however, the NH listeners (but not the CI users) appear to have more memory load when attending to the visual lip movement as opposed to the auditory speech signal.

4.4. CI users and NH listeners show an attention effect on audiovisual speech

The present study compared the effect of (top-down) focused attention on the sensory cortical processing between CI users and NH listeners. Similarly, a study by Tinnemore et al. (2020) compared CI users and NH listeners in terms of attention effects in audiovisual speech conditions, but they used a concurrent visual distraction and a secondary visual task to manipulate the focus of attention. Interestingly, the results showed that both groups were similarly affected by visual distractions and by the secondary task. Also in the current study, which examined the effects of focused attention on the visual and auditory speech signal, the findings revealed a comparable pattern of results between the NH listeners and the CI users. Comparing between the two attention conditions, both groups showed for the visually attended condition not only poorer task efficiency, but also enhanced GFP peak amplitudes and more occipitally pronounced topographies when compared to the auditory attended condition. Interestingly, these results were comparable across the different time points, indicating that this top-down effect of visual attention is not affected by CI experience. Nevertheless, our source analyses confirmed that the enhanced GFP peaks and the more occipitally oriented topographies originated from a greater activation in the visual cortex for the visually attended condition when compared to the auditory attended condition. Taken together, this suggests that the focus on the visual lip movement enhances the activation in the visual cortex (Gazzaley et al., 2008). In particular, focusing on explicit characteristics of the stimuli may result in increased neural responsiveness and thus stronger activation when processing the attended (visual part of the) audiovisual stimuli (Rufener et al., 2014). Our results extend previous research by suggesting that these effects of focused visual attention not only result in an enhanced visual-cortex activation, but they also lead to increased intra-modal connectivity between the left and right visual cortex, both in the CI users and the NH listeners.

Unlike the GFP, which represents a global response strength, the more differentiated analysis of frequency bands showed an interaction between group and condition specifically for the beta oscillation power (13–30 Hz) in the second time window (200–800 ms). In particular, the NH listeners revealed a decreased beta power in the visually attended as compared to the auditory attended condition. By contrast, the beta power in the CI users was comparable between the two attention conditions, and this beta power in both conditions remained unaffected by CI experience (see Fig. 4E). Thus, only the NH listeners showed an attention effect in the beta power. Because *decreased* beta power has been linked to *enhanced* memory load (Pesonen et al., 2006, 2007), our results suggest that in visually attended audiovisual speech conditions, the NH listeners need to increase their memory load to successfully complete the task when focusing on the visual lip movement. By contrast, the CI users, who showed comparable beta power between the two attention conditions, do not seem to need these additional cognitive resources in the visually attended condition. This is plausible because the CI users are experienced in using the visual speech cues in their everyday lives. Moreover, we found a correlation in the CI group between the beta power in the visually attended condition and the speech recognition ability (in a purely auditory test), revealing that the beta power was increased in individuals with poorer CI outcome. This leads to the conclusion that the CI users with poorer speech recognition ability need less cognitive load to attend the visual signal in audio-visual speech conditions.

In sum, our study showed (top-down) attention effects on the (bottom-up) sensory processing of audiovisual speech in both the NH listeners and the CI users. These effects seem to be particularly pronounced in the visually attended condition, leading to a comparable increase in visual-cortex activation in both groups. Nevertheless, we found group differences specifically in the beta frequency band (13–30 Hz), where the NH listeners but not the CI users revealed a decreased power in the visually attended condition when compared to the auditory attended condition. These results indicate that the NH group allocates more cognitive resources when processing the visual signal in the audiovisual speech context, whereas the CI users, who are experienced lip readers, do not seem to need these additional cognitive resources in visually attended conditions.

4.5. Limitations

As discussed in previous studies, the CI group is highly variable. There are major differences between early and late implanted individuals (Kral and Sharma, 2012). Thus, this study only included postlingually deafened individuals who were implanted as adults. However, it would also be interesting to compare this group with prelingually deafened CI users (implanted as adults) regarding their audiovisual word processing after implantation.

It has been previously suggested that individual factors, among them age, duration of deafness, and speech recognition ability may have an impact on the processing of audiovisual stimuli (Pepper and Nuttall, 2023; Stevenson et al., 2017; Lasfargues-Delannoy et al., 2021). In order to consider these factors, we performed correlation analyses with behavioural and electrophysiological data. However, the results did not show any relationships between these individual factors (age, duration of deafness, etc.) and the results of the conducted tasks (behavioural measures, electrophysiological measures), which could be explained by the small number of participants in our study.

In general, most of our results are pronounced in the early stages of cortical processing, more precisely in the time window of the auditory N1 component. Two reasons may account for this observation. First, it may be possible that facial expressions before the start of the lip movement are used to predict the word. Since we used a highly controlled computer animation model without any facial expressions other than the lip movement and words that started with the same letter, this does not account in our study. Second, this finding may be explained by the fact that the participants could distinguish the words based on the first syllable, which could be the case in our relatively easy task with only three different words. Therefore, future studies should include an extended speech material which allows a deeper understanding of alterations in cortical speech processing before and after cochlear implantation.

5. Conclusion

As far as we are aware, this is the first longitudinal study to systematically examine the cortical processing of audiovisually presented words in the course of the treatment with a cochlear implant in conditions with varying attentional focus. The findings suggest pronounced effects of auditory deprivation, as evidenced by enhanced lipreading ability, greater visual influence on auditory speech perception, as well as altered cortical response, in particular decreased theta oscillation power (4–8 Hz) and a smaller amplitude in the auditory cortex. However, these deprivation-induced changes seem to partially reverse after implantation, as suggested by a gradual increase in auditory-cortex activation and the development of a stronger intra-modal connectivity. Although both groups showed strong attention effects on task efficiency and activation in the visual cortex, only the NH appeared to expend the allocation of additional cognitive resources when processing visually attended words than auditory attended words. The CI users, not showing this condition difference, seem to be more accustomed to using the visual lip movement as a support for the understanding of the auditory input in their everyday lives. These results emphasise the relevance of including audiovisual speech in the testing and rehabilitation of CI users.

CRediT authorship contribution statement

Anna Weglage: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Data curation, Conceptualization, Formal analysis, Investigation. **Natalie Layer:** Writing – review & editing, Software, Investigation, Formal analysis. **Hartmut Meister:** Writing – review & editing, Resources, Methodology. **Verena Müller:** Writing – review & editing, Resources. **Ruth Lang-Roth:** Writing – review & editing, Resources. **Martin Walger:** Writing – review & editing, Resources. **Pascale Sandmann:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Data availability

Data will be made available on request.

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5

REDUCED VISUAL-CORTEX REORGANISATION BEFORE AND AFTER COCHLEAR IMPLANTATION RELATES TO BETTER SPEECH RECOGNITION ABILITY

This chapter is based on the project "Reduced visual-cortex reorganisation before and after cochlear implantation relates to better speech recognition ability" which is under review in the journal "Journal of Neuroscience Research" since 18th of July 2024.

Author contributions:
Anna Weglage: Conceptualisation; literature review; creation, editing and calibration of stimuli; programming of the experiment; pilot measurements; participant recruitment; data acquisition; data analysis; interpretation and presentation of results to research group; discussion of findings and further procedures; writing initial manuscript draft; incorporating suggestions of co-authors; submission to journal; presentation of results at national conferences. **Natalie Layer**: Assistance in data acquisition; assistance in data analysis; group discussions; proofreading of manuscript. **Verena Müller**: Initial assistance in participant enrolment; proofreading of manuscript. **Hartmut Meister**: Funding acquisition; conceptualisation; provision of software for stimuli generation; discussion; suggestions; proofreading of manuscript. **Ruth Lang-Roth**: Conceptualisation; proof-reading of manuscript. **Martin Walger**: Conceptualisation; proof-reading of manuscript. **Pascale Sandmann**: Supervisor of Anna Weglage; central role in project conceptualisation; funding acquisition; suggestions; discussions; assistance in writing manuscript and proofreading of manuscript.

SYNOPSIS

OBJECTIVES Hearing impaired individuals, as well as CI users, are known to be better lip readers (Rouger et al., 2007; Stropahl et al., 2015) and to reveal cortical reorganisation when compared to NH listeners (Lomber, Meredith, and Kral, 2010). Yet, it is by now not well understood how these visual changes before implantation are related to the CI outcome and to what extend they are induced by auditory deprivation and the limited CI input, respectively. Therefore, this prospective longitudinal study aims to examine the deprivation- and CI-induced alterations of visual cortical processing before and six months after implantation in comparison to NH controls.

METHODS In this prospective longitudinal study, the visual speech processing was compared between postlingually deafened individuals, who were supplied with a CI during the course of the study, and NH controls. Participants performed

two visual tasks on a computer animation of a talking head, one face-categorisation task and one word-identification task, while the cortical processing was measured using a 64 channel EEG. Both tasks were performed before implantation and after six months of CI use. Additionally, the lip reading ability was measured, as well as the speech intelligibility after six months of CI use.

ANALYSIS Behavioural data was examined by comparing the performance (percentage of correct answers) in lip reading as well as in the two visual tasks and by comparing the response times in the two tasks. The electrophysiological data was analysed regarding the P1 and P2 ERP component to the onset of the static face and a peak-to-peak measure to the onset of the lip movement on the sensor level. Amplitudes and latencies of each measure were compared between the groups (CI, NH), conditions (attended, unattended) and the timepoints (before implantation, after six months of CI use). Afterwards, event-related spectral perturbations (ERSP) were calculated to include frequency information. These were investigated within two time windows, one after the onset of the static face and one after the onset of the lip movement, both in the extended alpha frequency range of 8-18 Hz. The power inside both time windows was compared between groups, conditions and timepoints. Finally, a source analysis including a connectivity measure was conducted, focusing on the visual and auditory cortex, as well as on the fusiform gyrus. The activity in the cortices and the connectivity, as calculated via an envelope correlation between the cortices, were compared between the groups, conditions and timepoints.

RESULTS The behavioural data did not show any significant differences, except a better lip reading ability in CI candidates/users when compared to the NH listeners at both timepoints. Regarding the electrophysiological data, a smaller P1 ERP component was found for the CI candidates/users at both timepoints, which could be shown to result from a reduced visual cortex activation at P1 latency range, at both timepoints. Interestingly, this P1 ERP component correlates positively with the speech understanding after six months of CI use, revealing a relation between the visual processing before implantation and the CI outcome. Moreover, a stronger functional connectivity was found between the visual and auditory cortex for the CI candidates/users as compared to the NH listeners. A group-specific pattern in the ERSPs could also be shown, more precisely a pronounced power increase for unattended than attended faces for the NH listeners, but not the CI candidates/users.

DISCUSSION In general, the results revealed deprivation induced cortical alterations in visual processing of static and articulating faces, that seem to remain largely unchanged after six months of CI experience. These deprivation-induced changes relate to the CI outcome, as indicated by the observation of a positive correlation between the (reduced) visual P1 component before and after implantation and the speech intelligibility after six months of CI use. Hence, the P1 component provides an objective index of cortical visual reorganisation that may held to predict the CI outcome.

Reduced visual-cortex reorganisation before and after cochlear implantation relates to better speech recognition ability

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Keywords

- Visual face processing
- Cortical reorganisation
- Alpha power
- Allocation of attention

Grand information

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Abstract

People with severe to profound hearing loss show high lipreading ability and cortical reorganisation due to the limited auditory input. Although a cochlear implant (CI) can partially restore the auditory function by electrical stimulation of the auditory nerve, the CI recipients show alterations in auditory and visual cortical processing. Yet, it is not well understood how these visual changes relate to the CI outcome, and to what extent these changes are induced by auditory deprivation and the limited CI input, respectively.

Here we present a prospective longitudinal electroencephalography (EEG) study which examined the deprivation- and CI-induced alterations on cortical face processing by comparing visual evoked potentials (VEP) in CI users before and six months after implantation. A group of normal-hearing (NH) listeners served as control. The participants performed a word-identification task and a face-categorisation task to study the cortical processing of static and articulating faces in attended and unattended conditions.

The cortical alterations in CI candidates remained largely unchanged after six months of CI experience. Thus, our results suggest that the CI users' alterations in cortical face processing are mainly induced by auditory deprivation and not by CI experience. Importantly, these deprivation-induced changes seem to be related to the CI outcome. Our results suggest that the visual P1 amplitude as recorded *before* implantation provides an objective index of cortical visual reorganisation that may help predict the CI outcome.

Significance Statement

Individuals suffering from any hearing impairment are usually more sensitive to the visual surrounding and most importantly the lip movement of any conversational partner. Therefore they are able to compensate the missing auditory input by lipreading. Even though a cochlear implant (CI) can restore the hearing ability, the input is still limited. Our study aims to explain the underlying cortical alterations of the visual processing in hearing impaired individuals receiving a CI as compared to normal hearing (NH) individuals, as well as the effect of attention directed to or revoked from the lip movement.

Conflict of interest

None of the authors has any conflict of interest.

1. Introduction

Severe to profound hearing loss can have drastic effects on a person's daily routine and quality of life (for review see Nordvik et al., 2018). Due to the limited auditory input, affected individuals rely on the intact modalities and compensatory strategies (Bavelier, 2006). The visual system, in particular, is critical because it helps with orientation, environmental change detection, and speech recognition through lipreading. Previously, several studies have reported enhanced visual abilities in congenitally deaf individuals, although these enhancements appear to be specific to certain stimuli and tasks (Hauthal et al., 2013). Specifically, these individuals show not only larger visual fields (Buckley et al., 2010; Codina et al., 2011; Stevens & Neville, 2006) but also faster reaction times in visual detection (Bottari et al., 2010; Chen, Zhang, & Zhou, 2006; Loke & Song, 1991) and visuo-spatial localisation tasks (Dye, Hauser, & Bavelier, 2009). It seems that this facilitated visual information processing is especially pronounced in the peripheral visual field (e.g., Loke and Song, 1991; but see Bottari et al., 2010).

Previous studies using electrophysiology and neuroimaging techniques have reported that the visual improvements in deaf individuals are accompanied by cortical reorganisation (Lomber, Meredith & Kral, 2010; Bavelier et al., 2006), as reflected by functional changes within the visual cortex (i.e., intra-modal plasticity) and/or by take-over of the deprived auditory regions by the remaining sensory systems (i.e., cross-modal plasticity) (for reviews, see Stropahl, Chen, Debener et al., 2017 and Kral & Sharma, 2023). Specifically, congenitally deaf individuals, when tested with visual stimuli, recruit not only the visual but also the auditory cortex (Finney et al., 2001). Similarly, cross-modal activation in the auditory cortex has been reported in individuals with postlingual onset of hearing loss, which seems to develop within a few months of auditory deprivation (Campbell & Sharma, 2014). There is also increasing evidence of cross-modal cortical changes in postlingually deafened individuals who use a cochlear implant (CI) (Sandmann et al., 2012; Rouger et al., 2012). With regard to CI users, however, it has been debated whether the cross-modal changes have a positive or negative effect on the restoration of hearing function. On the one hand, some studies have found a *negative* relationship between the cross-modal (visual) activation in the auditory cortex and auditory rehabilitation (Doucet et al., 2006, Sandmann et al., 2012), suggesting that cross-modal reorganisation limits the capacity of the auditory cortex to adapt to the new sensory input after implantation. On the other hand, previous studies have reported that the visual recruitment of auditory brain regions is *positively* related to speech recognition ability, which indicates a benefit of visual speech for auditory rehabilitation with a CI (Anderson et al., 2017; Fullerton et al., 2023; Paul et al., 2022). Thus, cross-modal plasticity has been conceived as either maladaptive or adaptive, although this dichotomous view seems to be oversimplified (Heimler et al., 2014).

The CI is a bionic device which can be implanted in individuals with profound sensorineural hearing loss and who do not sufficiently benefit from conventional hearing aids. The CI can partially restore the auditory function by direct electrical stimulation of the auditory nerve (Zeng et al. 2011). However, unlike natural acoustic hearing, the CI's electrical signals are limited in spectral and temporal information (Drennan and Rubinstein, 2015). It is therefore not surprising that the speech recognition ability with a CI, as referred to as the CI outcome in clinical context (Hoppe et al., 2019), is limited. Nevertheless, the CI outcome is known to be affected by various individual factors such as the age at implantation or the time of deafness before implantation (Green, 2005; Lazard et al., 2012). Specifically, deprivation-induced cortical reorganisation is thought to affect the CI outcome, although the adaptiveness or maladaptiveness of this plasticity prior to implantation has been debated (Heimler et al., 2014; Paul et al., 2022). Besides, the novel auditory experience via the CI may induce additional cortical changes (Ito, 2004; Sandmann et al., 2015). Given the low number of prospective longitudinal studies, it is currently not well understood whether the cortical reorganisation as induced by sensory deprivation persists, reverses, or even proceeds after implantation (Stropahl, Chen, Debener, 2017; Rouger et al., 2012). A better knowledge of cortical alterations before and after implantation, therefore, is clinically relevant, as cortical measures that indicate the degree of cortical reorganisation may be helpful to predict the CI outcome already at the time before implantation (Anderson et al., 2019; Rouger et al., 2012; Strelnikov et al., 2013).

Several previous studies have examined the processing of faces in congenitally deaf individuals and in CI users. It has been shown that the congenitally deaf individuals rely on visual information during face-to-face communication to compensate for the missing auditory input (Kral et al., 2013, Mitchell et al., 2013, Woodhouse et al., 2009). Compensatory processes have also been reported for CI users, showing superior lipreading abilities before and after implantation (Rouger et al., 2007; Stropahl et al., 2015; Anderson et al., 2019) and pointing to a functionally specialised pattern of cortical face processing (Stropahl et al., 2017). Specifically, Stropahl et al. (2017) reported alterations in the N170 evoked potential, which is elicited approximately 170 ms after a face stimulus onset (Bentin et al., 1996; Bötzel and Grüsser, 1989; Rossion and Jacques, 2008), and which originates from the fusiform area (Haxby et al., 2000, Kanwisher et al., 1997, Kanwisher and Yovel, 2006). Interestingly, the N170 response to faces was enhanced in CI users when compared to normal-hearing (NH) listeners, suggesting experience-related alterations in cortical visual face processing in these individuals (Stropahl et al., 2015).

Electroencephalography (EEG) represents an interesting tool for studying cortical plasticity in congenitally deaf individuals (Bottari et al., 2011; Hauthal et al., 2014) and in postlingually deafened CI users (Sandmann et al., 2009, Sandmann et al., 2015, Sharma et al., 2002, Viola et al., 2012). Visual evoked potentials (VEPs) have a high temporal resolution, allowing to track single steps of the cortical processing (Biasiucci et al., 2019, Michel and Murray, 2012). Time-frequency analysis of the EEG data provides additional, i.e. frequency-related information about the neural processes involved in visual perception. For instance, neural activity in the alpha frequency range (8-12 Hz) varies as a function of the level of attention (Berger 1929; Adrian and Matthews 1934) and is affected by anticipation of upcoming stimuli (Andersen et al., 2008; Zhang and Luck, 2009), as reflected by a decrease in alpha power in sensory regions that process upcoming targets. This observation converges with the generally accepted view that the cortical processing in the primary sensory cortex is influenced not only by bottom-up sensory inputs, but also by top-down task-dependent processes, such as the attentional state (Polley et al., 2006). Regarding CI users, however, it remains to be clarified whether these individuals show experience-related alterations in the alpha power during the processing of attended and unattended articulating faces, which would point to changes in the allocation of attention during visual processing. Therefore, employing an alpha power analysis for VEPs recorded in conditions with different static faces on the one hand, and attended and unattended articulating faces on the other hand, seems to be a promising approach for a differentiated understanding of cortical alterations in CI users. Indeed, a first insight into the attentional processing of articulating lips has been given by Paul and colleagues (2022) who found a group-specific pattern of increase and decrease in alpha power for the CI users when compared to NH listeners.

Here we present a prospective longitudinal EEG study which examined CI users before and after cochlear implantation and a group of NH controls by means of a word-identification task and a face-categorisation task. As far as we are aware, this is the first study to systematically analyse deprivation- and CI-induced effects on cortical processing of static and articulating faces in attended and unattended conditions. In contrast to previous studies which focused on more simple stimuli such as dot patterns (Hauthal et al., 2013) and chequerboards (Sandmann et al., 2012), the present study used more complex, articulating face stimuli that were produced by a computer animation of a talking head (Fagel and Clemens, 2004, Schreitmüller et al., 2018). Importantly, the articulated words were physically identical in the two tasks, but they differed in terms of behavioural relevance, as these words were attended in the word-identification task (Target stimuli), and they were ignored in the face-categorisation task (NonTarget stimuli). In sum, the use of different groups, recording sessions and conditions allowed us to address the following research questions:

1. Is there a difference in the cortical (sensory) processing of static and articulating faces between postlingually deafened individuals (before implantation) and NH listeners?
2. Do postlingually deafened individuals (before implantation) and NH listeners differ in their allocation of attention to static and articulating faces?
3. Does CI experience affect the cortical (sensory) processing and allocation of attention in visual conditions with static and articulating faces?
4. How do visual cortical alterations in CI users relate to the CI outcome, as measured by an auditory monosyllabic word test?

Based on previous results from congenitally deaf individuals and CI users (Hauthal et al., 2014; Stropahl et al., 2017), we expected deprivation- and CI-induced alterations in cortical face processing. We also expected a relationship between cortical visual activation and auditory speech recognition ability, which would support previous reports of a link between cortical reorganisation and the CI outcome (Sandmann et al., 2012; Strelnikov et al., 2013). Overall, our results are of clinical relevance. Given that cortical reorganisation has been identified as one out of several factors that contribute to the variability in CI outcome (Lazard et al., 2013), it is important to better understand whether VEPs provide an objective index of intra-modal cortical reorganisation which might help predict the speech recognition ability with the CI after implantation. Indeed, the results of this study point to altered cortical processing of static and articulating faces in postlingually deafened individuals, both before and after cochlear implantation. Importantly, the results of this study have also revealed a correlation between the cortical visual P1 amplitude as recorded before implantation and the auditory speech recognition ability 6 months after implantation, suggesting that the objective P1 VEP measure may provide valuable information for the prognosis of the CI outcome.

2. Materials and methods

2.1 Participants

The total number of adult volunteers in this study was 37, of which 20 suffered from profound to severe hearing loss and were supplied with a CI during the time of the study. The first of two experimental sessions took place prior to implantation (29.65 ± 34.22 days), and the second measurement occurred approximately six months (5.71 ± 0.47 months) after the initial fitting of the sound processor. Three of the participants did not continue study participation after the first measurement and thus were excluded from the analysis. One CI candidate withdrew from the implantation and the other two were not able to attend the second measurement due to personal reasons. The resulting seventeen hearing impaired participants (9 females, 8 males) had a pure tone average (PTA) of 99.91 ± 16.42 dB HL and their age ranged from 36 to 74 years (mean 56 ± 11.53 years) at the first measurement. Seventeen age and gender matched normal hearing (NH) controls participated as a control group (mean age: 57.95 ± 13.53 years). All participants had normal or corrected-to-normal visual acuity according to the Landolt test (Landolt C; Wesemann, Schiefer, & Bach, 2010), and were German native speakers. Participants reported no history of mental illness and Beck depression inventory was unobtrusive (Beck et al., 1961). Among the seventeen cochlear implant candidates, two individuals had already been implanted on the contralateral side, thirteen individuals used a hearing aid (HA) on the contralateral side, and two individuals were unaided (see Table 1). On average, the duration of deafness was 24.71 ± 18.13 years, and all participants had a postlingual onset of hearing loss. The 'age at onset of profound hearing loss' (45.28 ± 15.97 years) refers to the age at which the hearing loss in the implanted ear became too severe to be treated with conventional hearing aids and the 'duration of deafness’ was calculated as the time between the ‘onset of profound hearing loss’ and the experiment date. To verify age-appropriate cognitive abilities, the DemTect Ear test battery was used (Brünecke et al., 2018), an adjusted version of the conventional DemTect (Kalbe et al., 2004), especially developed for patients with hearing disabilities. Speech recognition abilities six months after the initial fitting of the speech processor were measured using the German Freiburg monosyllabic word test (Hahlbrock, 1970) at a sound intensity level of 65 dB SPL.

All participants gave written informed consent in line with the Code of Ethics of the World Medical Association (Declaration of Helsinki, 2013). The study was approved by the Ethics Commission of Cologne University’s Faculty of Medicine (application number 18-197).

Table 1 Demographic information of the CI participants (AB = Advanced Bionics; AS/AN = auditory synaptopathy/auditory neuropathy; HA = hearing aid; HL = hearing loss; PTA = pure tone average). The monosyllabic word test score was obtained six months after implantation.

Age [years]	Gender	CI side	Etiology	Duration HL [years]	PTA [dB HL] (CI ear, pre implantation)	other ear	CI manufacturer	Monosyllabic word test [%]
44	f	right	progredient	12	94	HA	Cochlear	75
56	m	left	hereditary	43	111.5	CI	MedEl	75
64	m	left	sudden deafness	31	84.25	HA	AB	80
70	f	right	hereditary	4	118	HA	MedEl	75
68	m	left	sudden deafness	19	77.25	HA	Cochlear	60
46	f	right	AS/AN	16	71.75	HA	Cochlear	80
75	m	right	unknown	4	107.25	HA	MedEl	65
39	f	left	unknown	32	100.75	HA	Cochlear	75
63	m	left	progredient	53	84	HA	MedEl	30
36	m	right	progredient	32	91.25	HA	Cochlear	45
74	f	left	unknown	12	96.25	CI	AB	75
57	f	right	sudden deafness	1	135	-	AB	65
66	m	left	unknown	21	98	HA	AB	60
56	f	left	sudden deafness	6	94.25	HA	MedEl	80
59	f	right	hereditary	59	107.75	HA	Cochlear	70
54	f	right	unknown	49	122.75	-	Cochlear	10
59	m	left	unknown	26	104.5	HA	Cochlear	45

2.2 Behavioural lipreading task with natural speakers

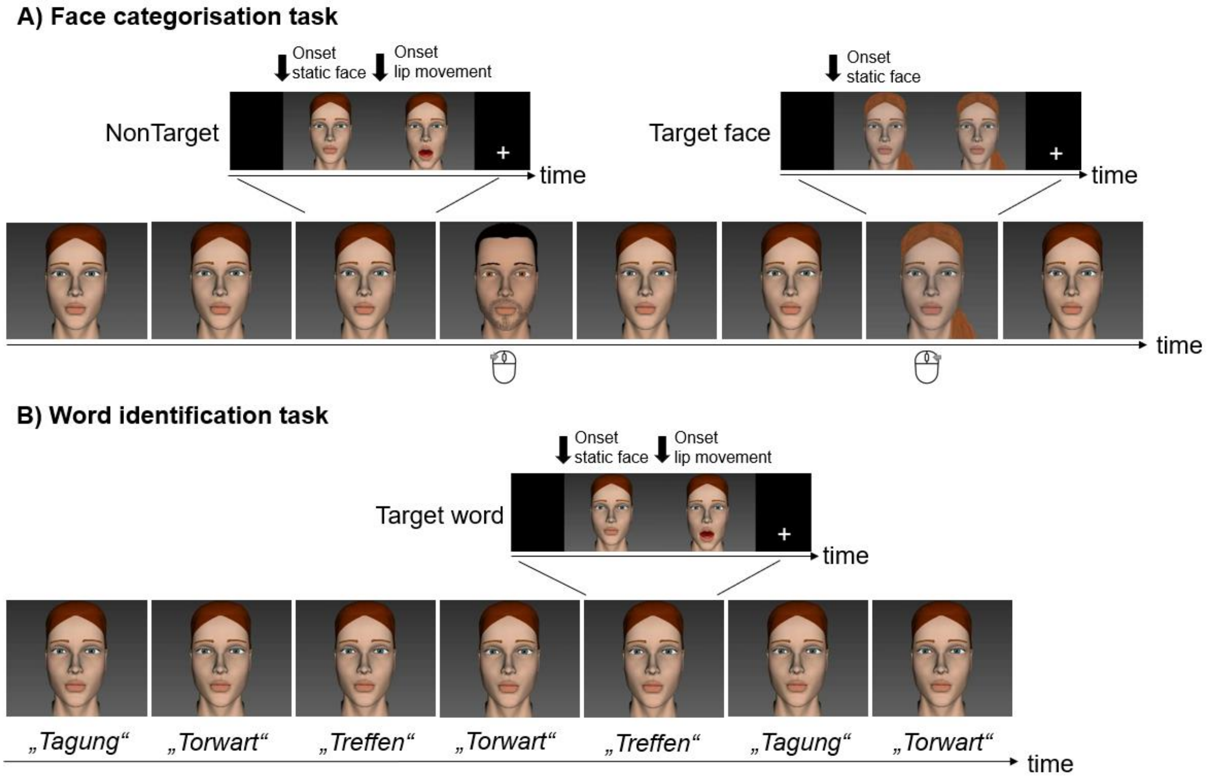
Like previous studies (Stropahl et al., 2015; Stropahl & Debener, 2017; Layer et al., 2022), we measured the lipreading ability by means of a behavioural lipreading test, using three natural speakers (see Stropahl et al., 2015) who articulated 21 different monosyllabic words from the German Freiburg monosyllabic word test (Hahlbrock, 1970). These words were presented on a computer screen in front of the participants. The participants were asked to verbally report the word they understood after each muted video.

2.3 Stimuli and Procedure for the EEG paradigms

The purely visual stimuli for the two EEG paradigms consisted of videos produced by ‘The Modular Audiovisual Speech Synthesizer’ (MASSY; Fagel & Clemens, 2004), a computer-based video animation of a talking head. A talking head was used as it allows creating highly controlled stimuli tailored to the different tasks described below. The animation either articulated one of three different German words (‘*Tagung*’ [ˈtaːɡʊŋ] *(conference), ‘Torwart’* [ˈtoːɐ̯vart] *(goalkeeper),* *‘Treffen’* [ˈtrɛfn̩] *(meeting)*) or showed a static face, whereby the face was adapted to be either clearly male or female (Figure 1). The three words were selected in advance so that the distinction of the lip movement is well possible by the time of the first vowel, without the initial lip movement (first letter) already allowing a decision. All stimuli were preceded by a blank screen for 500 ms, which was followed by the respective video (duration: 1660 ms). The video started with a static face for 500 ms in each condition before the onset of the lip movement. The trials ended with a fixation cross for no longer than 1500 ms. The fixation cross disappeared by a button press of the participants.

The participants were seated in front of a screen in a dimly lit and sound attenuated room. The stimuli were presented using the Presentation software (Neurobehavioral Systems, version 21.1) on a 68 cm wide screen at a viewing distance of 160 cm. Two different paradigms were completed during each experimental session: A face categorisation task (Figure 1A) and a word identification task (Figure 1B). Regarding the *face categorisation task*, the presented video sequence comprised 402 stimuli (321 NonTarget stimuli consisting of a static face and a lip movement, and 81 Target face stimuli consisting of different static faces) which were presented in a pseudorandomized order. This task, which can also be referred to as a visual oddball paradigm, required the participants to detect the infrequent Target face stimuli while ignoring a series of NonTarget stimuli (20 % probability of Target stimuli). A Target face stimulus was at least followed by three NonTarget stimuli. Participants were instructed to ignore the NonTarget stimuli and to categorise the Target face stimuli into male or female by an assigned button press (Figure 1A).
With this paradigm, the cortical response could be analysed not only to the onset of the Target face stimuli, but also to the lip movements of the ignored, i.e. unattended, Non-Targets. The experiment was divided into three blocks of seven minutes each, resulting in a total of 21 minutes recording time.
In the second task (*word identification task)* the participants were asked to recognise one of the three different words as a Target word and to press an assigned button for the Target word and another one for the NonTargets (Figure 1B). In contrast to the first task, this paradigm required the participants to focus their attention on the lip movements of the talking head, that is, the words were processed in an attended condition. The second experiment was also divided into three blocks with a total number of 243 stimuli (81 per word, each word was the Target word in one block), presented in a pseudorandomised order. Each trial had an approximate length of 3 s, resulting in a total time of 12 minutes for this paradigm. Note that the articulated words presented in the word identification task were physically identical to the NonTarget stimuli in the face categorisation task, with the difference that the words (i.e., lip movements) were processed in an attended condition, while in the face categorisation task the NonTarget stimuli (i.e., lip movements) were processed in an unattended condition. Both paradigms were practised in advance to allow the subjects to become acquainted with the different faces and the lip movements they had to recognise.

Figure 1 A: Depiction of the face categorisation task with frequent NonTarget stimuli and infrequent Target face stimuli. The Target face stimuli were either clearly male or female and had to be assigned by button press. B: Depiction of the (purely visual) word identification task with Target word stimuli consisting of the three German words *Tagung (conference), Torwart (goalkeeper)* and *Treffen (meeting).* Note that the physically identical articulated words were presented once in the face categorisation task in an unattended condition (NonTarget), and once in the word identification task in an attended condition (Target word). Also note that all face stimuli started with a static face. A subsequent lip movement (after 500 ms) was present only in the NonTargets (face categorisation task) and the Target words (word identification task).



2.4 Data recording and analysis

EEG data was continuously recorded by 61 Ag/AgCl actiCAP slim active electrodes (EasyCap) placed across the head according to the extended 10/20 system. Two additional electrodes were placed on the outer canthi and under the left eye to record electro-oculograms. A reference electrode was placed at the tip of the nose and the ground electrode was placed on the midline, anterior to AFz. Two BrainAmp DC amplifiers (Brainproducts, http://www.brainproducts.de) were used in the AC coupled mode with a time constant of 10 s to record the data, the sampling rate was 1000 Hz and electrode impedances were kept below 10 kΩ.

2.4.1 Behavioural data

In a first step, all trials with missing or false alarm responses were removed from the dataset. The mean hit rate and the reaction time, as defined by a response in the time range between 200 and 2000 ms after stimulus onset, were calculated for the deviant stimuli of the face categorisation task and the stimuli of the word identification task.

2.4.2 EEG preprocessing

Data was analysed with EEGLAB (Delorme and Makeig, 2004) for the MATLAB environment (R2020a; Mathworks). The data were downsampled to 500 Hz and filtered offline using a FIR-filter. The high pass half amplitude cut-off frequency was 0.1 Hz with a transition bandwidth of 0.2 Hz, and the low pass cut-off frequency was 40 Hz with a transition bandwidth of 2 Hz (Kaiser-window, beta = 5.653, max. stopband attenuation = -60 dB, max. passband deviation = 0.001) (Widmann et al., 2015). At the second measurement time point, the channels located over the scalp region of the sound processor and transmitter coil were removed for the CI users (2.82 ± 0.63). An independent component analysis (ICA) (Bell and Sejnowski, 1995) was computed on additionally bandpass-filtered (1 Hz – 40 Hz) dummy segments with a duration of two seconds, to identify and remove components assigned to ocular artefacts and other sources of stereotypical, non-cerebral activity (Jung et al., 2000). Additionally, following the procedure of prior studies with CI users (Debener et al., 2008, Sandmann et al., 2009, Viola et al., 2012), independent components related to the electrical artefact of the CI were also identified and removed. The remaining ICA weights were then applied to the raw data filtered between 0.5 and 40 Hz. Previously removed channels in the CI users were interpolated by using a spline interpolation (Perrin et al., 1989), which enables a good localisation of the dipole sources (Debener et al., 2008, Sandmann et al., 2009). Afterwards, the EEG data was segmented into epochs from -200 to 3000 ms relative to the onset of the static face, and a baseline correction was applied (-200 to 0 ms). Artefact-afflicted epochs were removed using an amplitude threshold criterion of four standard deviations. ERPs were computed for each group (CI, NH), timepoint (pre, post implantation) and condition (Target, NonTarget).

2.4.3 VEP analysis: Sensor level

The analysis of the sensor-level VEPs was divided into two steps. In a first step, we analysed the VEPs in response to the onset of the static face (NonTarget, Target face). In a second step, we focused on the VEPs in response to the onset of the lip movement (NonTarget, Target word).

Regarding the first step, we analysed the P1 and P2 VEPs in response to the onset of the static face. This was done by using an occipital region of interest (ROI) which included the electrodes PO3, POz, PO4, O1, Oz and O2 (see Figure 3). A parietolateral ROI including the electrodes P7, PO7, P8 and PO8 was used for the face-selective N170 component. Since the face categorisation task was performed by means of an oddball paradigm, the P3b component was analysed. Therefore, a parietal ROI including the electrodes P1, Pz, P2, PO3, POz and PO4 was used for the P3b component following the onset of the static face for the Target face stimuli (face categorisation task). For VEP quantification, individual peak amplitudes and latencies were measured by detecting the peak maximum and latency for each participant in commonly used latency bands of the P1, P2, N170 and P3b VEPs (Luck, 2014; P1: 80-180 ms; N170: 160-180 ms, P2: 200-400 ms; P3b: 430-630 ms).

Regarding the second step, we used an explorative approach since the literature about VEPs to the lip movement onset is scarce. We computed a peak-to-peak measure, precisely the difference of the positive peak and the following negative peak in the time window between 600-800 ms (100-300 ms after the lip movement onset), which was compared between the groups (NH vs. CI), the conditions (attended vs. unattended words) and the timepoints (before vs. after implantation).

Time-frequency analysis

To get a deeper understanding of ongoing cortical face processing in CI users, we calculated event-related spectral perturbations (ERSP) for each participant at each channel using a sinusoidal wavelet-based analysis implemented in EEGLAB (Delorme and Makeig, 2004). The number of cycles increased with frequency (start point 3-cycle wavelet with sliding Hanning-tapered window, 30 frequency steps from 1 to 30 Hz). Power changes across frequencies were baseline-corrected by subtracting the mean baseline power spectrum (-200 to 0 ms). Similar to the more conventional VEP analysis (see last section), the ERSPs were averaged for an occipital ROI (PO3, POz, PO4, O1, Oz, O2), and ERSP differences were computed between the separate conditions (attended vs. unattended words) within the groups. For statistical evaluation, two time-frequency-windows were defined, one after the onset of the static face (300-500 ms) and one after the onset of the lip movement (800-1100 ms), both in the frequency range of 8-18 Hz. The definition of those time-frequency windows was based on the grand averages across all conditions and groups, so that they include the time-frequency areas with the greatest values.

2.4.4 VEP analysis: Source level

The Brainstorm software (Tadel et al., 2011) was used to compute cortical source activities following the tutorial of Stropahl and colleagues (2018). The software applies dynamic statistical parametric mapping (dSPM; Dale et al., 2000) to the data, which uses the minimum-norm inverse maps with constrained dipole orientations to estimate the electrical activity of the neurons based on the scalp-recorded measures. It localises deeper sources more accurately compared to the standard minimum norm, but the spatial resolution is still blurred (Lin et al., 2006). Individual noise covariance matrices, and thereby individual noise standard deviations at each location, were calculated using the single-trial pre-stimulus baseline interval (-200 to 0 ms; Hansen et al., 2010). A standard three-compartment boundary element head model was used as implemented in OpenMEEG (Gramfort et al., 2010; Stenroos et al., 2014). Based on the Destrieux-Atlas (Destrieux et al., 2010), a visual and an auditory region of interest (ROI) were defined. The visual ROI consisted of one subregion to approximate the visual cortex ("S_calcarine"), whereas the auditory ROI consisted of three smaller regions to approximate Brodmann areas 41 and 42 ("G_temp_sup-G_T_transv", "G_temp_sup-Plan_tempo", "S_temporal_transverse"). Additionally, a subregion of the atlas was used to approximate the face area in the fusiform gyrus ("S_oc-temp_med_and_Lingual"). Source activities were evaluated in these ROIs using the peak activation magnitude and latency for each individual participant. The activation data has absolute values and arbitrary units calculated by the normalisation within the dSPM algorithm.

Connectivity analysis

To get measures of the connectivity between the used ROIs, a pre-implemented procedure in Brainstorm was used (envelope correlation). In particular, a correlation is performed on the instantaneous amplitude, also called envelope, of the analytic signal derived from the original data. This analytic signal is the result of a Morlet wavelet transformation. To reduce volume conduction and cross-talk effects, the pairs of envelopes were orthogonalised prior to the connectivity computation (Hipp et al., 2012). The connectivity measure was calculated for the time window previously used for the source analysis (0-900ms after stimulus onset).

2.4.5 Statistical analysis

The statistical analysis of the data was performed with the software R (Version 3.6.3, R Core Team 202, Vienna, Austria). The VEP data was separately examined on the sensor level (P1, N170, P2 and P3) and on the source level (visual, auditory, and fusiform ROI). Therefore, mixed-model repeated-measures ANOVAs with the between-subject factor "group" (CI/NH) and the within-subject factors "condition" (Target word/NonTarget) and timepoint (before implantation/after implantation) were computed for each analysed component. Significant interactions and main effects ($p < 0.05$) were followed-up by paired t-tests and were corrected for multiple comparisons by the Holm-Bonferroni approach (Holm, 1979). In case of a violation of sphericity, a Greenhouse-Geisser correction was applied. To investigate the relationship between the measured VEPs and the speech perception with the CI, a correlation analysis was conducted using Pearson's correlation analysis.

3. Results

3.1 Behavioural results

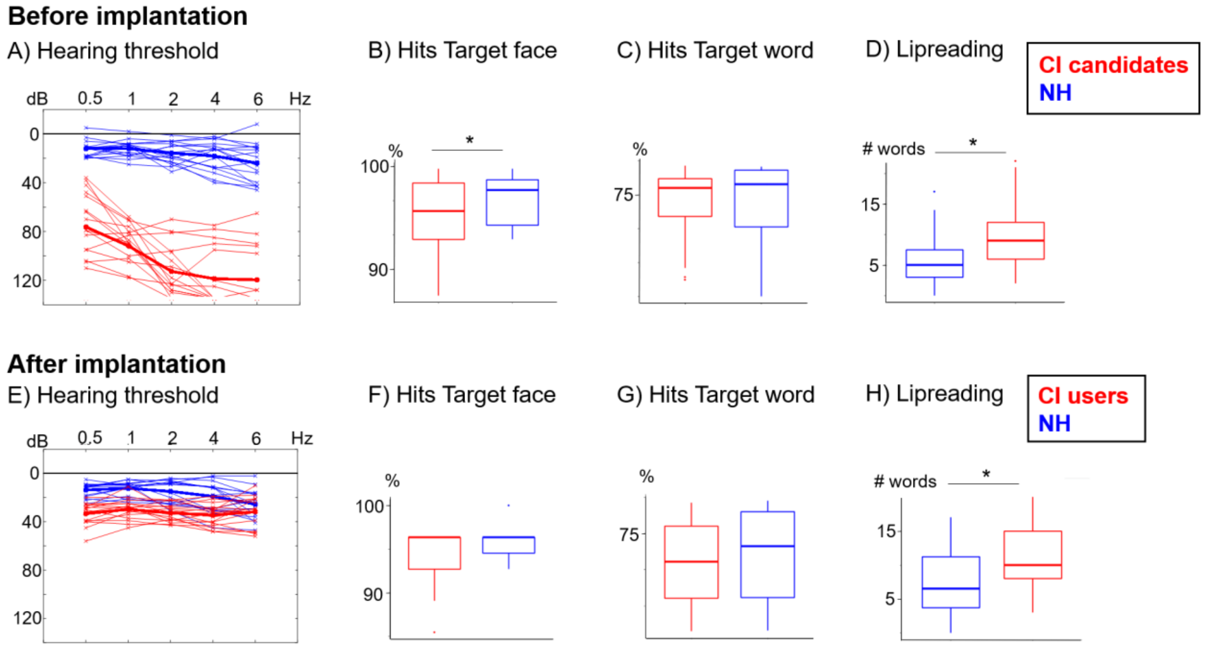
Figure 2A and 2E show the hearing threshold of the participants, illustrating the regained hearing ability of the deafened participants after the CI switch-on. The NH controls maintained a normal hearing ability throughout the study.

Regarding the two EEG paradigms, all participants showed hit rates of ≥ 79 % in the face categorisation task and ≥ 72 % in the word identification task. This indicates that all participants were able to perform both tasks properly. The mean reaction times (RTs) ranged from 697 ms to 1250 ms (mean: 1025 ± 129 ms) in the face categorisation task and from 1413 ms to 1963 ms (mean: 1703 ± 126 ms) in the word identification task. T-tests between the groups (CI candidates / CI users vs. NH participants) showed for the *face categorisation task* significantly better hit rates in the NH participants ($p = 0.03$, Cohens $d = 0.70$) than the CI candidates (Figure 2B). This group difference was observed specifically for the time before but not after implantation (Figure 2B).

However, the performance in the *word identification task* and the response times were not different between the two groups at any timepoint.

Regarding the *additional behavioural lipreading task* (with natural speakers), the number of correctly reported words was compared between the groups at each timepoint (Figure 2D and H). This comparison revealed significantly better lipreading ability in CI users at both timepoints (before implantation (Figure 2D): p = 0.04, Cohens d = 0.75; after implantation (Figure 2H): p = 0.05, Cohens d = 0.69).

Figure 2 A: Hearing threshold of all participants at the first timepoint (CI candidates before implantation). B: Group-specific hit rates for the Target face stimuli in the face categorisation task at the first timepoint (CI candidates in red, NH in blue). C: Group-specific hit rates for the Target word stimuli in the word identification task at the first timepoint. D: The number of correctly identified words in the additional behavioural lipreading task with bisyllabic words at the first timepoint. E: Hearing threshold of all participants at the second timepoint (CI users after implantation). F: Group-specific hit rates for the Target face stimuli in the face categorisation task at the second timepoint (CI users in red, NH in blue). G: Group-specific hit rates for the Target word stimuli in the word identification task at the second timepoint. H: The number of correctly identified words in the additional behavioural lipreading task with bisyllabic words at the second timepoint.



3.2 VEP results: sensor level

3.2.1 Cortical processing of static and articulating faces

Figure 3 shows the grand average of VEPs in response to faces articulating Target words (i.e., attended processing of articulated words in the word identification task) and VEPs in response to faces articulating NonTargets (i.e., unattended processing of the same articulated words in the face categorisation task) for both groups and timepoints in the occipital ROI. For all groups and conditions, the plots show pronounced VEP peaks in response to the face onset around 130 ms (P1) and 250 ms (P2), respectively (Figures 3A and 3D). In addition, there is a second, albeit smaller positive deflection around 660 ms in response to the onset of the lip movement (Figures 3A and 3D).

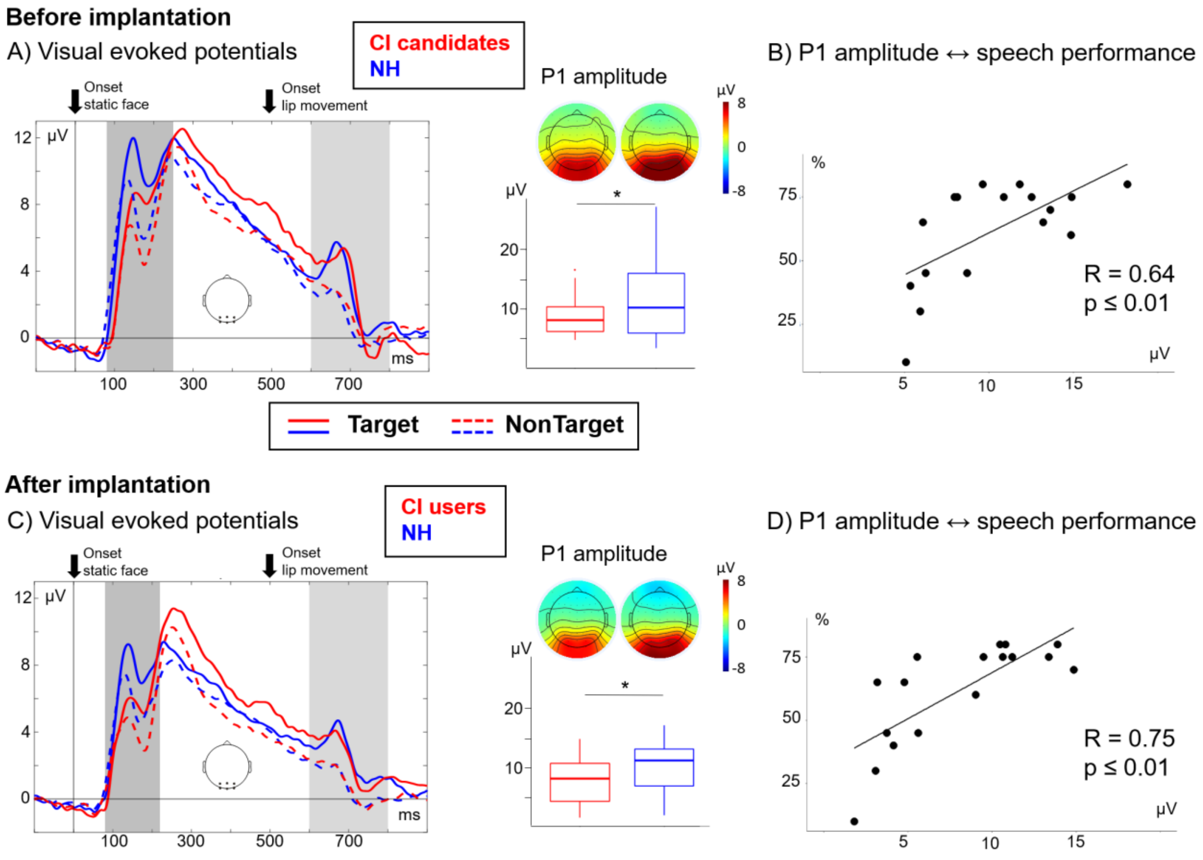
To address the question if there is a difference in the cortical processing of faces and lip movements between postlingually deafened subjects and NH listeners (Question 1), we compared the VEP peaks of the Target stimuli between the groups. Specifically, for the *P1 VEP face-onset response* we computed 2x2x2 mixed-model repeated-measures ANOVAs with the between-subjects factor group (CI patients, NH participants) and the within-subjects factors condition (Target face, NonTarget) and timepoint (before implantation, six months after implantation), separately for amplitudes and latencies. For P1 peak amplitudes, we found a main effect of group ($F_{1,31} = 4.7$, $p = 0.04$, $\eta^2 = 0.1$), revealing a greater amplitude for the NH participants compared to the CI candidates/CI users independent of the condition and the timepoint. The *face-selective N170 component*, occurring around 170 ms after the onset of the static face, was also evaluated by using similar 2x2x2 mixed ANOVAs. No effect of group was found, but a main effect of condition for the amplitude ($F_{1,31} = 83.03$, $p < 0.01$, $\eta^2 = 0.04$), resulting in a greater N170 amplitude for the Target face stimuli when compared to the NonTargets, regardless of group or timepoint. Neither the P1 latency, nor the N170 latency revealed any significant effects. Regarding the *P3 VEP* amplitude and latency, which was analysed by a 2x2 mixed ANOVA with the within-subjects factor timepoint (before implantation, six months after implantation) and the between-subjects factor group (CI patients, NH participants), we did not observe any significant effects.

A correlation analysis between the P1 amplitude (recorded at the time before and after implantation) and the Freiburg monosyllabic word test (performed at the time with six months of CI experience) resulted in a positive correlation at both timepoints (P1 before implantation (Figure 3B): $R = 0.64$, $p < 0.01$; P1 after implantation (Figure 3E): $R = 0.75$; $p < 0.01$), showing that a greater response to the static face results in a better speech recognition ability after cochlear implantation.

3.2.2 Attention effect on VEPs

To investigate the influence of attention (attended Target words versus unattended NonTargets) on VEPs elicited by articulating faces (Question 2), we computed a 2x2x2 ANOVA on the peak-to-peak amplitude for the time window after the lip movement. This ANOVA included the between-subjects factor group (CI candidates/users, NH participants) and the within-subjects factors condition (Target word, NonTarget) and timepoint (before implantation, six months after implantation). The results revealed a main effect of condition ($F_{1,32} = 41.6$, $p \leq 0.01$, $\eta^2 = 0.18$), indicating a larger peak-to-peak amplitude for the Target word condition (i.e., attended processing of articulated words in the word identification task) than for the NonTarget condition (i.e., unattended processing of the same articulated words in the face categorisation task), independent of the group and the timepoint.

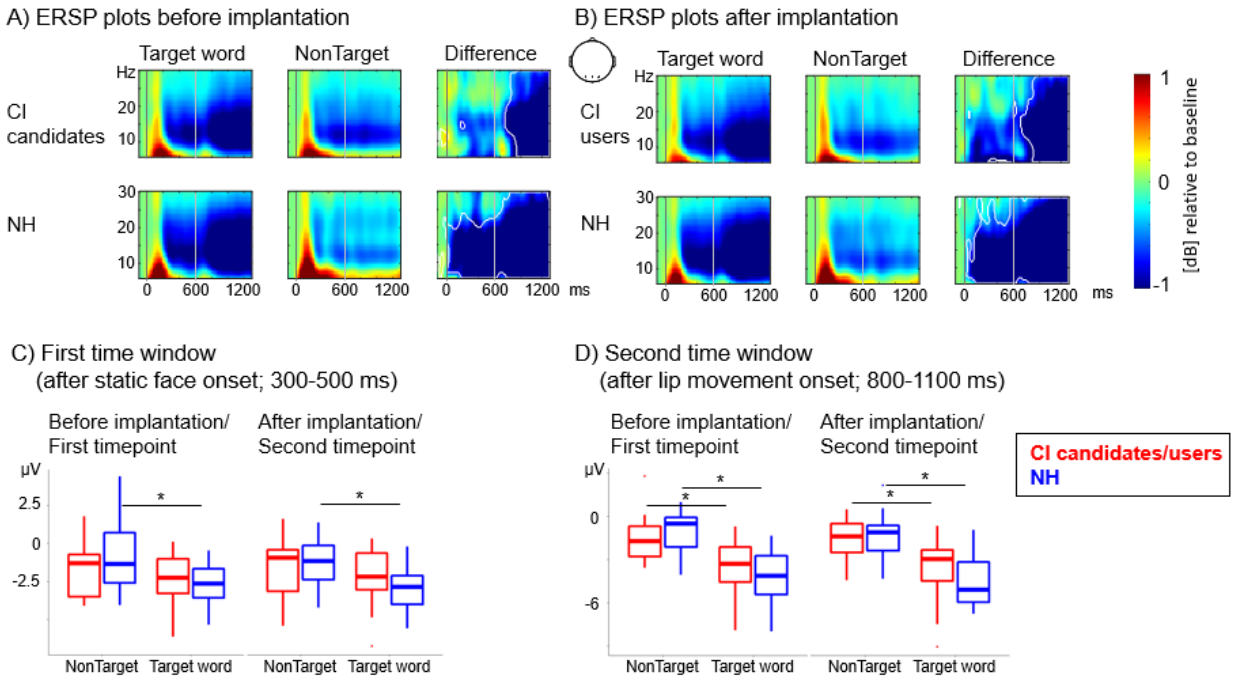
Figure 3 A: VEPs over an occipital ROI showing a decreased P1 amplitude after the onset of the static face for the CI users (red) before implantation when compared to NH listeners (blue). Solid lines show the VEPs for the Target word stimuli (attended; word identification task), dashed lines show the VEPs for the NonTarget stimuli (unattended; face categorisation task). The darker grey area marks the time range for the P1 VEP following the onset of the static face, and the lighter grey area marks the time range for the analysis of the VEP following the onset of the lip movement. Note that the difference between Targets and NonTargets reflect an attention effect, as the physically identical articulated words were processed attentively only in the Target word condition but not in the NonTarget condition. Boxplot showing the group difference for the P1 amplitude (averaged over both conditions) and topographies for both groups in the time range for the P1 (darker grey area). B: Positive correlation between the P1 amplitude (face-onset response) prior to implantation and the speech recognition ability after six months of CI use. C: VEPs over an occipital ROI showing a decreased P1 amplitude after the onset of the static face for the CI users after implantation when compared to NH listeners. Boxplot showing the group difference for the P1 amplitude (averaged over both conditions) and topographies for both groups in the time range for the P1 (darker grey area). D: Positive correlation between the P1 amplitude (face-onset response) after implantation and the speech recognition ability after six months of CI use.



Additionally, we performed a time-frequency analysis by means of event-related spectral perturbations (ERSP). Figure 4 shows the time-frequency plots for the Target words (attended processing in the word identification task) and the NonTargets (unattended processing in the face categorisation task) for both groups and timepoints (Figure 4 A/B). Further, the figure illustrates the condition differences for both groups in the occipital ROI. All conditions show an increase in power (i.e. synchronisation) for both groups *after the onset of the static face (first time window; 0-300 ms)*, especially in the lower frequencies (≤ 10 Hz). This is followed by a time window with negative values (i.e. desynchronisation) starting around 300 ms after the onset of the static face in the frequency range of 8-18 Hz. Although both groups show these negative values in both the Target word condition and the NonTarget condition, they are mostly pronounced in NH listeners in the Target word condition (i.e. strongest desynchronisation). A second time window of enhanced power (i.e. synchronisation) in the low frequencies (≤ 7 Hz) can be seen *after the onset of the lip movement (second time window; 650-800 ms)* in both groups, especially for the Target word condition. This power increase is again followed by a time window with negative values (i.e. desynchronisation) in the 8-18 Hz range.

The statistical analysis, realised using a 2x2x2 ANOVA with the between-subjects factor group (CI candidates/users, NH participants) and the within-subjects factors condition (Target word, NonTarget) and timepoint (before implantation, six months after implantation) for each predefined time-frequency-window, revealed an interaction between group and condition ($F_{1,32} = 4.22$, $p = 0.048$, $\eta^2 = 0.016$) for the *time window following the static face onset*. Post-hoc tests showed specifically for the NH listeners but not for the CI group a significantly decreased power (i.e stronger desynchronisation) in the 8-18 Hz frequency range for the Target condition compared to the NonTarget condition ($p \leq 0.01$). For the *time window after the lip movement onset*, both groups showed decreased power (i.e. stronger desynchronisation) for the Target word condition when compared to the NonTarget condition (NH: $p \leq 0.01$, CI: $p \leq 0.01$). We did not find a significant effect of the factor timepoint on the ERSP.

Figure 4 A: Event-related spectral perturbation (ERSP) plots for the time before (A) and after (B) implantation. The darker grey line represents the onset of the static face, while the lighter grey line represents the onset of the lip movement in each plot. The analyses were conducted in two time windows, in particular one after the onset of the static face (300-500 ms = first time-frequency-window) and one after the onset of the lip movement (800-1100 ms = second time-frequency-window). The conditions Target word (word identification task) and NonTarget (face categorisation task) are shown separately (first and second column), as well as the difference between these two conditions within each group (third column). Note that significant within-group differences reflect an attention effect, as the physically identical articulated words were processed attentively only in the Target word condition but not in the NonTarget condition. C: Boxplots of mean power values (8-18 Hz) in the first time-frequency-window (after the onset of the static face) for the CI group in red and the NH group in blue for both timepoints (before/after implantation). The asterisks indicate significant differences ($p< 0.05$). Note that the NH listeners but not the CI candidates/CI users showed a significantly decreased power in the 8-18 Hz frequency range (i.e. significant desynchronisation) for the Target condition compared to the NonTarget condition. D: Boxplots of mean power values (8-18 Hz) in the second time-frequency-window (after the onset of the lip movement) for the CI group in red and the NH group in blue for both timepoints (before/after implantation). The asterisks indicate significant differences ($p< 0.05$). Note that both groups showed a significantly decreased power in the 8-18 Hz frequency range (i.e. significant desynchronisation) for the Target condition compared to the NonTarget condition.



3.3 VEP results: source level

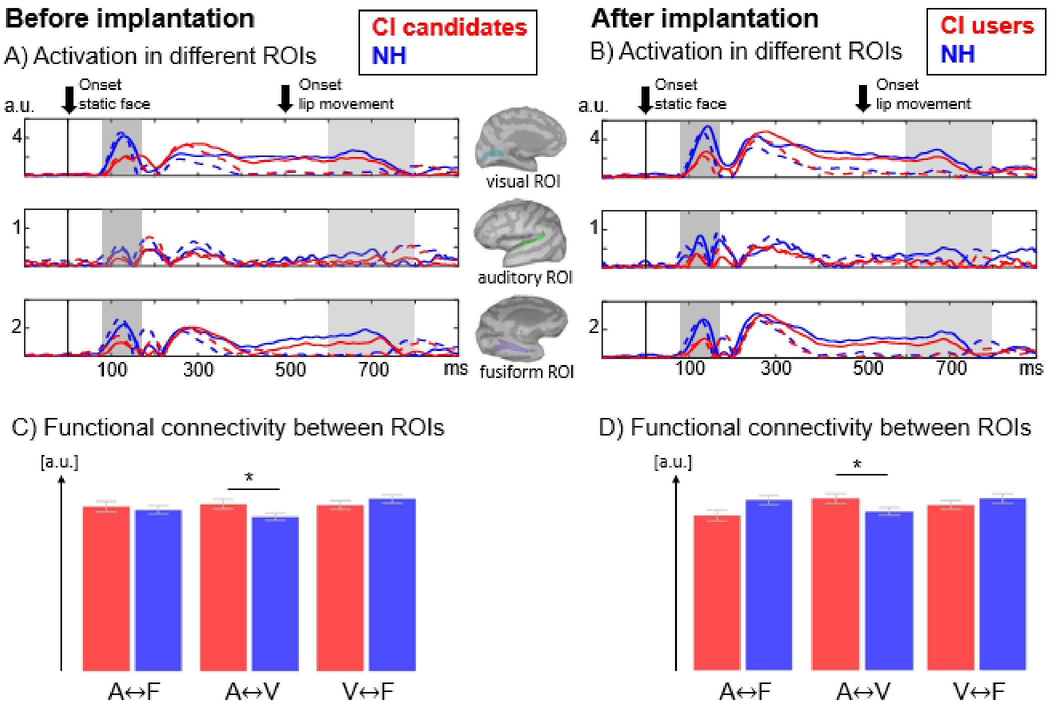
3.3.1 Cortical processing of static and articulating faces

Figure 5 illustrates the activation in the visual ROI, the auditory ROI, and the fusiform gyrus for the Target word (word identification task) and the NonTarget stimuli (face categorisation task) for both groups and timepoints. The activation in the different ROIs showed deflections to the onset of static faces and lip movements with latencies that are comparable to the sensor level. A 2x2x2 ANOVA with the between-subjects factor group (CI patients, NH participants) and the within-subjects factors condition (Target word, NonTarget) and timepoint (before implantation, six months after implantation) was computed for the peak activation magnitude and latency within each ROI. The results revealed a main effect of group in the visual ROI for the face-onset response at P1 latency range ($F_{1,30} = 5.3$, $p = 0.03$, $\eta^2 = 0.13$). Similar to the observations at the sensor level, the NH listeners showed greater responses when compared to the CI patients. Additionally, a main effect of condition was found for the face-onset response at P1 latency range in the fusiform gyrus ($F_{1,32} = 5.6$, $p = 0.02$, $\eta^2 = 0.02$), showing a greater activation in response to the Target word condition when compared with the response to the NonTarget condition. Regarding the cortical activation following the onset of *lip movements*, a main effect of condition was found in the visual ROI ($F_{1,32} = 16.7$, $p \leq 0.01$, $\eta^2 = 0.14$) and the fusiform gyrus ($F_{1,32} = 11.6$, $p \leq 0.01$, $\eta^2 = 0.11$), with the result of greater activation for the Target word compared to the NonTarget condition.

3.3.2 Connectivity

The analysis of the functional connectivity (Figure 5C and 5D) was done by a 2x2x3 ANOVA with the between-subjects factor group (CI patients, NH participants) and the within-subject factors timepoint (before implantation, six months after implantation) and direction (auditory ROI vs. visual ROI, auditory ROI vs. fusiform gyrus, visual ROI vs. fusiform gyrus) for the Target word condition. The results revealed a greater connectivity between the auditory and visual ROI for the CI candidates/CI users compared to the NH participants ($F_{1,32} = 9.95$, $p = 0.05$, $\eta^2 = 0.14$). No significant group differences were found for the connectivity between the fusiform gyrus on the one hand, and the auditory or visual ROI on the other hand.

Figure 5 A: Mean activities for the visual ROI, the auditory ROI, and the fusiform gyrus for both groups at the first timepoint. The CI group is shown in red, the NH group is shown in blue. Solid lines show the VEPs for the Target word stimuli (attended; word identification task), dashed lines show the VEPs for the NonTarget stimuli (unattended; face categorisation task).The darker grey area marks the time range for the P1 VEP following the onset of the static face, and the lighter grey area marks the time range for the analysis of the VEP following the onset of the lip movement. B: Mean activities for the visual ROI, the auditory ROI, and the fusiform gyrus for both groups at the second timepoint. The plot shows a decreased activation following the face onset at P1 latency range for the CI candidates and CI users when compared to the NH listeners. C: Mean connectivity, as indicated by envelope correlation values (0-900ms after stimulus onset), for all combinations of the three ROIs at the first timepoint: auditory ROI (A) vs. fusiform gyrus (F), auditory ROI (A) vs. visual ROI (V), visual ROI (V) vs. fusiform gyrus. D: Mean connectivity, as indicated by envelope correlation values (0-900ms after static face onset), for all combinations of the three ROIs at the second timepoint. The plot shows enhanced functional connectivity between the visual and auditory ROI for the CI candidates and the CI users when compared to the NH listeners.


Before implantation
A) Activation in different ROIs
CI candidates
NH
After implantation
B) Activation in different ROIs
CI users
NH
a.u.
Onset static face
Onset lip movement
4
1
2
100
300
500
700
ms
visual ROI
auditory ROI
fusiform ROI
C) Functional connectivity between ROIs
D) Functional connectivity between ROIs
[a.u.]
*
A↔F
A↔V
V↔F

4. Discussion

The present prospective longitudinal study compared visual-evoked potentials (VEPs) to static and articulating faces between NH listeners and postlingually deafened individuals before and after cochlear implantation. As far as we are aware, this is the first study to examine visual face processing in attended and unattended conditions before and after cochlear implantation within the same individuals. Regarding our first research question of whether postlingually deafened individuals and NH listeners differ in the cortical processing of static and articulating faces (Question 1), the results revealed a reduced cortical response in the visual cortex at P1 latency and an enhanced functional connectivity between the visual and the auditory cortex for the CI candidates when compared to the NH controls. Comparing the groups in terms of attention effects (processing of attended vs. unattended faces; Question 2), the event-related spectral perturbations (ERSP) revealed a group-specific pattern particularly in the (extended) alpha frequency range (8-18 Hz). The NH listeners but not the CI candidates showed a significant attention effect after face onset, as indicated by a pronounced power decrease (i.e. stronger desynchronisation) for ~~un~~attended than unattended faces. The alterations in cortical face processing of CI candidates remained largely unchanged after six months of CI experience (Question 3). Nevertheless, we observed a positive correlation between the (reduced) visual P1 amplitude *before* implantation, and the speech recognition ability *after* implantation, pointing to a link between cortical visual reorganisation and CI outcome (Question 4).

4.1 Behavioural data

Sensory deprivation can have an impact on the remaining senses. Two explanations of this impact have been proposed in the literature. The so-called *perceptual deficit hypothesis* states that a deficit in one sensory modality can affect the organisation and development of other sensory systems (e.g., Myklebust 1964), whereas the *sensory compensation hypothesis* states that a deficit in one sensory modality can be compensated by making the other modalities more sensitive (e.g., Gibson 1969). Both hypotheses have been supported by studies in hearing-impaired individuals. Some studies revealed deficient visual abilities in congenitally deaf compared to hearing individuals (e.g., Quittner et al. 2004; Parasnis et al. 2003), while others found supranormal abilities for deaf individuals (e.g., Bottari et al. 2011; Loke and Song 1991; Neville and Lawson 1987). A third group of results even indicated comparable visual performance between deaf and hearing individuals (e.g., Parasnis 1983; Bavelier et al., 2006; Mitchell and Maslin 2007). These variations in results underscore the ongoing debate of perceptual and cognitive functions in sensory deprived individuals. Part of the heterogeneity can be explained by different groups of participants (e.g., native signers/non-signers), the characteristics of the stimuli, the eccentricity of the visual stimuli (periphery/focus) and the task conditions (bottom-up/top-down).

Consistent with previous results about congenitally deaf individuals (Bottari et al., 2014, Finney et al., 2003, Hauthal et al., 2014), we found an enhanced lipreading ability in the postlingually deafened CI group not only before implantation, but also six months after implantation (Rouger et al., 2007; Layer et al., 2022) as compared to NH subjects. These findings highlight that hearing-impaired individuals rely on visual cues to understand speech, and that this visual compensation does not decrease after cochlear implantation. The fact that the group difference was only found in the additional behavioural lipreading task (including a list of 21 monosyllabic words frequently used in the clinical context), but not in the EEG word identification task, can be explained by a ceiling effect in the latter. Although the NH listeners from this study were poorer lipreaders than the CI users, they accustomed to the three articulated words in the EEG word identification task, resulting in high performance levels. Similarly, previous EEG studies have reported comparable performance between CI users and NH subjects for syllables in conditions with low task difficulty (Layer et al., 2022; Stropahl and Debener, 2017). Hence, our results confirm previous conclusions that behavioural visual improvements in hearing-impaired individuals and CI users are specific to certain stimuli and tasks, and that these improvements are especially pronounced in difficult conditions with complex speech stimuli (Rouger et al., 2008, Tremblay et al., 2010; Hauthal et al., 2013).

In contrast to former studies (e.g., Bottari et al., 2011), we did not find enhanced visual reactivity for the deafened participants before and after implantation. This can be explained by the heterogeneity of the visual characteristics of the stimuli and the diversity in the sample characteristics across studies. Indeed, in the current study we presented the stimuli in the centre of the screen, whereas most of the previous studies reported faster visual reactivity in deaf individuals when stimuli were presented in the peripheral visual field (e.g., Bavelier et al., 2000).

In conclusion, our behavioural results support the *sensory compensation hypothesis*, since our auditory deprived patients (before and after implantation) showed enhanced visual lipreading ability particularly in difficult task conditions.

4.2 Cortical reorganisation following sensory deprivation and cochlear implantation

4.2.1 Intra-modal reorganisation in the visual cortex before and after implantation

The present results show a decreased scalp-recorded visual P1 amplitude following the onset of a static face for the CI group compared to NH listener*s*. This observation was confirmed by the source analysis, which revealed a decreased amplitude in the visual cortex of deafened participants (before and after implantation) when compared to the NH subjects. Basically, a smaller VEP can be explained either by a smaller congregation or by reduced synchronisation of the activated neurons in the deafened individuals' visual cortex (Nunez, 1981), however the applied source analysis does not distinguish between these two mechanisms. In conclusion, we found evidence for intra-modal reorganisation in the visual cortex of postlingually deafened individuals before implantation, which was previously reported for early deaf individuals (Bavelier et al., 2000, Bottari et al., 2014, Hauthal et al., 2013) and postlingually deafened CI users after implantation (Sandmann et al., 2012).

In early deaf individuals, Bottari et al. (2014) found a *reduced* P1 response in *visual cortical areas* for visual stimulation of the central visual field when compared to NH listeners. By contrast, Bavelier et al. (2000) reported *enhanced* activation in the *motion-selective area MT/MST* in deaf individuals, especially for moving visual stimuli in the periphery. Although previous results (with visual stimulation in the central visual field) have suggested that a reduced response in the visual cortex is paired with a recruitment of the auditory cortex (Bottari et al., 2014; Sandmann et al., 2012), the present results did not show significant group differences in the auditory cortex and the fusiform gyrus. This discrepancy in results may be explained by differences in stimuli (basic vs. more complex) and experimental tasks (detection vs. categorisation and lipreading). Importantly, however, our CI users showed functional connectivity that was specifically enhanced between the visual and auditory cortex, both before and after implantation. This points to stronger interactions between the visual and auditory cortex that are induced by auditory deprivation and that persist even after six months of CI experience (see section 4.2.2 for a more detailed discussion of the functional connectivity). Thus, our results obtained with static and articulating face stimuli only partially support previous results. Although they cannot confirm a pronounced cross-modal activation of auditory cortex for static and articulating faces, they are in line with previous reports of enhanced audio-visual interactions in CI users (e.g., Chen et al., 2017; Schierholz et al., 2015).

Intra-modal changes in visual cortical areas have been reported not only in congenitally deaf individuals but also in CI users (Giraud et al., 2001; Strelnikov et al., 2010). Indeed, Sandmann et al. (2012) also found a decreased visual cortical response at P1 latency range in response to simple, reversing chequerboard patterns. Since Sandmann et al. (2012) performed a cross-sectional study, they could not conclude whether the changed visual processing was linked to the period of deafness or to the adaptation to the new auditory input via the CI. However, the current longitudinal study shows that a deprivation-induced alteration in the processing of static and articulating faces hardly changes over the first six months of CI use. Thus, the visual intra-modal cortical alterations observed in CI users seem to be mainly induced by auditory deprivation and not by CI experience.

4.2.2 Cross-modal reorganisation and audio-visual connectivity before and after implantation

Although we could not replicate previous observations of pronounced cross-modal activation in the auditory cortex of CI users, our results confirm previous reports of greater functional connectivity between the visual and auditory cortex for visual processing in postlingually deafened participants compared to NH controls (Chen et al., 2017; Fullerton et al., 2023). This indicates a stronger cross-modal association which may help the hearing-impaired individuals to compensate for the missing (before implantation) or limited (after implantation) auditory input (Schierholz et al., 2015). The underlying mechanism of stronger functional connectivity could indicate an enhancement of pre-existing connections between the visual and auditory cortices (Merabet et al., 2010). This is consistent with previous studies with congenitally deaf animals and humans which found increased structural and functional connectivity between the visual and auditory cortex (Kok et al., 2014; Kral, 2007). Moreover, Lazard and Giraud (2017) found a right hemispheric phonological network with participation of the visual cortices, predicting poor CI outcome. They used a rhyme decision task and fMRI measures to capture functional connectivity. However, MRI scans are difficult to perform with CI users, because the implants overshadow large areas of the brain (Majdani et al., 2009), making it difficult to measure connectivity with the auditory cortex after implantation. By contrast, the present study used EEG measures which allowed to study the functional connectivity between the visual and auditory cortex in CI users both at the time points before and after implantation. Given that we found comparably strong audio-visual connectivity at the two timepoints, our results suggest that this cross-modal enhancement is mainly induced by auditory deprivation and not by CI experience. Nevertheless, future research is needed to understand the pinpoint mechanisms more precisely. Furthermore, because our study used face stimuli, while others used simpler stimuli like chequerboards (Chen et al., 2017) or written words (Lazard & Giraud, 2017), stimulus-dependence should be considered in future studies.

4.3 Deaf people's attention to visual lip movements is enhanced

To date, the cortical processing of lip movements has been mostly discussed in conjunction with simultaneous auditory input (Stropahl et al., 2017; Layer et al., 2022). A recent study by Paul and colleagues (2022) used purely visual stimuli of a male speaker, articulating monosyllabic words. They analysed the P1 and N1 VEP components following the onset of the video. Since the onset of the video was also the onset of the lip movement, they were not able to differentiate the processing between static faces and lip movements. Interestingly, they did not find a difference between CI users and NH listeners for P1 and N1 VEPs. The current study extends these previous findings by examining the face and word processing systematically at different stages in purely visual conditions. In particular, we analysed the evoked responses not only to the static face onset but also to the onset of the lip movement. As shown in Figure 3A and 3D, we found a larger VEP amplitude for the attended lip movement when compared to the unattended lip movement in both groups, which reflects an effect of attention in both groups (Gazzaley et al., 2008). In contrast to the ERSP results, which revealed a group-specific pattern particularly in the frequency range 8-18 Hz (see discussion in the next section), we did not find a significant group difference in the attention effect for the VEP amplitude (peak detection analysis) at both timepoints. This discrepancy in findings for different approaches supports the view that a time-frequency analysis allows a more differentiated insight into cortical processes than the more conventional VEP peak detection analysis.

Rhythmic activity in the alpha frequency band has been related to the expectation and allocation of attention to attended stimuli (Foxe & Snyder, 2011), where increased alpha power (i.e. synchronisation) is proposed to indicate the suppression of unattended stimulus features (Foxe & Snyder, 2011; Klimesch et al., 2007; Jensen & Mazaheri, 2010). In the presented results, the NH group shows a *decreased* (desynchronised) oscillatory activity in the 8-18 Hz frequency band (i.e., enclosing the alpha frequency band) after face onset and prior to lip movement onset for the attended Target word stimuli compared to the ignored NonTarget word stimuli. This relative *suppression* of alpha power prior to the onset of the *lip movement* might indicate the allocation of attention away from the irrelevant NonTarget stimuli (in the face-categorisation task), and towards the relevant Target stimuli (in the word-identification task). Consequently, the *suppression* of alpha power prior to lip movement in NH listeners can be interpreted as a *facilitation* of relevant information processing in the Target word condition. By contrast, no such significant differences between Target and NonTarget stimuli were observed in the CI group (Figure 4 A/B) before lip movement onset. This indicates reduced ability to *suppress* task-irrelevant visual information in the CI users before and after implantation.

CI candidates and, after implantation, CI users heavily rely on visual information due to the limited auditory input. Therefore, one might speculate that CI candidates/users would not deliberately withdraw processing resources from the visual modality to facilitate processing in other modalities (Foxe et al., 1998). Indeed, in experienced CI users, a more pronounced weighting of visual attention has been suggested previously to compensate for the (still limited) electrical hearing (Butera et al., 2018; Radecke et al., 2022). Also, in deaf individuals, a more distributed visual attention has been observed (Bottari et al., 2010), which further confirms the view of a modulated visual attention in hearing-impaired individuals. Similar mechanisms might have prevented the suppression or withdrawal of attention from task-irrelevant (unattended) visual face stimuli before lip movement onset in our CI candidates/users of this study. However, as soon as visually relevant information is present (i.e., starting with the lip movement onset), differences in 8-18 Hz power between Target and NonTarget stimuli might indicate the allocation of attention towards the relevant lip movements and a suppression of irrelevant face features in both NH and CI groups. This can be seen in the significant condition differences for both groups at both timepoints.

4.4 Face selective N170 component

Faces have been shown to be perceived in a different way than other abstract visual objects (Stropahl et al., 2017). A core region in the neural network for face processing is the fusiform face area (Haxby et al., 2000; Kanwisher et al., 1997; Kanwisher and Yovel, 2006). In electrophysiological data, face-selectivity is most prominent around 170 ms after face onset over occipito-temporal scalp regions (N170 component; Bentin et al., 1996; Bötzel and Grüsser, 1989; Rossion and Jacques, 2008). Some previous studies showed advantageous face processing for deaf compared to NH individuals, as evidenced by greater amplitudes of the N170 component for deaf individuals (e.g. Bentin et al., 1996). This is explained by the compensation of missing auditory input during face-to-face communication (Kral et al., 2013; Mitchell et al., 2013; Woodhouse et al., 2009; Stropahl et al., 2015). The present results do not replicate these previous findings, neither for (postlingually deafened) CI candidates before implantation nor for CI users after implantation. This lack of group difference may be explained by the fact that we used computer animated faces instead of real faces, and that in our paradigms there were similar faces rather than a variation with other objects, such as houses (Stropahl et al., 2017). However, we observed that in the *face categorisation task*, the N170 amplitude was enhanced for rare deviant faces when compared to the more frequent NonTarget word stimuli. This effect was observed across both groups and might be explained by the structure of the paradigm and cortical adaptation: In the face categorisation task, the *frequent* NonTarget words were *not task-relevant*, but the *rare* deviant Target face stimuli were *task-relevant*. Thus, our results indicate that the N170 response is enhanced in conditions with rare and task-relevant stimuli, regardless of whether the individuals have normal hearing or have a hearing loss.

4.5 Relationship between cortical markers and speech understanding via the CI

Several previous studies have focused on the relationship between cortical plasticity and the speech recognition ability via a CI. While cross-modal plasticity is conceived as adaptive for behaviour in the remaining senses after sensory loss (e.g., Amedi et al., 2003, Gougoux et al., 2005; see for a review Voss et al., 2010), it has been debated whether it is maladaptive for sensory restoration (e.g., Doucet et al., 2006; Rouger et al., 2012; Sandmann et al., 2012; Paul et al., 2022). Rouger et al. (2012) stated that auditory, visual, and audiovisual networks are involved in cortical changes after cochlear implantation and that audiovisual integration after cochlear implantation is supported by functional links between face and voice processing areas. We found no evidence for enhanced cross-modal activation in the auditory cortex of CI candidates/CI users, but we did find alterations in functional connectivity between the auditory and visual cortex in these individuals (see Figure 5C and 5D). Because our connectivity values do not correlate with speech recognition ability via the CI, we cannot contribute to the discussion about the adaptive or maladaptive effects of cross-modal plasticity based on our findings. However, our results show a positive correlation between the (reduced) scalp-recorded visual P1 amplitude before and after implantation on the one hand, and the speech recognition ability after six months of CI use on the other hand. This indicates that less deprivation-induced (intra-modal) cortical reorganisation within the visual cortex (as indicated by a larger, i.e. closer to the NH listeners' P1 amplitude) relates to a better CI outcome. Thus, the cortical marker P1 amplitude – reflecting the extent of cortical reorganisation – may be one out of several factors which can help explain the large variability in CI outcome. Indeed, Strelnikov et al. (2013) found a correlation between visual cortex activation and auditory speech perception in postlingually deafened CI users, indicating a synergy between both modalities. However, future studies with a larger sample size need to verify whether the cortical P1 VEP amplitude can help giving a better prognosis of the expected CI outcome at the time before implantation.

5. Conclusion

This prospective longitudinal study examined the cortical processing of static and articulating faces in attended and unattended conditions. We observed that CI users before implantation show enhanced lipreading ability and deprivation-induced changes in the cortical processing of static and articulating faces (Question 1). Specifically, these alterations emerge not only in functional changes within the visual cortex (as indicated by a reduced face-onset response at P1 latency) but also in an enhanced functional connectivity between the visual and auditory cortex at sensory processing stages. The same CI candidates (before implantation) also show altered allocation of attention to faces when compared to NH listeners, as indicated by more comparable alpha power in the response to task-relevant and task-irrelevant faces (Question 2). This finding suggests that CI candidates are highly attentive to faces and lip movements, regardless of whether these visual stimuli are task-relevant or task-irrelevant. Even after restoration of the auditory input via the CI, the (reduced) face-onset response in the visual cortex and the (enhanced) functional connectivity between the visual and auditory cortex remain largely unchanged. Also, the alpha power for task-relevant and task-irrelevant visual information remains comparable after implantation, pointing to a persistently reduced ability to *suppress* task-irrelevant visual information after implantation (Question 3). In sum, these results suggest pronounced, deprivation-induced cortical alterations in processing of static and articulating faces, which appear to be hardly changed over the first six months of CI usage. Our observation that the scalp-recorded P1 amplitude, as measured before implantation, was positively related to the speech recognition ability after implantation (Question 4), suggests a connection between the deprivation-induced cortical reorganisation and the CI outcome. Thus, the P1 amplitude, which might indicate the extent of intra-modal reorganisation of the visual cortex, may provide valuable information for the prognosis of the CI outcome.

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Part III

DISCUSSION

This part discusses the results obtained and places them in the existing literature.

6

DISCUSSION

6.1 SUMMARY

The generality of the presented projects includes a variety of research questions regarding speech processing in postlingually deafened individuals receiving a CI. Different perspectives are highlighted by the investigation of

- different CI user groups, particularly single-sided deaf CI users and bilaterally hearing impaired CI users,
- different speech conditions, particularly purely auditory, purely visual and audiovisual speech,

  and

- different study forms, particularly cross-sectional and longitudinal studies.

The systematical comparison of different speech aspects in a longitudinal study format including the time point of cochlear implantation is a rare finding in the existing literature. Additionally, we compared SSD CI users to CI users with bilateral hearing loss regarding their audiovisual speech processing and lip reading abilities. Lastly, the examination of attentional focus while processing audiovisual speech in CI users and NH listeners was done for the first time.
In the following sections the obtained results are briefly summarised and discussed in the context of Health Sciences.

6.2 ALTERED AUDITORY PROCESSING IN DIFFERENT CI USER GROUPS

The studies "Side-of-implantation effect on functional asymmetry in the auditory cortex of single-sided deaf cochlear-implant users" and "Electrophysiological differences and similarities in audiovisual speech processing in CI users with unilateral and bilateral hearing loss" investigate the auditory (and audiovisual) speech processing in CI users of different groups. As already mentioned in the Introduction of this thesis, the examination of SSD CI users is rather scarce since this group of patients was not implanted with a CI in the past due to their intact contralateral ear (Zeitler and Dorman, 2019; Arndt et al., 2011b; Buechner et al., 2010). Therefore, this group is an interesting addition to the existing literature of altered auditory processing in CI users with bilateral hearing loss. Since the purely auditory processing in CI users with bilateral hearing loss was not a great part in the included projects, it is only discussed briefly, while the auditory processing in SSD CI users is discussed in greater detail.

CI users with bilateral hearing loss Most of the CI users suffer from hearing loss in both ears and this group of patients was examined a lot in previous research. Many studies focused on the plasticity of the auditory cortex, which is crucial for the successful rehabilitation of hearing with a CI (Moore and Shannon, 2009). In previous EEG studies it was shown that CI users develop increased evoked responses (Pantev et al., 2006) and altered specificity of the secondary auditory cortex (Giraud et al., 2001a). Especially the N1 component is examined when the auditory processing is of interest. This component was shown to be decreased and prolonged in CI users with bilateral hearing loss as compared to NH listeners (Finke et al., 2016; Henkin et al., 2015; Sandmann et al., 2009). However, Sandmann et al. (2015) found an enhancement of the N1 amplitude and a decrease in N1 latency over the first weeks of CI use in postlingually deafened CI users, indicating a reversed plasticity towards the results of NH listeners. The results of our study "Electrophysiological differences and similarities in audiovisual speech processing in CI users with unilateral and bilateral hearing loss" focused more on the audiovisual processing (see chapter 6.4), but it also confirmed altered auditory processing, especially in the N1 component, for the CI users as compared to the NH listeners.

SSD CI users Regarding the SSD CI users, our results confirmed previous findings of different processing between the two ears. We found prolonged response times, increased subjective listening effort and reduced and delayed auditory ERPs for the CI ear when compared to the NH ear (Finke et al., 2017b; Bönitz et al., 2018; Legris et al., 2020). To further specify the differences in processing, "normal" and "vocoded" stimuli were compared in the NH controls. The vocoded stimuli were compiled to approximate the CI stimulation (Friesen et al., 2001) and NH controls were stimulated with both kinds of stimuli. Since the vocoded stimuli did not cause longer reaction times, the degradation of the stimuli via a CI seems not to be the (sole) cause for prolonged responses. A previous longitudinal study in SSD CI users showed an increasing N1 amplitude within the first months after implantation, which did not reach the level of the NH controls after 12 months of CI use (Legris et al., 2020). Therefore, it is assumed, that the differences between the processing of the NH and the CI ear is caused by a combination of cortical reorganisation and the degradation of the auditory stimulation via a CI.

Moreover, based on previous research showing a right ear advantage for speech processing (REA, see section 1.2.1) and a study showing stronger auditory-cortex asymmetry for right-stimulated CI users with bilateral hearing loss (Sandmann et al., 2009), the side-of-implantation effect in SSD CI users was examined in our study. In contrast to Sandmann et al. we found increased functional auditory-cortex asymmetry for left-implanted SSD CI users when compared to right-implanted SSD CI users for the stimulation of both ears. This could result from the different user groups, since auditory deprivation reduces the metabolism in the contralateral auditory cortex (Speck et al., 2020) and induces cortical reorganisation in the auditory cortex (Stropahl, Chen, and Debener, 2017), leading to different activation patterns. Additionally, the stimulus types were different, with tones in the study of Sandmann et al. and syllables in our study. Given that the two cortical hemispheres have been shown to be engaged differently for different types of stimuli (Poeppel, 2003; Belin and Zatorre, 2000; Zatorre and Belin, 2001), this also affects the different results. Observing similar processing patterns in NH controls when stimulated with vocoded stimuli leads to the suggestion that our observed side-of-implantation effect does mostly originate from the limited auditory input. As far as we are aware, our study is the first one to additionally compare the NH ears of the two groups. The comparison between processing of the NH ear of the SSD CI users and the NH ear of the control group (stimulated with the original stimuli) also revealed a functional asymmetry in the auditory cortex of the left-implanted SSD CI users, but not in the NH controls. Hence, we assumed that the cortical reorganisation following auditory deprivation of one ear also affects the processing of the contralateral NH ear, making it different from the processing of individuals with two NH ears.

Since in SSD CI users it is possible to directly compare acoustic and electrical hearing in the same patients, both behaviourally and on the cortical level, they provide an interesting study group (Zeitler and Dorman, 2019). The downside of this is, that the rehabilitation process in this group of patients is often longer compared to CI users with bilateral hearing loss (Muigg et al., 2020), because the integration of the maximally asymmetric hearing sensation has to be learned (Gordon, Jiwani, and Papsin, 2013; Kral, 2013). In the past it was even stated to be impossible for the central auditory system to successfully process the acoustic and electrical hearing simultaneously (Zeitler and Dorman, 2019), leading to no benefits following cochlear implantation. In contrast, various studies found remarkable benefits of cochlear implantation for SSD CI users as expressed in tinnitus reduction, directional hearing, speech-in-noise intelligibility and quality of life (Van Den Noort et al., 2008; Kitterick, Lucas, and Smith, 2015; Arndt et al., 2017; Dorbeau et al., 2018; Galvin III et al., 2019; Grossmann et al., 2016; Távora-Vieira et al., 2015). Even for SSD children it has been shown that cochlear implantation is beneficial regarding academic performance and social interactions (Kay-Rivest, Roland Jr, and Friedmann, 2022; Ramos Macías et al., 2019; for a review see Benchetrit et al., 2021). Consequently, behavioural evidence for the capability of the central auditory system to process the extremely different inputs exist, even though the processing is delayed for the CI ear (Finke et al., 2017a; Bönitz et al., 2018). The latter could also be replicated in our study.

To get a deeper understanding of the underlying mechanisms, more research in this special CI user group is needed. Future studies should try to investigate the side-of-implantation effect on both the CI ear and the NH ear in greater detail and with different kinds of stimuli to better understand the extend of cortical reorganisation in SSD CI users compared to CI users with bilateral hearing loss. Furthermore it would be interesting to examine these patients in a longitudinal study to gain insights into the alterations of the cortical processing before and after cochlear implantation.

6.3 ALTERED VISUAL PROCESSING IN POSTLINGUALLY DEAF INDIVIDUALS AND CI USERS

The longitudinal study "Reduced visual-cortex reorganisation before and after cochlear implantation relates to better speech recognition ability" focuses on the visual processing in postlingually deafened individuals that are supplied with a CI. Since the sensory deprivation of one sense can have an impact on the other senses, the consideration of purely visual processing is important in hearing impaired individuals. Previous research proposed two different explanations of altered visual processing in these individuals, namely the *perceptual deficit hypothesis* and the *sensory compensation hypothesis*. While the first states that a deficit in one modality affects the organisation and development of the remaining sensory systems (Myklebust, 1960), the latter states that a deficit in one sensory modality is compensated by more sensitive remaining systems (Gibson, 1969). Both hypothesis were supported by different studies in hearing impaired individuals, where some found deficient visual abilities in congenitally deaf when compared to normal hearing individuals (e.g. Quittner, Leibach, and Marciel, 2004; Parasnis, Samar, and Berent, 2003), while others showed supranormal abilities in the deaf (e.g. Bottari et al., 2011; Hong Lore and Song, 1991; Neville and Lawson, 1987). Others even revealed comparable results in the visual performance for deaf and hearing individuals (e.g. Parasnis, 1983; Bavelier, Dye, and Hauser, 2006; Mitchell and Maslin, 2007). The variations of results underscore the still ongoing debate of (visual) perception and cognitive functions in sensory (hearing) deprived individuals. Some of the heterogeneity may be explained by different task conditions (bottom-up vs. top-down), the characteristics of used stimuli, the eccentricity of the (visual) stimuli (periphery vs. focus), and the different groups of participants (e.g. signers vs. non-signers).

In our study we found an enhanced lip reading ability in the postlingually deafened CI group at both timepoints, before and six months after implantation, when compared to the NH group. These results are comparable to previous results in congenitally deaf individuals (Bottari et al., 2014; Finney et al., 2003; Hauthal et al., 2013) and in CI users (Rouger et al., 2007; Layer et al., 2022). The findings highlight the dependence of hearing impaired individuals on visual cues to understand (audiovisual) speech, and that this visual compensation does not decline after restoration of the auditory input via cochlear implantation. Nevertheless, this effect was only found in the more difficult behavioural task with 21 monosyllabic words, but not in the EEG task with only three different words, which can be explained by an accustoming of the NH individuals to the repeatedly used three words. Comparable results were reported in EEG studies with low task difficulty (Layer et al., 2022; Stropahl and Debener, 2017), underlining the stimulus and task selective effects in behavioural visual improvements. Especially difficult conditions and complex speech stimuli yield to greater differences between hearing impaired and NH individuals (Rouger et al., 2008; Tremblay et al., 2010; Hauthal et al., 2013). Therefore it would be of great interest to further investigate the visual compensation by using complex speech stimuli in different groups of hearing impaired individuals and CI users at the same time. While the study "Electrophysiological differences and similarities in audiovisual speech processing in CI users with unilateral and bilateral hearing loss" (see the following section 6.4) showed, that the audiovisual processing in SSD CI users is similar, but not identical, to that of CI users with bilateral hearing loss, the purely visual processing of this group should be taken into further consideration in future studies.

It is often speculated that altered behavioural visual processing is also connected to reorganisation of the auditory cortex towards visual processing, also called cross-modal reorganisation (Lomber, Meredith, and Kral, 2010). Indeed, previous studies including congenitally deaf individuals reported the recruitment of the auditory cortex during visual processing (Fine et al., 2005; Finney, Fine, and Dobkins, 2001; Finney et al., 2003). Although our results did not replicate the observation of enhanced activation of the auditory cortex for visual processing in postlingually deafened individuals or CI users, we found a greater functional connectivity between the visual and auditory cortex in these individuals as compared to NH listeners, indicating a stronger cross-modal association between these cortices. This may also help to compensate for the missing (before implantation) or limited (after implantation) auditory input (Schierholz et al., 2015). In line with previous studies with congenitally deaf animals and humans (Kok, Chabot, and Lomber, 2014; Kral and Eggermont, 2007), our increased functional connectivity could arise from the enhancement of pre-existing connections between the auditory and visual cortices (Merabet and Pascual-Leone, 2010). Since the enhanced audiovisual connectivity was found for both timepoints (before and after implantation), it is suggested that the cross-modal enhancement is mainly induced by the auditory deprivation, not by CI experience.

Despite not replicating an enhanced cross-modal reorganisation in postlingually deafened individuals or CI users, we found evidence for intra-modal reorganisation in the visual cortex for these individuals. The postlingually deafened individuals, as well as the CI users, revealed a decreased P1 amplitude in the visual cortex when compared to the NH listeners. This is in line with previous studies in congenitally deaf individuals (Bavelier et al., 2000; Bottari et al., 2014; Hauthal et al., 2013) and postlingually deafened CI users (Sandmann et al., 2012). Again, these alterations in intra-modal cortical processing seem to be mostly induced by auditory deprivation, since the results are comparable between the two time points (before and after implantation).

6.4 ALTERED AUDIOVISUAL PROCESSING IN POSTLINGUALLY DEAF INDIVIDUALS AND CI USERS

The study "Changes in visually and auditory attended audiovisual speech processing in cochlear implant users: A longitudinal ERP study" focuses on the deprivation and CI induced alterations in audiovisual processing in postlingually deafened CI users with bilateral hearing loss, while "Electrophysiological differences and similarities in audiovisual speech processing in CI users with unilateral and bilateral hearing loss" focuses on the comparison of the two CI user groups at a timepoint after at least one year of CI use.

6.4.1 *Behavioural measures and cortical plasticity*

Various previous studies focused on the intra-modal and cross-modal changes in CI users with bilateral hearing loss before and after implantation (for a review see Stropahl, Chen, and Debener, 2017). Also numerous studies have demonstrated the importance of visual information for speech processing in CI users, as shown by enhanced lip reading skills (Desai, Stickney, and Zeng, 2008; Butera et al., 2018; Giraud et al., 2001b; Strelnikov et al., 2015; Rouger et al., 2008; Stropahl et al., 2015). On the other hand, research including SSD CI users is scarce, since they were not implanted with a CI due to their intact contralateral ear until recently (Zeitler and Dorman, 2019; Arndt et al., 2011b; Buechner et al., 2010). However, the restoration of binaural hearing has been shown to imply various behavioural advantageous (Kitterick, Lucas, and Smith, 2015; Arndt et al., 2017). Even fewer studies systematically compared the two user groups regarding their auditory or audiovisual speech processing. Moreover, longitudinal studies, examining deprivation and CI induced cortical alterations, are a rarity in the literature and the existing studies mostly focused on congenitally deaf children (Sharma, Dorman, and Kral, 2005; Sharma et al., 2007; Kral and Sharma, 2012). Still, some studies examined postlingually deafened adults before and after cochlear implantation (Pantev et al., 2006; Naito et al., 2000; Sandmann et al., 2015), using auditory stimuli and different measuring techniques.

Our studies therefore aimed to fill these gaps by systematic comparison of audiovisual speech processing at timepoints before and after implantation, as well as of CI users with unilateral and bilateral hearing loss.

By comparing the two user groups and the NH listeners, we found similarities as expressed by a visual modulation of the auditory response, which has been shown previously for CI users in the auditory cortex (e.g. Schierholz et al., 2015). This modulation is reflected in a multisensory effect leading to shorter audiovisual response times compared to the unimodal responses (auditory and visual). Referring to this, the P2 component revealed a distinct topography and a reduced amplitude for visually modulated auditory responses (AV-V) compared to the purely auditory response (A) in the visual cortex. In conclusion, audiovisual information is beneficial for all three groups, which has been shown in CI users (Schierholz et al., 2015) and NH listeners (Cappe et al., 2010) in previous studies. The missing group difference in the behavioural and part of the electrophysiological data may seem surprising, as CI users are normally entitled "better audiovisual integrators" (Rouger et al., 2007), but this result could be caused by the low complexity of the used speech stimuli (syllables). Schierholz et al. (2015) did also not find differences between CI users and NH listeners in an ERP study using non-linguistic stimuli, while Rouger et al. (2007) presented audiovisual words. This leads to the assumption that the audiovisual integration may be dependent on the complexity of the auditory stimuli with greater audiovisual integration for more complex stimuli in CI users. Hence, further research should focus on different types of stimuli to reveal the underlying mechanisms of behavioural differences between NH listeners and the different CI user groups. Especially more complex linguistic stimuli are of great interest, since they represent the real world situation best.

Contrarily, the N1 component showed a group difference as expressed in a significantly altered topography for AV-V compared to A in the CI users with bilateral hearing loss, indicating a strong visual influence in auditory processing. The SSD CI users and the NH listeners showed a clear N1 topography for both AV-V and A in the same extend, indicating similar neural processes for both modalities.

6.4.2 *Influence of attentional focus on (audiovisual) speech processing*

As shown in many previous studies, hearing impaired individuals rely more strongly on visual cues while processing speech during multisensory communication. They are better in lip reading, are more sensitive to visual stimulation in the periphery and they are better multisensory integrators. To our knowledge, none of the existing studies, however, focused on the effect of top-town attention on this sensory processing. Both studies, "Changes in visually and auditory attended audiovisual speech processing in cochlear implant users: A longitudinal ERP study" and "Reduced visual-cortex reorganisation before and after cochlear implantation relates to better speech recognition ability" therefore included different attentional focuses and time-frequency-analysis to study the effect of directed attention on the (bottom-up) sensory processing of visual and audiovisual speech in postlingually deafened CI users and NH listeners.

Previous research showed an effect of attention on ERPs by means of an enhanced amplitude for the attended as compared to the unattended stimuli (Gazzaley et al., 2008). Harris and Kamke (2014) even compared the attention to visual and auditory stimuli in adolescent CI users and showed that the visual attention, but not the auditory attention, is altered when compared to NH listeners. Nevertheless, the research mostly focused on unimodal and simple stimuli, but not on visual or audiovisual speech stimuli, as we did in our studies.

The use of time-frequency-analysis methods in ERP studies is growing more and more, since it was shown that different frequency bands can be associated with different cognitive functions (see table 1.2). Especially the alpha and beta band were shown to correlate with attention in a negative manner, such that decreased power in these frequency bands represents more attention/use of cognitive resources (Foxe and Snyder, 2011; Pesonen et al., 2006; Pesonen, Hämäläinen, and Krause, 2007).

For the purely visual processing of static and articulating faces a group difference was found in the extended alpha band for the time period between the onset of the static face and the lip movement. While the NH listeners showed a relative suppression of alpha power prior to the lip movement for the Target stimuli as compared to the NonTarget stimuli, indicating the allocation of attention away from the irrelevant NonTarget stimuli and towards the relevant Target stimuli, this effect was not observed in the postlingually deafened individuals, nor in the CI users. This matches previous studies, revealing a more pronounced weighting of visual attention to compensate for the limited electrical hearing in CI users (Butera et al., 2018; Radecke et al., 2022) and a more distributed visual attention in deaf individuals (Bottari et al., 2010).

Regarding the audiovisual word processing we found a group difference in the beta frequency range. The NH listeners showed a decreased beta power for the visually attended words as compared to the auditory attended words, indicating an increased memory load when attending the visual lip movement (Pesonen et al., 2006, Pesonen, Hämäläinen, and Krause, 2007), while the CI users did not exhibit this difference. The effect may be explained by the fact that hearing impaired individuals, whether the auditory input is missing due to auditory deprivation or it is limited due to CI use, use visual cues more frequently in their everyday lives and are therefore more accustomed to the processing of (visual) lip movements.

Taken together the results obtained from time-frequency-analysis indicate an alteration of, especially visual, processing in different states of attention. As a consequence of auditory deprivation, the visual system is more encouraged, even in situations where the attention is not deliberately drawn to visual hints.

Additional to the time-frequency-analysis, the project "Changes in visually and auditory attended audiovisual speech processing in cochlear implant users: A longitudinal ERP study" also compared the top-down effect of attention on the sensory cortical processing between postlingually deafened individuals receiving a CI and NH listeners. Similar to previous studies (e.g Tinnemore, Gordon-Salant, and Goupell, 2020), comparable results were found for the two groups as expressed in poorer task efficiency for the visually attended condition as compared to the auditory attended condition, as well as in enhanced GFP peak amplitudes and more occipitally pronounced topographies. The latter originate from a greater activation in the visual cortex for the visually attended condition, suggesting an enhancement of activation in the visual cortex when focusing on the visual lip movement. All of these results, again, seem to not be affected by CI use. Our results follow the view that focusing on explicit characteristics of stimuli results in an increased neural responsiveness and hence in stronger activation when processing the attended stimuli (Rufener, Liem, and Meyer, 2014).

6.5 AUDITORY REHABILITATION OF CI USERS

The adaptation of the patient's brain to the new electrical input of the CI takes some time, in which active and passive learning mechanisms play a crucial role (Fu and Galvin III, 2011). For the passive part of the adaptation the patient does not have to do anything else than wearing the speech processor throughout the day to give the brain the possibility to adapt to the new distorted, shifted of inadequate incoming signals (Fu and Galvin III, 2011). To achieve a good outcome, however, it is important to actively train the new auditory situation. Therefore speech therapists guide the patients through exercises like vowel discrimination, word and sentence recognition in closed sets and open speech understanding.

Several previous studies showed an activation of the auditory cortex in postlingually deafened CI patients in different conditions like noise, multi-talker babble or speech (Green et al., 2005; Mortensen, Mirz, and Gjedde, 2006; Naito et al., 1995; Petersen et al., 2013). They mostly found a positive correlation between the strength of the auditory cortex activation and the speech intelligibility (e.g. Green et al., 2005), indicating that an effective activation of the auditory cortex via the CI results in satisfying speech perception.

Nowadays the rehabilitation methods are mainly purely auditory, even though recent findings suggest an audiovisually based training to be even more effective. This is based on the fact that multisensory input is crucial in the everyday life, especially for hearing impaired individuals, and that the bond between different modalities may be useful to support and strengthen auditory rehabilitation in CI users. Findings of previous research (e.g. Rouger et al., 2007; Schierholz et al., 2015; Layer et al., 2022), as well as results obtained in our studies, point to an enhanced audiovisual interaction in CI users. Additionally some of our results underline the fact that the visual modality plays a big role in the (audiovisual) speech processing of postlingually deafened individuals and CI users.

First results for the effectiveness of audiovisual rehabilitation programs point into different directions. On the one hand a PET study by Nishimura et al. (2000) proposed a competition or rivalry between the auditory and visual modality, especially in recently implanted CI users but not in experienced CI users. On the other hand some studies in NH listeners, stimulated with and without CI simulation, reported findings in favor of audiovisual rehabilitation (Kawase et al., 2009; Matusz et al., 2015; Seitz, Kim, and Shams, 2006; Shams and Seitz, 2008; Strelnikov, Rosito, and Barone, 2011; Thelen and Murray, 2013), which are not all verified in CI patients yet. In sum, the findings support the potential benefit of audiovisual rehabilitation methods in CI users, but more research should focus on the question which way and manner is optimal for which CI user group.

6.6 THE CONNECTION BETWEEN ELECTROPHYSIOLOGICAL MEASURES AND THE SPEECH PERCEPTION IN CI USERS

Since speech perception is the most important outcome parameter for patients receiving a CI and it seems to not be solely dependent on the rehabilitation, studies try to predict the speech perception on the basis of different parameters.

Some previous studies focused on the relationship of demographical and audiological factors that influence the speech perception with a CI (e.g. Blamey et al., 2012, Holden et al., 2013, Lazard et al., 2012b, for a recent systematic review see Velde et al., 2021). The majority found a negative influence of the time of deafness and the age at implantation. Additionally, implant specific and surgical factors were found to influence the CI outcome (e.g. Francis et al., 2008, Finley et al., 2008, O'Connell et al., 2016). A recent study of Hoppe and colleagues (Hoppe et al., 2019) found a robust prediction model including the age at implantation, the maximum recognition score for monosyllabic words prior to implantation and the word recognition score with a hearing aid at 65 dB sound pressure level. Their main message says that the patients with remaining preoperative speech perception achieve better speech perception with a CI.

None of those prediction models is able to explain the greatest part of variability in the CI outcome and therefore it is assumed that also cognitive factors could play a role. Besides the cortical plasticity may have an impact on the success of the auditory rehabilitation of different CI users. Our results of study 4 showed a positive relationship between a visually evoked electrophysiological component (P1) and the speech intelligibility after six months of CI use. This is a first evidence for markers of cortical plasticity having an influence on the speech intelligibility with a CI.

> *Das Wichtigste ist, dass man nicht aufhört zu fragen.*
>
> **— Albert Einstein**

6.7 LIMITATIONS AND OUTLOOK

Our studies have dealt with the speech processing of different CI user groups in various modalities. Nevertheless, none of our studies included different groups, timepoints and modalities at the same time, which makes direct comparisons difficult. Future research, including longitudinal study designs and the incorporation of different CI user groups in the same study, may allow to get a deeper understanding of the auditory, visual and audiovisual speech processing in all those individuals. The results may be used to develop more multisensory and individual training procedures for CI users by using scenarios that are similar to their everyday life.

Besides, the sample size is a limitation in all the presented studies. This constraint resulted from the inclusion criteria for the experiments and the available time frame. All our studies only included postlingually deafened individuals, because the timepoint of the onset of deafness plays a crucial role in language acquisition and in the extend of cortical plasticity. It would be of great interest to include both groups, pre- and postlingually deafened individuals that are supplied with a CI, into one study to investigate the differences in speech processing. Further, the number of SSD patients that are supplied with a CI is still small, which made the participant recruitment more difficult. As generally known, a small sample size limits the significance of the results, hence it would be nice to have future studies with a greater sample size to replicate the obtained results.

Moreover, the computer-based animation used in our studies ("MASSY"; Modular Audiovisual Speech SYnthesizer (Fagel and Clemens, 2004)) was reported to be too static and did not show any emotions or facial expressions other than the lip movement. Using more realistic head models or even models of whole people would allow to control all aspects of the stimuli while creating scenarios close to the real world. Moreover, the use of more speech stimuli, e.g. various different words or even whole sentences and stories, would extend the validity of results regarding the real world.

Another aspect that is worth future consideration is the prediction of speech intelligibility after cochlear implantation based on parameters obtained prior to implantation. We found a positive relationship between an electrophysiological parameter (P1 component) and the CI outcome after six months of use, giving first evidence in this direction. Including more parameters, such as cognitive factors and different electrophysiological measures, could improve the existing models. A deeper understanding of the underlying mechanisms and a more precise prediction would help people facing the decision for or against a CI.

6.8 CONCLUSION

Taken together, the results presented in this thesis provide further evidence that the auditory processing is altered in postlingually deafened CI users when compared to NH listeners, despite of whether they suffer from hearing impairment in one or both ears. These alterations comprise a side-of-implantation effect, depicted in a functional asymmetry of the auditory cortex activation, in SSD CI users, a stronger visual cortex activation for audiovisual speech processing in both CI user groups in combination with greater lip reading ability when compared to NH listeners and deprivation induced cortical alterations in postlingually deafened individuals, expressed in a reduced auditory cortex activation and a stronger functional connectivity between the auditory and the visual cortex, that remain largely unchanged after six months of CI use. All results are shown to be detectable in subjective, behavioural, and objective measures and some are related to the CI outcome.

The findings contribute to a better understanding of the auditory, visual and audiovisual cortical speech processing in CI users and may be helpful for predictive models of the CI outcome, as well as for an enhanced clinical rehabilitation procedure.

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COLOPHON

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Übersicht der Publikationen:
Weglage, A., Müller, V., Layer, N., Abdel-Latif, K. H., Lang-Roth, R., Walger, M., & Sandmann, P. (2022). Side of-implantation effect on functional asymmetry in the auditory cortex of single-sided deaf cochlear-implant users. Brain Topography, 35(4), 431-452.

Layer, N., **Weglage, A.**, Müller, V., Meister, H., Lang-Roth, R., Walger, M., Murray, M., & Sandmann, P. (2022). Electrophysiological differences and similarities in audiovisual speech processing in CI users with unilateral and bilateral hearing loss. Current Research in Neurobiology, 3, 100059.

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Weglage, A., Layer, N., Müller, V., Meister, H., Lang-Roth, R., Walger, M. & Sandmann, P. (under review). Reduced visual-cortex reorganisation before and after cochlear implantation relates to better speech recognition ability. Journal of Neuroscience research. Sumitted on 18 July 2024

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Köln, 18.02.2025

Anna Weglage