Cortical auditory plasticity of cochlear implant users

A multi-year longitudinal study

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Abstract

Introduction: In this research, the goal was to investigate the cortical auditory neural plasticity of adult CI users over time. The study investigates whether subjects demonstrate changes in the evoked potential P300's latency and amplitude, as well as speech perception, after nine years of CI use.

Methods: In this longitudinal study, auditory cortical responses of the P300 evoked potential, elicited by pure-tone stimuli within an oddball paradigm, were recorded in twenty CI users, divided in three groups: congenital (N = 4), prelingual (N = 7) and postlingual (N= 9) deaf individuals. Additionally, the speech recognition score of each subject was assessed using speech audiometry. All subjects participated in a similar research, executed nine years ago, which allows a within-subject comparison between the two times of measurements.

Results: Significant shorter P300 latencies were found for the measurement of 2023 compared to 2014 ($p = .033$). The amplitude of the P300 was also higher for the measurement of 2023, however only partial significant. No significant difference was found for the speech recognition between the two times of measurement. Additionally, no significant correlation was found between the speech recognition and the P300 characteristics. The postlingual group showed better speech recognition than the congenital and prelingual group ($p = .009$).

Conclusion: the auditory cortex of adult CI users appears to show neural plasticity, reflected in, generally seen, shorter latencies and higher amplitudes of the P300 after nine more years of CI use.

Introduction

Cochlear implants

For over the last thirty years, multichannel cochlear implants (CI) have been proven to be a successful method of auditory rehabilitation for deaf individuals or individuals with severe hearing loss. At first, only people with severe to profound hearing loss were eligible for CI. Currently, CI is the most effective method for the revalidation of hearing impaired individuals, for whom amplification no longer provides significant benefits (Boo & Jeong, 2022), which also includes deaf individuals. Recently, Arndt et al. (2023) stated that cochlear implantation is a successful treatment for single-sided deafness, for both congenital/prelingual as postlingually deaf individuals .

CIs are devices that directly stimulate the auditory nerve by bypassing the inner ear. The hardware consists of an external and internal device. The internal device receives and processes the acoustic sounds, whereas the external device transduces the received signal and directly stimulates the cochlear nerve (Naples & Ruckenstein, 2020). This electric stimulation induces an activity pattern that differs significantly from acoustic stimulation. Nonetheless, it still mimics the tonotopic principles of the cochlea, which allows CI users to interpret auditory input and differentiate speech sounds (Távora-Vieira et al., 2022).

Interpreting and differentiating this new auditory information, requires adjustment, also called adaptation, from the central auditory system after the operation. The auditory brain areas need to create new connections due to the new auditory input. Adaptation can be defined as the process of adjusting structures or physiology in order to become more suited to the new situation. When the brain is able to adapt and create new connections, the brain is called plastic. It is well known that brain plasticity plays a significant role in the extraordinary success of cochlear implant in providing functional hearing to deaf individuals, despite the reduced and unnatural input of the device (Moore and Shannon, 2009). In other words, the degree of the plasticity of the brain determines the ability to adjust to the new, unfamiliar

auditory input of the cochlear implant. However, the outcomes after surgery vary greatly amongst the CI users. One individual benefits tremendously from the implant, while another can't get used to the new input. The factors that influence CI outcomes (e.g. age at implantation) have been the subject of numerous studies the last decades, but still up to 80% of the variability stays unexplained (Anderson et al., 2019). The question that arises is whether the outcomes after the implantation will be better, when the brain shows adaptation. But first, how can the adaptation and plasticity of the brain be measured?

Cortical Auditory Evoked Potentials (CAEPs)

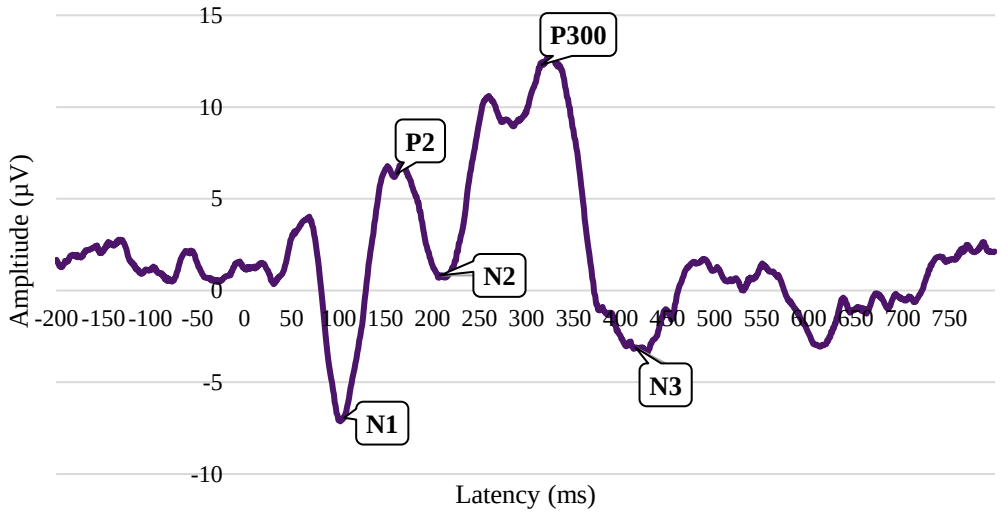
The cochlea sends impulses to the auditory cortex in response to an acoustic stimulus that is presented to the ear. The neural responses generated in the auditory cortex can be detected by a method, in which electrodes are placed on the scalp and measure the electric energy: electroencephalography (EEG). These neural responses are also known as cortical auditory evoked potentials (CAEPs) or Late Latency Auditory Evoked Potentials. The CAEPs consist of multiple components, each presented by a peak in the waveform of the EEG signal. The four exogenous evoked potentials are the P1, the N1, P2, and N200 (McPherson, 1998). The P indicates the peak is a positive peak, whereas the N stands for negativity. The numbers relate to the latency of the peak in milliseconds (e.g. N2 is expected at about 200 milliseconds after stimulus onset). These early pre-attentive responses often take place during the first 250 milliseconds and do not indicate cognitive processing (Lightfoot, 2016). See Figure 1 for a visualization of the different exogenous evoked potentials and their latencies and amplitudes.

To be able to assess the maturational status of the auditory cortex, CAEP recordings can be used as an objective measure (Boo & Jeong, 2022). Several studies have investigated the maturation of the auditory cortical areas in deaf children by using CAEP measurements, such as Sharma et al. (2002) and Saki et al. (2021). Sharma et al. (2002) showed that children implanted before the age of 3.5 years, had a P1 latency within normal limits for their age,

based on the data of normal hearing children. Most studies that investigate CAEPs in CI users look at the P1 component in deaf children, since the CAEP waveform in young children is dominated by P1. Only after this time, between 9 and 12 years, other EEG peaks appear, eventually developing into a powerful negative peak (N1), that now dominates the CAEP waveform (Sharma et al., 1997; Ponton et al., 2000) and following P2. So, looking at the P1 component, will not reveal much about the adult auditory cortex' maturation or development. Therefore, the maturation of higher-order auditory areas in adults can be investigated by looking at the N1-P2 components (Wunderlich et al., 2007).

Figure 1

Illustration of the ERP Response of a Normal-Hearing Individual with Peaks P1, N1, N2, P3 and N3.



In the study of Boo & Jeong (2022), the plasticity of the auditory cortex of adult CI users was investigated by addressing the CAEP components P1, N1, and P2. Their main interest was the status of the auditory cortex when it fully develops in adulthood rather than during childhood. Therefore, they measured CAEPs in individuals with early childhood-onset progressive hearing loss (group 1) and individuals with prelingual deafness (group 2), who received the CI on a young age. Each individual listened to a tone burst of 1000 Hz while

watching an animation movie without sound. The results showed clear CAEP responses for all CI users. For the first group, with prelingual onset of deafness, prolonged latencies were found for P1 and N1 compared to the control group. On the contrary, for the second group, consisting of progressive deaf subjects with early childhood onset, no prolonged latencies were found for the P1 compared to the control group. The authors concluded that patients in both groups developed primary and higher-order auditory areas when they became adults. Nevertheless, the latencies were prolonged to the controls, so the development of the auditory areas is still suboptimal, despite the implantation at a young age.

P300

Another component of the CAEPs, is the P300 component. The P300 is an endogenous cognitive event-related potential with a relatively high amplitude (McPherson, 1998). The P300 indexes the ability to identify and differentiate task relevant targets and cues (Helfrich and Knight, 2019). The P300 can be subdivided into two parts: the P300a and P300b. The P300b is the positive peak that occurs at about 300 milliseconds after the onset of an unexpected stimulus. In contrast, the P300a component, is an earlier, positive deflection that takes place around 200 milliseconds after the stimulus onset. Both P300 components are related to cognitive processing, but researchers are generally more interested in the P300b, because of its specific relationship to the evaluation or rare and deviant stimuli with tasks contexts (Polich, 2007). From now on, the P300b is meant when discussing the P300.

How can the P300 be elicited in experimental tasks? A variety of paradigms have been used in order to evoke the P300. Following McPherson (1998), the P300 occurs specifically when individuals recognize a change in an auditory stimulus. One of the most utilized paradigms, is the oddball paradigm (Duncan et al., 2009; Polich, 2007). In this paradigm, various stimuli are introduced through an active attention process, in which one of the stimuli, known as the oddball, occurs less frequently than the other, standard stimulus (Squires et al.,

1975). This leads to a sudden change in auditory stimuli. Examples of these stimuli could include tone burst with varying frequencies or different speech stimuli, such as two different phonemes (e.g. /pa/ and /ba/).

The P300 potential is measured by assessing its latency and the amplitude. The latency (ms) is the interval between the start of the stimulus and the point maximum peak amplitude within the given time window. The latency of the P300 is considered a direct index of information-processing speed (van Dinteren et al. (2014)), where a shorter latency corresponds to faster processing speed. The amplitude is known as the difference in μV between the largest positive peak and the mean baseline voltage of the waveform within a time window (Polich, 2007). The amplitude of the P300 represents the amount of the neuronal activity and the capacity of neuronal systems to respond to the input (Ashford et al. 2011). Simply said, an increase of P300 amplitude, elicited by an auditory stimulus, represents more neural activity in the auditory cortex.

CI and neural plasticity

Following the literature, the idea is that the ability of the auditory nerve to restore fully and being able to discriminate phonemes, is dependent of different factors like the age of the implantation, the amount of time of use of the CI and the auditory deprivation, i.e. the time an individual was deprived from auditory sound. Ghiselli et al. (2020) investigated the auditory restoration after a cochlear implant of prelingually deaf people. Among other things, they wanted to know the relation between the auditory restoration, measured with electroencephalography (EEG), and the age at implantation and the length of CI use. The subjects underwent auditory event-related registration, where the P300 was measured by presenting sinusoidal tones (1000-2000 Hz) in an oddball paradigm. They found that the P300 latencies were significantly longer for the CI users than for the controls. Besides that, the amount of cortical activation had a significant positive correlation with the duration of the use

of the CI and a negative significant correlation with the age of the implantation. In other words, the earlier someone was implanted and the longer the CI use, the more cortical P300 activity. Whereas Ghiselli et al. (2020) found prolonged latencies for the prelingual group compared to the control group, Grasel et al. (2018) could not find prolonged latencies for the postlingual group compared to the controls.

In a study by Grasel et al. (2018), the objective was to compare the P300 potential's latencies and amplitudes in adult CI users with postlingual deafness to normal hearing adults. These CI participants were divided into two groups: poor or good speech recognition scores. The stimuli used to evoke the P300 were tone bursts in two different conditions: the first condition with a target stimulus of 2000 Hz and non-target 1000 Hz and the second with the target stimulus 1000 Hz and non-target 1500 Hz. The authors found that the group with poor speech recognition scores showed significant longer P300 latencies than the good speech recognition group and their control group. The good performing group and the matched control group did not show any significant differences in latencies. In amplitude, there was no difference between the CI users and control group. In addition, there was no difference between the two frequency conditions between the control group and CI recipients. The authors did not elaborate on the difference within subjects in the latencies for both conditions, to see if the P300 latencies are significantly longer for the more difficult condition. In conclusion, the authors found longer P300 latencies for the poor speech recognition than for the good performers and control group in this experiment.

Speech recognition and CI

Although adults with acquired hearing loss can successfully regain access to auditory input due to CIs, not all individuals experience the same advantage when it comes to speech recognition. One of the most important current issues in CI research, is the fact that language and speech outcomes after CI, vary greatly among CI users (Han et al., 2019). Patients with

cochlear implants often miss a serious amount of auditory input before implantation, which leads to less exposure to the phonemes of their language. A language can be characterized by a specific repertoire of phonemes, a form of speech sounds, which represent the building blocks for the words. These words can sound quite similar, but differ in the meaning. So the correct identification of a phoneme is of crucial importance, as well for the correct perception of a word as for the understanding of the larger context (Ortmann et al., 2017). Speech recognition is therefore very important and one of the main outcomes measures of cochlear implantation (Messersmith et al., 2019).

Speech recognition typically improves quickly in the initial post-implantation phase and remains stable over time (Rak et al., 2017; Cusumano et al. 2017). In this time after implantation, the rehabilitation phase, patients have to learn to decode the CI's deteriorated auditory signal and identify the speech and word sounds within this signal (Ma et al., 2022). To assess the auditory discriminating abilities of CI users and the auditory plasticity, the cognitive P300 potential could be used, since it offers pertinent information about an individual's auditory plasticity and speech recognition (Grasel et al., 2018). Furthermore, Jacquemin et al. (2019) found a significant positive correlation between the speech perception and the degree of plasticity. However, most of the studies in the field, only perform one time-point measurement. Given the discussion of the plasticity of the auditory cortex, it would be interesting to examine how people's speech perception, P300 latencies- and amplitudes change over time. Will the auditory central brain area show plasticity, even after many years of CI use?

P300, speech recognition and auditory plasticity – a longitudinal study

One of the first studies investigating the plasticity of the auditory cortex in CI users, employing the features of AEP components and speech recognition, was conducted by Groenen et al. (2001). The authors compared the latencies and amplitudes of the N1, P2 and

P300 components in postlingual deaf CI users with those of normal-hearing individuals. The auditory stimuli consisted of four different speech sound contrast, presented at frequencies of 500 and 1000 Hz. In general, the CI group showed prlonged latencies for all they found AEP components compared to the control group. Besides that, a positive relation was observed between the speech perception abilities and the characteristics of the P300 component.

In 2002, Beynon et al. further explored the relation between speech perception and AEP components, with a specific focus on the P300. While Groenen et al. (2001) focused on postlingually deaf CI users, the present study involved two different groups. Group A consisted of five congenitally deaf young CI users with relatively poor speech recognition, whereas Group B comprised five prelingually deaf individuals, with relatively good speech recognition scores. The stimuli used included speech sound contrasts and pure tone stimuli, presented in an oddball paradigm. For Group A, delayed or absent P300 latencies were found when the stimuli consisted of speech sounds, whereas P300s were detected using pure tone stimuli. Group B did not show significant different P300 potentials from the control group. In addition, higher P300 amplitudes were positively correlated with better speech recognition performances.

In 2005, Evers repeated the research by Beynon et al. (2002) and invited the same population of CI users. The study aimed to determine whether the subjects showed any signs of plasticity, reflected in shorter latencies and higher amplitudes than the previous measurement, after six years of CI use. In this interval, the participants continued to use the CI, providing the auditory cortex with additional time to adapt to the electrical auditory input. Within the group of good performers (N = 4), half of the subjects showed significant improvement in both the latency and amplitude of the P300 component, compared to the measurement of Beynon et al. (2002). In the group of poor performers (N = 4), an overall significant improvement was found for the P300 compared to the previous study. Evers

concluded that congenitally deaf CI users still showed plasticity of the auditory cortex and do benefit from the auditory input of the CI.

About ten years later, Hendriks (2015) extended the research initiated by Beynon et al. (2002) and Evers (2005). For the current study, five individuals from the original group of ten, participated, accompanied by 42 more adult CI users. The primary objective of the study was to compare the speech perception and characteristics of the P300 among three groups of deaf individuals: congenitally, prelingually and postlingually deaf adults. Additionally, the outcomes of the five subjects were compared to the prior results. The study also involved an examination of the impact of various factors that might affect the P300 and speech perception, such as the 'age of implantation'. Data showed improved P300 characteristics and speech recognition scores for all the five subjects who participated in the longitudinal study. Furthermore, the postlingual group showed the best P300 characteristics and speech recognition score, followed by the prelingual and at last the congenital. The conclusion drawn was that plasticity does occur in the auditory cortex, even in later-implanted adults, as observed in the improvement of the five CI users.

The current study

The current study is part of a longitudinal study, building upon the research conducted in previous decades by Beynon et al. (2002), Evers (2015) and Hendriks (2015). In this research, the goal is to investigate the cortical auditory neural plasticity of adult CI users over time. The study investigates whether subjects demonstrate changes in the evoked potential P300's latency and amplitude, as well as speech perception, after nine years of CI use. Since cochlear implants are a relatively recent area of study, there are limited multi-year studies on cortical auditory neural activity, such as the study by Fitzroy et al. (2015). Providing longitudinal scientific evidence is crucial for evaluating the behavior of the auditory nerve after implantation. Therefore, the main research question in this study is: what is the long-

term effect of the auditory stimulation at the neural auditory cortical processing, expressed in the presence and amplitude of the P300 potential measured with EEG, evoked by an auditory stimulus within the population of congenitally, prelingually and postlingually deaf CI users?

This study partially replicates the study done by Hendriks in 2015. The same method of testing and analyzing is being used, to be able to perform a reliable within-subject comparison of the subjects over time. The research question will be addressed by an EEG experiment. The participant's neural activity will be tracked while listening to a variety of tone bursts. This results in a signal in which the AEP components (N1, P2, N2, P300 and N3), expressed in latency and amplitude, can be indicated. In addition, the speech discrimination score, expressed in a phoneme score, of the CI users will be addressed. The P300 amplitude, latency and phoneme score outcomes of the current measurement will be compared to the measurement of 2014. Besides the longitudinal comparison, the effect of the following variables on the P300 amplitude and latency will be taken into account: age, age of implantation, duration of using the CI, auditory deprivation, etiology (congenital, prelingual or postlingual). In analogy to the study of 2015, a comparison between two frequencies of tones will be compared, similar to the two conditions in the study by Grasel et al. (2018), to see what the effect of octave distance is on the latency and amplitude of the P300.

Method

Participants

The participants were recruited from the Radboudumc database, which consisted of individuals who had taken part in the studies conducted in 2002, 2005 and 2015. All of the participants from this database, who met the following criteria were contacted: using their CI on a daily basis and having no (interfering) diseases. This resulted in the participation of twenty, Dutch-speaking CI users (13 female, 7 male), with a mean age of 49;8 ± 13;1 (range: 26;10 – 67;8), of whom two participants also participated in the study of Beynon et al. (2002)

(and Evers (2005)). The mean age at the day of CI implantation was 27;9 ± 16;9 (range: 3;7 – 50;1) and the mean experience with the CI, i.e. the amount of time the participants had been using the CI, was 21;11 ± 7;2 (range: 12;5 – 32;11) years. Additionally, the total amount of time the participants were deprived from sound, i.e. the auditory deprivation, was 18;8 ± 17;2 (range: 2;2 – 49;3) years. Lastly, the mean age of onset of deafness was 9;2 ± 11;4 (range: 0;0 – 35;0) years. Table 1 shows the demographic information of the CI participants. Each participant used a Nucleus multichannel-type implant manufactured by Cochlear Corp (Australia).

The participants were divided into three groups: congenital, prelingual and postlingual CI users. The congenital CI users were individuals with an onset of deafness from the age before 1;0 years. The prelingual CI had an onset of deafness between the age of 1;0 and 3;0 years, whereas the postlingual CI group exists of individuals who became deaf after the age of 3;0 years. Four individuals are congenitally deaf, seven prelingually and nine postlingually. The mean ages and standard deviations of the demographic information for the three CI groups are shown in Appendix A. Besides the pathological groups, one control group was implemented in the study. This groups consisted of fifteen normal-hearing participants (7 male, 8 female) with a mean age of 26;5 ± 6;8 (range = 21;9 – 49;9) years, tested in 2014 within the study of Hendriks (2015).

Tabel 1

Descriptives of the Twenty CI Users

Subject	**Group**	**Age**	**Age at imp.**	**CI use**	**CI side**	**Onset deaf.**	**Auditory depr.**	**Cause of deafness**
1	Congenital	64;8	33;5	31;3	AS	0;0	33;3	Unknown: Suspicion of hereditary deafness
2	Congenital	63;2	46;5	16;9	AS	0;0	46;5	Anoxia at birth
3	Congenital	62;7	39;3	13;4	AS	0;0	49;3	Hereditary deafness

4	Congenital	53;11	40;10	13;1	AS	0;8	40;2	Unknown
5	Postlingual	35;0	8;1	27;4	AS	5;2	2;6	Haemophilus influenza meningitis
6	Postlingual	46;7	16;0	30;7	AD	11;6	4;6	Deafness after medication
7	Postlingual	46;0	16;2	30;5	AD	24;4	2;3	Unknown
8	Postlingual	60;8	43;1	17;7	AD	11;0	32;1	Progressive hearing loss
9	Postlingual	58;5	39;4	17;9	AS	17;0	23;8	Stapedotomie & Otosclerose
10	Postlingual	26;10	8;11	17;8	AD	6;1	3;1	Progressive hearing loss
11	Postlingual	57;4	33;2	24;3	AD	24;0	9;1	Hereditary bad hearing
12	Postlingual	67;8	38;4	67;8	AD	33;0	5;4	Unknown
13	Postlingual	62;6	50;2	62;7	AS	35;0	15;1	Unknown
14	Prelingual	35;8	6;2	29;4	AS	2;0	4;10	Pneumococcal meningitis
15	Prelingual	35;8	5;8	30;6	AS	3;0	2;2	Haemophilus influenza meningitis
16	Prelingual	38;1	5;2	32;11	AD	3;0	2;2	Pneumococcal meningitis
17	Prelingual	53;3	33;8	19;7	AD	3;0	30;8	Pendred syndrome
18	Prelingual	35;8	22;0	13;8	AS	1;6	20;6	Pneumococcal meningitis
19	Prelinguaal	31;1	3;2	27;6	AS	1;5	2;2	Pneumococcal meningitis
20	Prelinguaal	59;7	44;8	14;11	AD	1;5	43;4	Meningitis & ototoxic medication

Note. Age (in years), age at imp. (age at implantation in years), CI use (time in years the device is used), CI side (with AD = right and AS = left), onset deaf. (age in years at onset deafness), auditory depr. (time in years of auditory deprivation.

Materials and procedure

Speech recognition

For assessing the behavioral perception of speech in CI users, a standard speech audiometry test procedure was employed, conducted at the Radboudumc. The measurement was performed in the free field at one meter distance in a sound-treated booth. A potential additional CI or hearing aid was removed from the ear and turned off. The participant was presented with a word and prompted to repeat the word. Monosyllabic Dutch wordlists of the NVA-lists (Bosman lists; Bosman, 1989) were employed. Every lists contains eleven well

known words, all consisting of one syllable and three different phonemes. In total, 33 different phonemes were presented to the participant in each list. Every word follows a CVC order (consonant – vowel – consonant). The list always started with a practice word, which was not considered in the scoring.

In this experiment, the participants were required to repeat at least two NVA lists, both presented at 70 dB SPL in a free field. After the participant had repeated the word, the researcher counted the number of correctly reproduced phonemes. The average score of the two lists formed the speech recognition score, expressed in a percentage. The task was carried out by using the speech audiometry function within the Affinity Suite of Audiologicx (version 1.0.6, MarYor, the Netherlands).

Electroencephalography (EEG) measurement

Stimuli. The experiment employed an active oddball paradigm, where the subject was presented with different frequencies of pure tone stimuli, which were selected to elicit P300 responses, consistent with the approach of previous studies (Obuchi et al. (2012); Grasel et al. (2018); Wedekind et al. (2021)). Perez et al. (2016) compared speech stimuli and pure tone stimuli in the context of the P300. Their findings indicated that pure tone stimuli showed better P300 reproducibility than speech stimuli. Furthermore, all the general settings for the experiment resembled those of Evers (2005) and Hendriks (2015). In each run, a set of 200 tone burst stimuli is presented in the sound field, with 170 being standard stimuli and 30 being deviant stimuli, which corresponds to an 85% probability rate for the standard stimulus. The stimuli were delivered at a stimulation rate of 0.5 Hz and with 10% jitter inter-stimulus interval (ISI). The duration of each sound stimulus was 90 milliseconds (10 ms rise, 70 ms plateau and 10 ms fall-time). A high pass filter of 0.1 Hz and low pass filter of 30 Hz were used to filter the AEP responses. Initially set at 50 µV, the rejection level could be adjusted during the measurement, depending on the noise level of the patient during the measurement.

The experiment consisted of two conditions. In the first condition, the standard stimulus represents a tone burst of 500 Hz, whereas the deviant stimulus consists of a tone burst of 1000 Hz. At least two AEP waveforms for each stimulus were obtained to check reproducibility and increase reliability. In between two runs, at least two minutes were taken for relaxation for the participant. In the second condition of the experiment, the settings were changed to a deviant stimulus of 2000 Hz instead of 1000 Hz. This second condition was thought to be less difficult, since the difference between the stimuli was now 1500 Hz instead of 500 Hz in the first condition. All the other factors remain unchanged. The order of these two conditions was randomized for all subjects.

Procedure. The subject sat in a reclining seat in a sound-treated booth, facing a loudspeaker at one meter in front of the subject, on eye-level height. Before starting the measurements, the subject completed a consent form and received instructions, both in written form and verbally from the investigator. First of all, it was made sure the subject could hear the sounds easily, so the volume was adjusted to their preference, i.e. at most comfortable level (MCL), for most patients around 70 dBHL. The next step involved acquainting the subject with the different sounds and ensuring the perception of the differences. Although, when this wasn't the case, the participants were still included to obtain true negative P300 responses. Prior to the experiment, the oddball paradigm was explained, by presenting standard and deviant stimuli in the form of respectively triangles and a square to illustrate the paradigm.

To obtain the EEG signals, three disposable AgCI surface electrodes were placed at three sites on the head of the subject. These sites were according to the international used 10-20 system (Jasper, 1958) for EEG electrode placement. The electrodes were placed on the following locations: the non-inverting electrode on CPz (1), the inverting electrode on the mastoid bone (M1/2), directly behind the ear, contralateral to the side of the CI. The ground

electrode was placed near the temple at the face, also contralateral to the side of the CI (3), to avoid measuring electrical stimulus artefacts originated by the cochlear implant rather than the brain. Before attaching the electrodes, the skin was disinfected and scrubbed, to lower the impedance of the skin. Electrode impedances were checked and should not exceed 5kΩ. The EEG device used for this experiment was the 'Medelec Synergy EMG EEG system' (VIASYS, Healthcare 2005). The electrodes were plugged into the preamplifier to amplify the cortical response.

The subject was instructed to mentally count all the deviant tones they heard and later report the count. This approach aimed to maintain the attentiveness to the sounds and wakefulness of the participants. Additionally, the subject was advised to sit still, relax and preferably close their eyes, to be able to obtain and average EEG signals under optimal signal-to-noise ratio. The subject's neural activity (the 'running EEG') was displayed real-time on the computer as a raw EEG. Ideally, running EEG signal amplitudes should not exceed 20μV to ensure an adequate signal-to-noise ratio. When the signal remained calm and steady for approximately five seconds, the measurement was started.

Analysis

EEG response signals. The two EEG signals, i.e. the responses of the standard and deviant stimulus, were displayed separately. After two repeated runs, the two responses of standard and of deviant are separately summed to a grand average. Then, the grand average of the deviant responses was subtracted from the grand average of the standard responses, which resulted in the difference signal response, resulting in a 'true' P300 (or P300b) response, to avoid possible misinterpretation of a P300a that is also present in response to the standard stimulus.

The definitions of the P300 latency (ms) and amplitude (μV) were based on the definitions of Polich (2007). The latency range for the N1, P2 and N2 components was

defined between 50 and 300 milliseconds. For the P300 between 250 and 350 milliseconds and for the N3 between 260 and 360 ms. The reproducibility of the peaks was observed in the two separate signals, to see if the peak was consistent throughout the runs. Mean peak latency was calculated by taking the mean peak of the grand average response. N1 and P2 were marked in the grand average of both standard and deviant response, whereas the for the deviant and difference responses, additionally N2, P300 and N3 components were marked. To prevent potential baseline drift, that might have influenced the absolute peak amplitude, peak-to-peak amplitudes were used as an outcome measure of the amplitude (N2P3 and P3N3 peak-to-peak amplitudes). Two different researchers independently assessed each AEP component. Since the data of 2014 will be compared to the current results, the same protocol was used for marking the peaks in the response wave. Since this process is quite subjective, all peaks from the previous research of 2014 were re-interpreted.

Statistical analysis and hypotheses. For the statistical analysis, the statistical program JASP (version 0.17.3; JASP Team, 2023) was used. The statistical analysis can be divided into five sub parts.

Longitudinal differences. To assess the extent of plasticity of the auditory cortex, after nine years of CI use, for different etiologies (i.e. congenitally, prelingually and postlingually deafness), a longitudinal within-subject comparison between the measurements of 2014 and 2023 was executed. For this purpose, variables phoneme score, P300 latency, N2P3- and P3N3 peak-to-peak amplitudes were compared, using a paired-samples t-test. Additionally, for the two prelingual CI users who also participated in 1998 and 2005, their previous measurements were compared to the current outcomes. Improvement in the values of the variables (i.e. earlier latencies, higher amplitudes- and phoneme score) is expected for the most recent measurement.

Difference between groups. To evaluate differences between the four groups:

congenitally, prelingually and postlingually deaf CI users and the control group, a one-way analysis of variance (ANOVA) was used to analyze the dependent variables phoneme score, P300 latency, N2P3 and P3N3 peak-to-peak amplitudes. The hypothesis for this comparison posits that the values of the neural responses and phoneme score will differ significantly, with better wave morphology for the postlingual group compared to the congenital and prelingual. Moreover, it is assumed that higher amplitudes and earlier latencies will be found for the control group compared to all the pathological groups.

Correlation with phoneme score. The relationship between phoneme score and the dependent variables P300 latency, N2P3 and P3N3 peak-to-peak amplitudes, was tested using a correlation analysis using Pearson's correlation coefficients (r); firstly, the correlation for all groups, followed by the correlations for the three CI groups. A positive correlation is expected for the amplitude and the phoneme score, which indicates that individuals with high amplitudes of the P300, also show better speech recognition. A negative correlation is expected for the speech recognition scores and the latency: individuals with relatively short latencies of the P300, will perform relatively good at the speech recognition test.

Correlations with other possible influencing variables. To investigate the effects of the independent variables age, age of implantation, duration of using the CI, auditory deprivation and onset deafness on the dependent variables phoneme score, P300 latency and N2P3 and P3N3 peak-to-peak amplitudes, the correlation of each independent variable and dependent variable was calculated. The first hypothesis is that an increase in CI use will have a positive correlation with the P300 latency and amplitude and the phoneme score. This positive correlation suggests that the longer someone is using their CI, the better the neural responses and the speech recognition. Secondly, it is hypothesized that variable 'age' will show a negative correlation with the P300 latency and amplitude (Schiff et al. (2008), Juckel et al. (2012), Bourisly (2016)) and phoneme score (e.g. Murr et al. 2021). The same relation is

expected to be found for the variables ‘age at implantation’ and ‘auditory deprivation’. This suggests that the neural responses and speech recognition are better in patients with younger age, younger age of implantation and less auditory deprivation.

Different deviant frequency stimuli frequency deviant stimulus. Difference in frequency of the deviant stimulus (1000 Hz vs 2000 Hz) might affect the P300 latency and N2P3- and P3N3 peak-to-peak amplitudes. A paired samples t-test was used to compare the frequencies of the deviant stimuli. The hypothesis posits that the stimulus of 2000 Hz is easier to discriminate from the standard stimulus (i.e. 500 Hz) than the deviant of 1000 Hz. However, Grasel et al. (2018) did not find significant differences for similar distinct frequencies. Therefore, no significant differences will be found for the different frequencies of the deviant stimuli.

Results

Data points out that for the measurement of 2023, one congenital and one prelingual subject (resp. subject 1 and 20, see Appendix B), did not show the P300 potential in the response waves of the measurement of 2023. Besides that, no P300 was found within the response wave in 2014 of postlingual subject 12. Thus, in the analysis of the measurements in 2014 and 2023, seventeen participants were included (three in the congenital group, six in the prelingual and eight in the postlingual group). For the analysis of the phoneme score, all subjects were included.

Longitudinal results

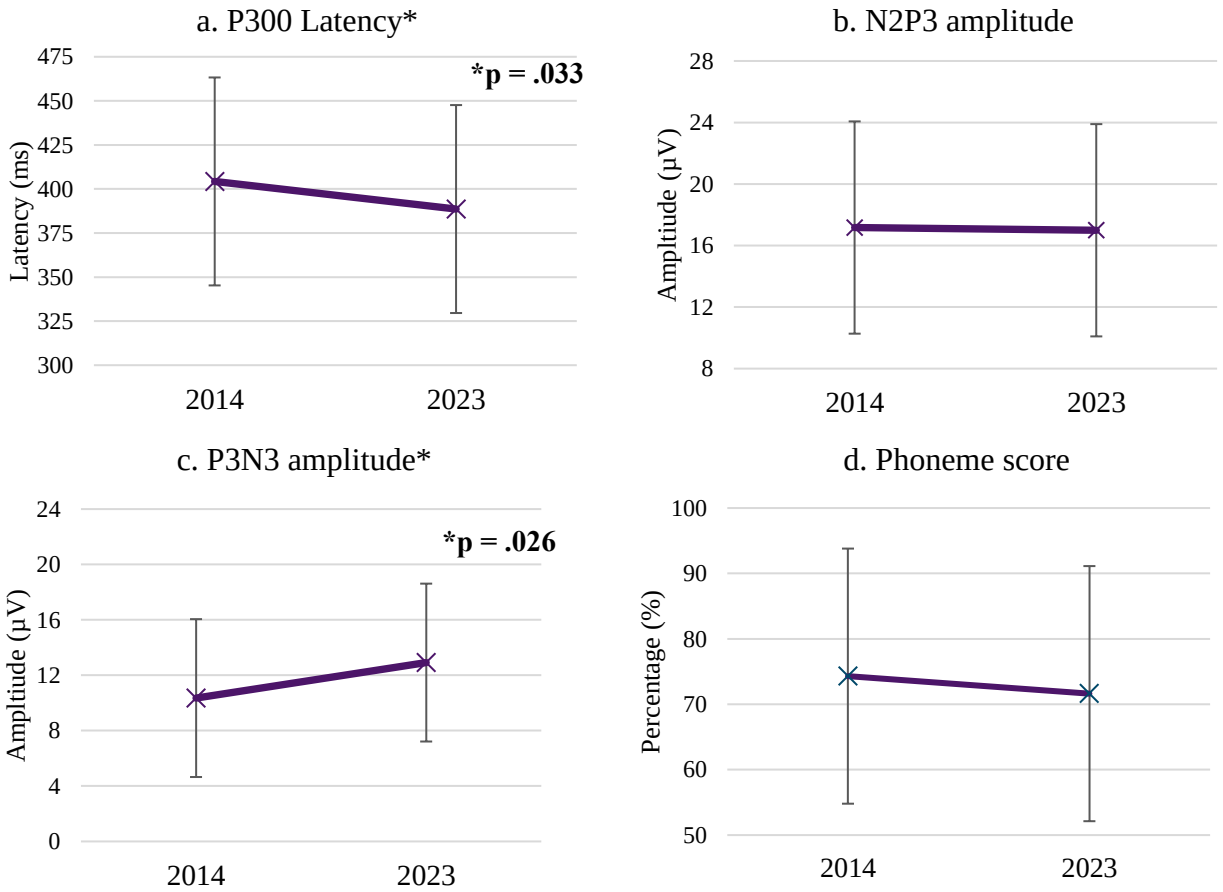
Longitudinal difference for all participants 2014-2023

The independent variables phoneme score, P300 latency, N2P3 peak-to-peak amplitude and the P3N3 peak-to-peak amplitude were compared for all subjects for the measurement of 2014 and 2023. A paired-samples t-test revealed no significant difference in the N2P3 amplitude for the entire group (2014: 16,9 μV; 2023: 17,7 μV) ($t(16) = .31$; $p =$

.76) and the phoneme score (2014: 74,3%; 2023: 71,6%) (t (19) = .92; p = .37), see Figure 2b and 2d. However, a significant difference was seen for the P300 latency (2014: 404,3 ms; 2023: 388,6) and P3N3 peak-to-peak amplitude (2014: 10,4 µV; 2023: 21,9 µV) (P300 Latency (t (16) = 2.33; p = .033); P3N3 amplitude (t (17) = -2.43; p = .026). Both variables show an improvement in 2023 compared to 2014 (shorter latencies and higher amplitudes), see Figure 2a and 2c.

Figure 2

Comparison of the Outcomes of 2014 and 2023 of the Total Group



Note. Outcomes for all the subjects (N = 17 (phoneme score, N = 20)) for a. P300 latency (ms); b. N2P3 peak-to-peak amplitude (µV); c. P3N3 peak-to-peak amplitude (µV) and d. Phoneme score (%) for the measurements in 2014 (left) and 2023 (right).

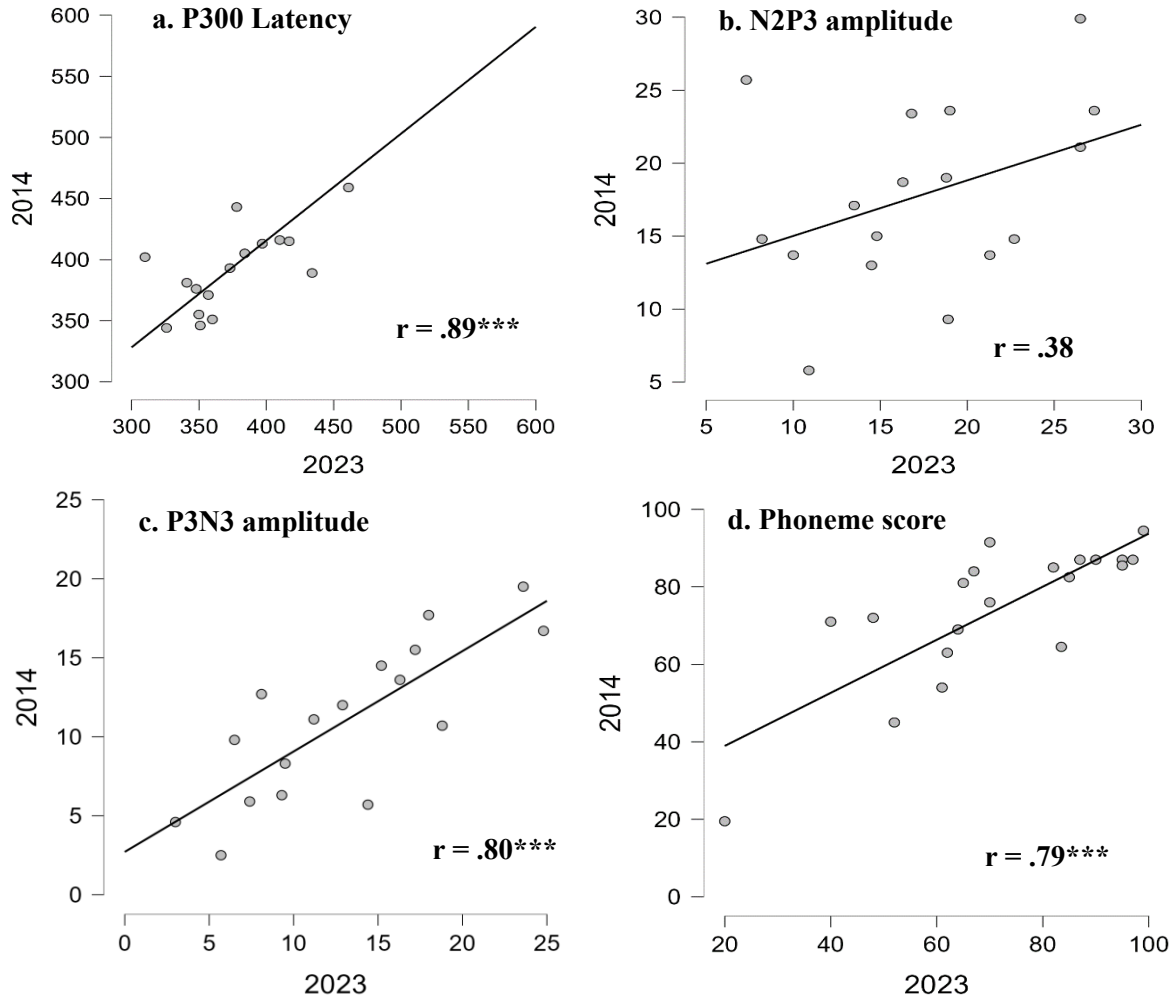
Correlations between 2014 and 2023

In addition to analyzing the differences between the two times of measurements, the correlation between the P300 amplitude and latency and the phoneme score are also analyzed.

The correlations are based on the total group of subjects. A positive high significant correlation was found between the P300 latencies of 2014 and 2023 ($r = .89$, $p < .001$), see Figure 3a. The correlation between the measurement of 2014 and 2023 for the amplitude of N2P3 peak-to-peak is not significant ($r = .38$, $p = .13$), see Figure 3b. The P3N3 peak-to-peak amplitude exhibited a statistically significant, positive correlation between the two times of measurement ($r = .80$, $p < .001$), just as for the phoneme score ($r = 0.79$, $p < .001$) (resp. Figure 3c and 3d).

Figure 3

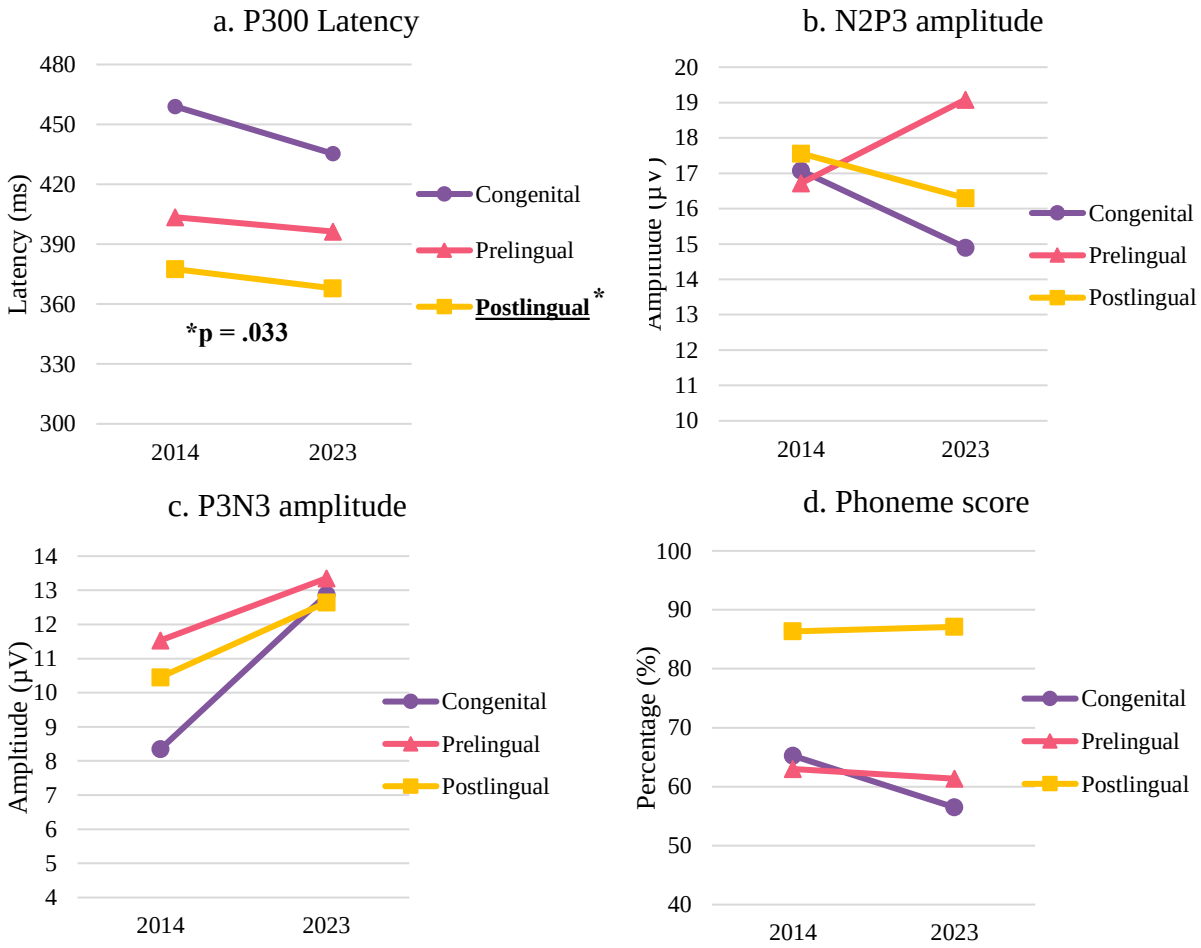
Correlation Plots of the Outcomes of 2014 and 2023



Note. Correlations shown as scatter plots of the four dependent variables (a. P300 latency (ms) with outliers; b. P300 latency (ms) without outlier; c. N2P3 amplitude (µV); d. P3N3 amplitude (µV); e. phoneme score (%) with outlier; f. phoneme score (%) without outlier) for the measurements in 2014 (y-axis) and 2023 (x-axis) for all subjects. N = 17 for the P300 latency and N2P3- P3N3 amplitudes, N = 20 for the phoneme score. * $p < 0.05$, **$p > .005$, ***$p < .001$.

Figure 4

Comparison of the Outcomes of 2014 and 2023 for the CI groups.



Note. Outcomes for the a. P300 latency (ms); b. N2P3 peak-to-peak amplitude (µV); c. P3N3 peak-to-peak amplitude (µV) and d. Phoneme score (%) for the measurements in 2014 (left) and 2023 (right) for the congenital (N = 3), prelingual (N = 6) and postlingual groups (N = 8). N.B. The number of participants differs for the phoneme score (resp. N = 4, N = 7 and N = 9).

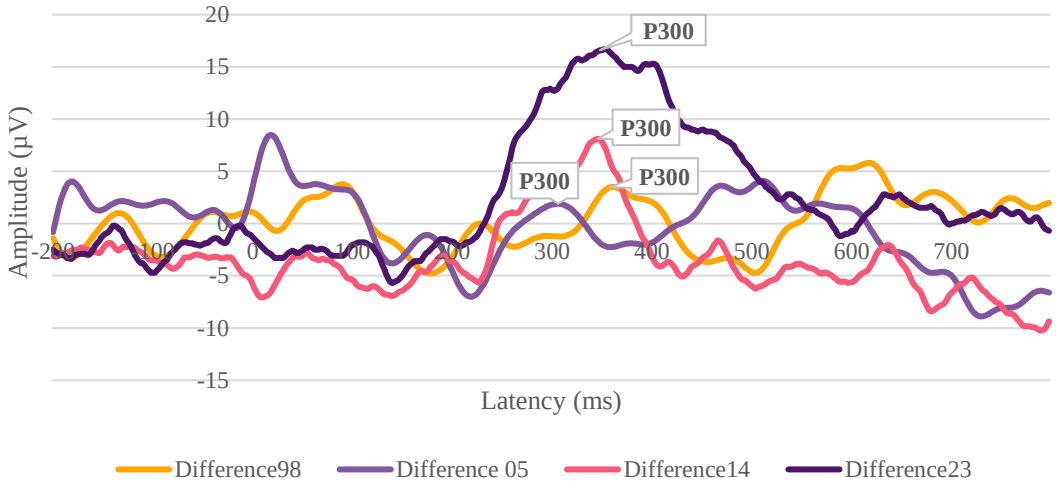
Two prelingual subjects

Two of the twenty subjects also participated in (some of) the earlier studies of Beynon (2002) and Evers (2005). The first subject, subject 14, participated in all the previous experiments; 1998, 2005 and 2014. Subject 15 participated in 1998 and 2014. In Figure 5, the response waves are shown for the difference between the deviant and standard stimulus for the four measurements for subject 14. Table 2 shows the corresponding values of the latency, P300 amplitudes and phoneme scores. In Figure 6, the difference waves are shown for subject 15 for the three different measurements and Table 3 again shows the corresponding values.

Since the previous measurements only reported the amplitude of the P300, the separate N2P3 and P3N3 peak-to-peak amplitudes are not reported.

Figure 5

Longitudinal Outcomes of Prelingual Subject 14



Note. The difference waves (subtraction of deviant and standard response waves) with labelled P300 components for the three measurements of 1998, 2005, 2014 and 2023 for subject 14. On the y-axis the amplitude (µV) of the difference wave is shown; on the x-axis the latency in milliseconds (ms).

Table 2

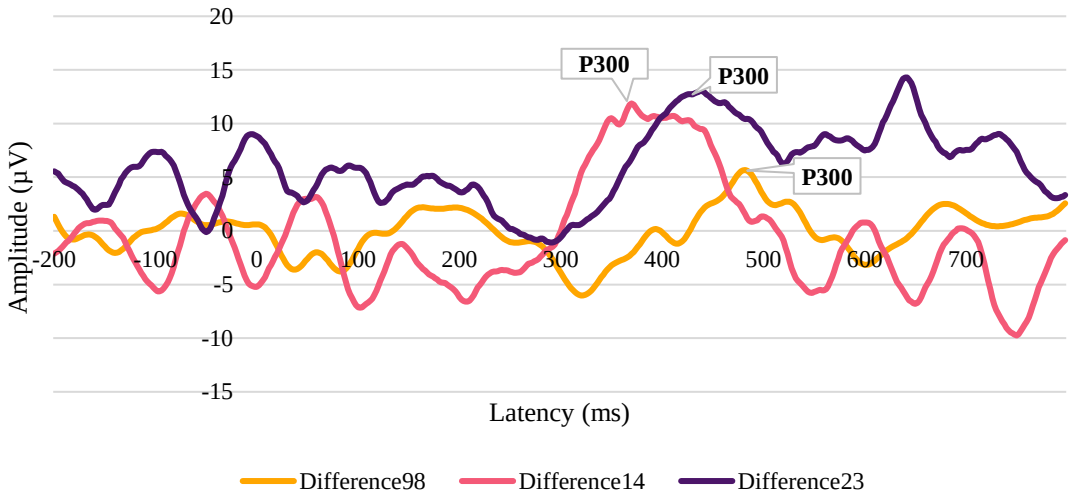
Values of the P300 Latency, Amplitude and Phoneme Score of Subject 14 for 1998 - 2023

Subject 14	**1998**	**2005**	**2014**	**2023**
P300 latency	385.0	335.0	346.0	351.0
P300 amplitude	4.8	2.7	8.0	16.7
Phoneme score	87.0	66.0	72.0	48.0

Note. The values of the P300 latency (ms), P300 amplitude (µV) and phoneme score (%) for subject 14 for the measurement of 1998, 2005, 2014 and 2023.

Figure 6

Longitudinal Outcomes of Prelingual Subject 15



Note. The difference waves (subtraction of deviant and standard response waves) with labelled P300 components for the three measurements of 1998, 2014 and 2023 for subject 15. On the y-axis the amplitude (µV) of the difference wave is shown; on the x-axis the latency in milliseconds (ms).

Table 3

Values of the P300 Latency, Amplitude and Phoneme Score of Subject 14 for 1998 - 2023

Subject 15	**1998**	**2014**	**2023**
P300 latency	480.0	389.0	434.0
P3 amplitude	6.0	10.1	12.8
Phoneme score	87.0	64.5	83.5

Note. The values of the P300 latency (ms), P300 amplitude (µV) and phoneme score (%) for subject 14 for the measurement of 1998, 2014 and 2023.

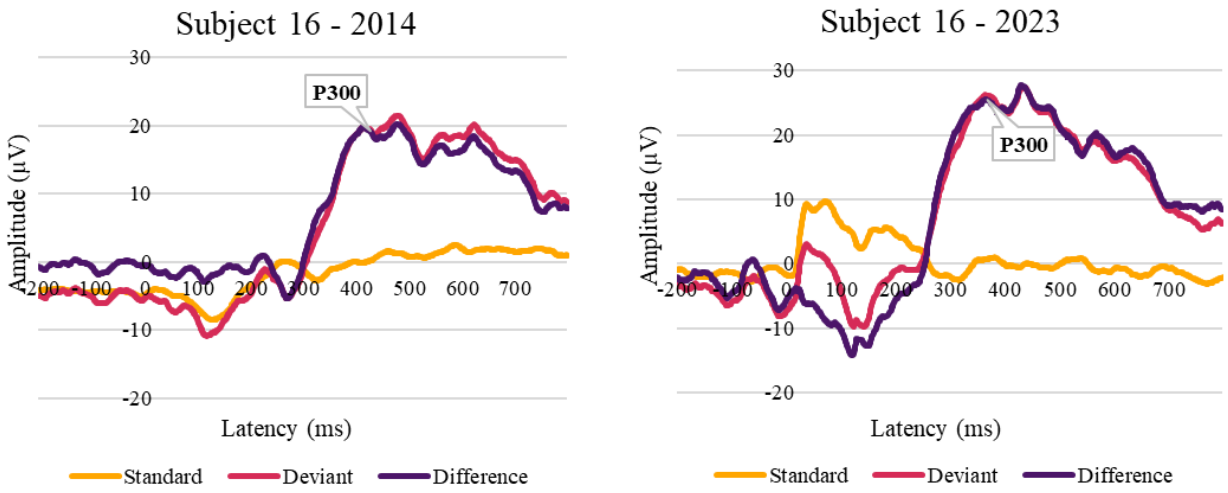
Individual comparisons

Given the averaging of the outcomes, discerning individual improvement or deterioration becomes challenging, as they are obscured within the overall average of the total group. Therefore, the neural response waves of two subjects within each group will be shown. One of the two cases exhibits an improvement in the P300's latency or amplitude. The other example shows a consistent pattern or decline of the P300's characteristics between the times of measurement. In Appendix B, the remaining individual data are shown.

Prelingual case 1. The first case is subject 16, a prelingually deaf CI user, who shows an improvement of the P300's amplitude and latency. Figure 7 illustrates how the P300's amplitude is slightly higher in 2023 than in 2014 (resp. N2P3 = 27,3 µV vs. 23,6 µV; P3N3 = 10,7 µV vs. 9,1 µV). In addition, the latency of the P300 is considerable shorter in 2023 (378 ms) than in 2014 (443 ms).

Figure 7

Cortical Neural Response Waves for Subject 16

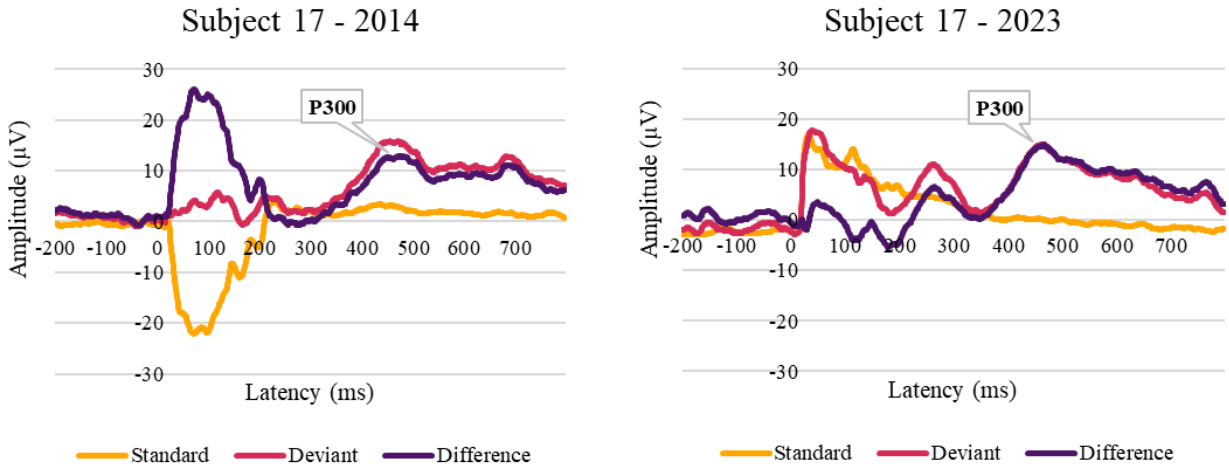


Note. The three response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 16. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter.

Prelingual case 2. The second case of the prelingual group is subject 17. As shown in Figure 8, a consistent pattern can be seen between the two times of measurement for the P300's latency (2014 = 459 ms; 2023 = 461 ms) and for the N2P3 (2014 = 13,0 µV; 2023 = 14,5 µV) and P3N3 peak-to-peak amplitude (2014 = 6,3 µV; 2023 = 9,3 µV). N.B. The big peak around 100 ms represents an artefact of the sound stimulus.

Figure 8

Cortical Neural Response Waves for Subject 17

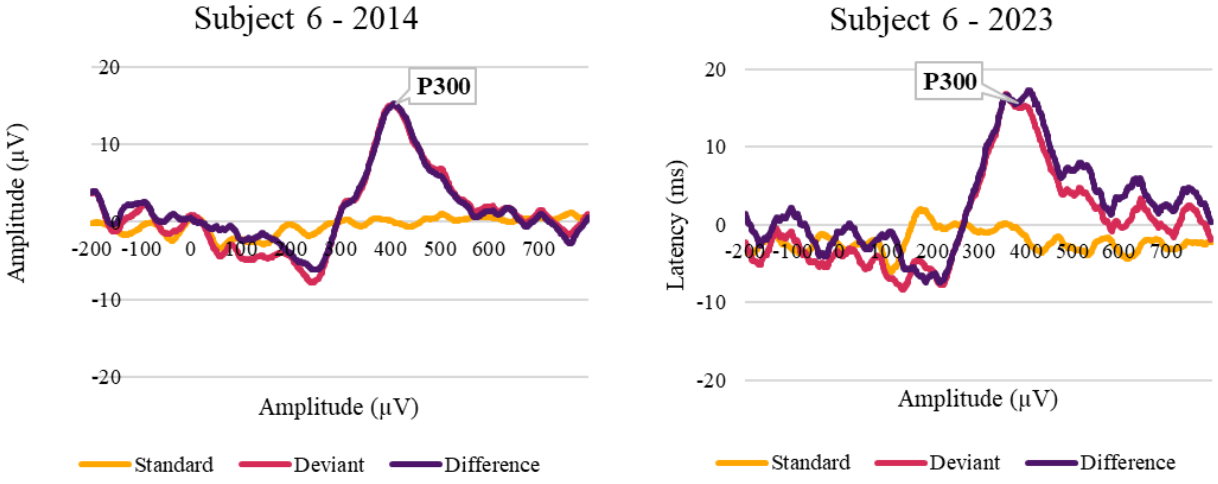


Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 17. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter. The big peak around 100 ms represent an artefact of the sound stimulus.

Postlingual case 1. An example of an improved neural response from a postlingual subject, is that of subject 6. The subject shows an improved P300 latency (384 ms) in 2023 pertaining to 2014 (405 ms) and amplitude of the P300 in 2023 versus 2014 (resp. N2P3 = 26,5 µV vs. 21,1 µV; P3N3 = 15,2 µV vs. 14,5 µV) as demonstrated in Figure 9.

Figure 9

Cortical Neural Response Waves for Subject 6

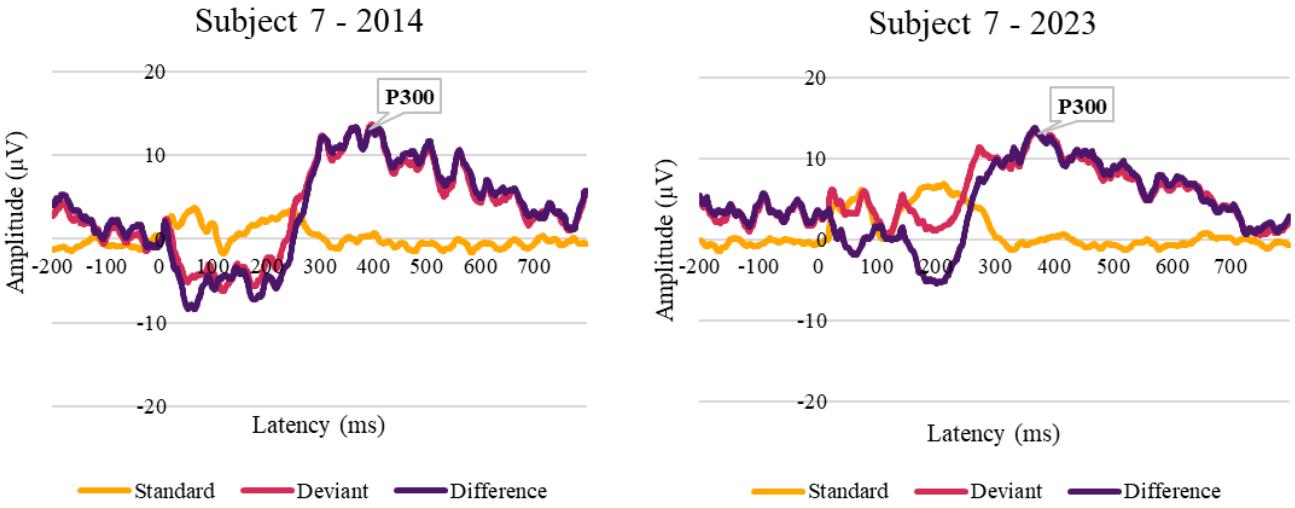


Note. The three response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 6. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter.

Postlingual case 2. The second example of a postlingually deaf CI is subject 7, who shows a quite consisent pattern over the years, see Figure 10. The P300 latency in 2014 was 393 ms, whereas it amounts 373 ms in 2023. However, the amplitude does only differ slightly for 2023 versus 2014 (resp. N2P3 = 19,0 µV vs. 18,8 µV; P3N3 = 12,0 µV vs. 12,9 µV).

Figure 10

Cortical Neural Response Waves for Subject 7

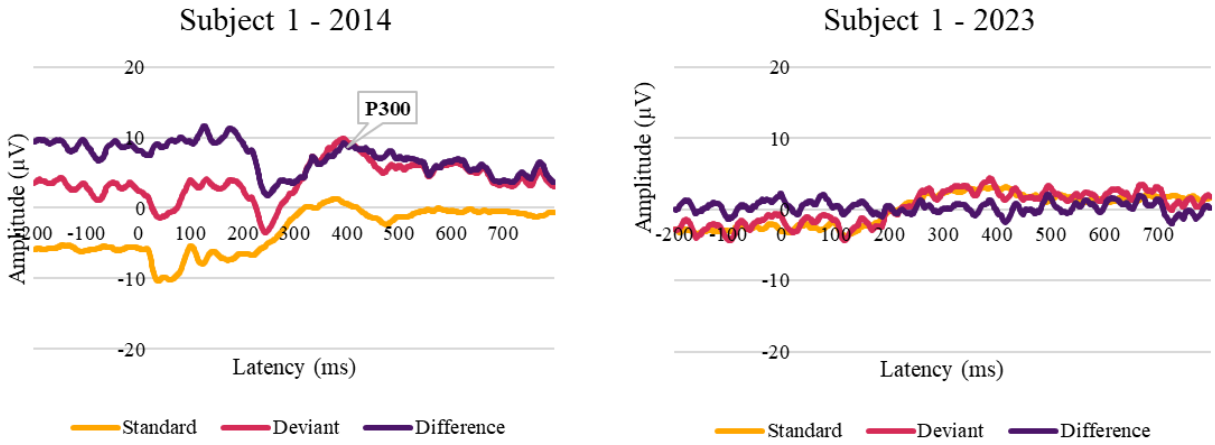


Note. The three different response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 7. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter.

Congenital case 1. For subject 1, a congenitally deaf CI user, the P300 was found at 402 ms (with N2P3 = 6.9 7,3 µV and P3N3 = 1.5 µV) in 2014. In the measurement of 2023, no P300 was detected, see Figure 11.

Figure 11

Cortical Neural Response Waves for Subject 1

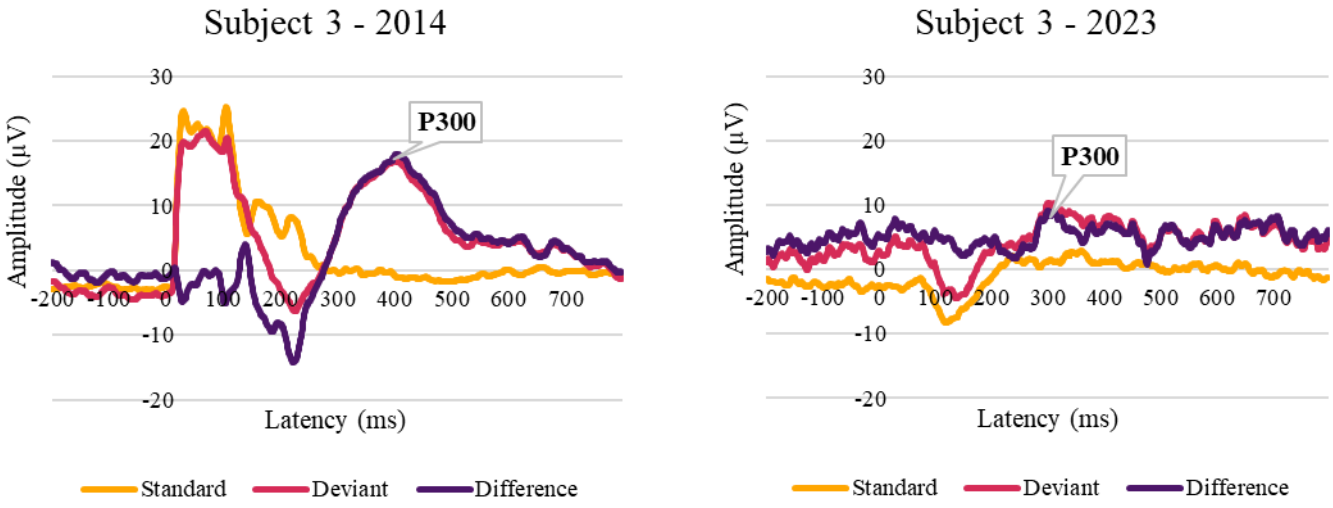


Note. The three response waves for the measurement of 2014 (left) and 2023 (right) for congenital subject 1. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter.

Congenital case 2. In the case of subject 3, also a congenitally deaf CI user, the latency of the P300 improved considerably, (402 ms in 2014 and 310 ms in 2023), whereas the peak-to-peak amplitude decreased in the measurement of 2023 compared to 2014 (resp. N2P3 = 7,3 µV vs. 25,7 µV; P3N3 = 8,1 µV vs. 12,7 µV) see figure 12.

Figure 12

Cortical Neural Response Waves for Subject 3



Note. The three response waves for the measurement of 2014 (left) and 2023 (right) for congenital subject 3. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter.

Differences between groups

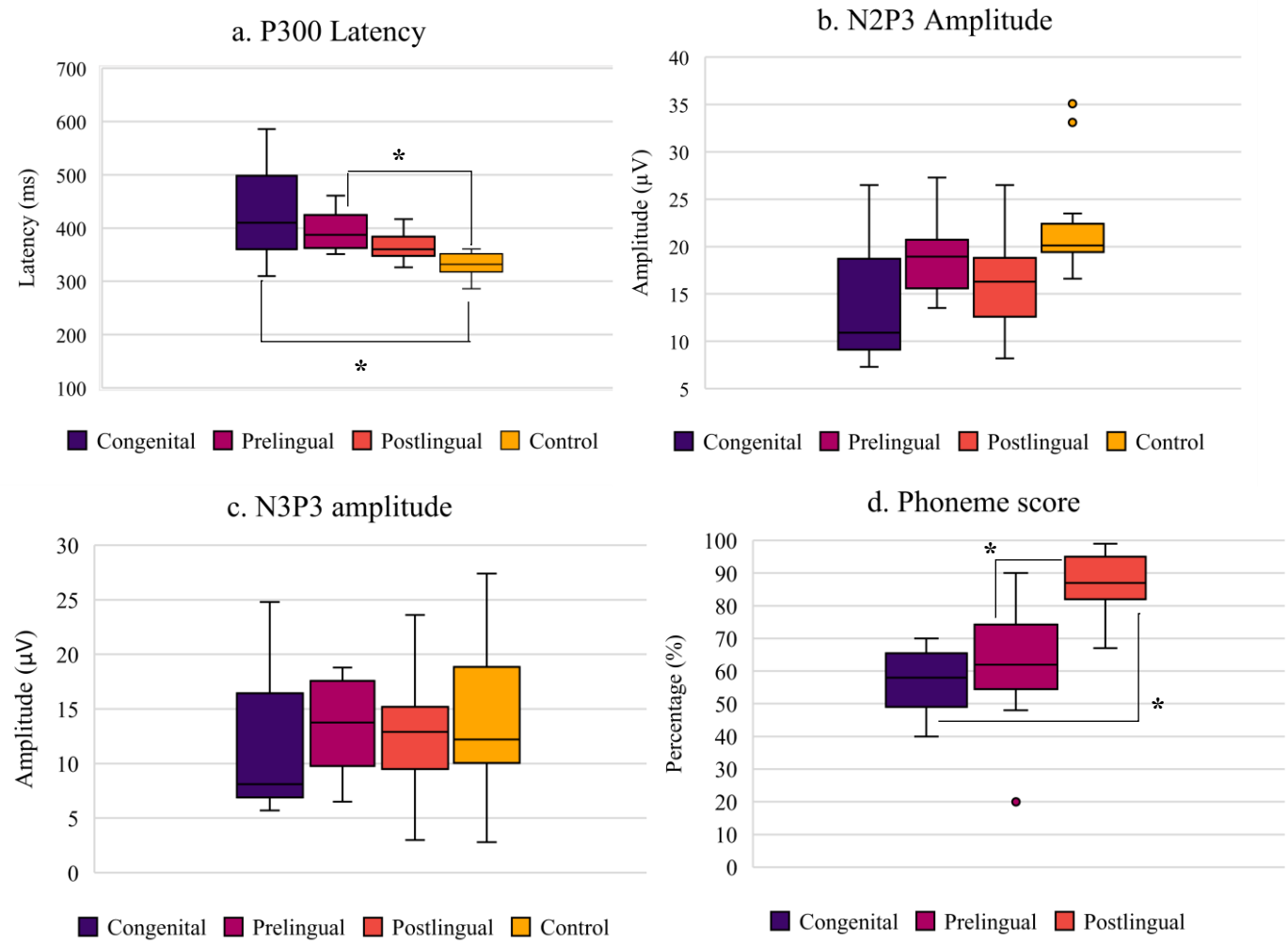
To find the difference between the three different groups of deaf CI users and the control group for the three dependent variables (P300 latency, N2P3 and P3N3 peak-to-peak amplitude), an ANOVA test is performed for every variable separately. Following the ANOVA, a significant difference was found for the P300 latency between the three groups ($F(3, 29) = 5.49$; $p = .004$), see Figure 13a. The Tukey post-hoc test showed no significant difference between the congenital and postlingual ($p = .16$) or the congenital and prelingual ($p = .65$) groups. A significant difference was found for the congenital group and the control group (resp. 435 ms and 333 ms, $p = .009$) and the prelingual and control group (resp. 396 ms and 333 ms, $p = .042$), where shorter latencies were found for the control group than the pathological groups. No significant difference was found between the postlingual and control groups (resp. 370 ms and 333 ms, $p = .31$). For the variable N2P3 peak-to-peak amplitude, no significant difference is found between the groups ($F(3, 29) = 2.59$; $p = .072$), see Figure 13b. The same accounts for the P3N3 peak-to-peak amplitude ($F(3, 29) = .069$; $p = .98$), see Figure 13c. For the phoneme score, only the three pathological groups will be compared. The ANOVA shows a significant difference for the three different groups for the phoneme score ($F(2, 17) = 6.34$; $p = .009$), see Figure 13d. From the Tukey post-hoc test showed that the congenital group scored lower than the postlingual group (resp. 56,5% and 86,3%; $p = .02$), just as the where the prelingual group (prel. = 61,4%; postl. 86,3%, $p = .02$). No significant difference was found between the congenital and prelingual group ($p = .89$).

Correlation phoneme score with P300 amplitude and latency

For each group, the relationship between the speech recogntion (phoneme score) and the P300 latency, N2P3- and P3N3 peak-to-peak amplitudes were analyzed. The Pearson's r correlation analyses showed no significant correlation between the phoneme score and any of the dependent variable for the total subject group, see Table 4.

Figure 13

Differences Between the CI and Control Groups



Note. Boxplots showing the difference between the congenital (N = 3), prelingual (N = 6), postlingual (N = 9) and control groups (N = 15) for a. P300 latency (ms), b. N2P3 amplitude (µV); c. P3N3 amplitude (µV) and d. Phoneme score. (N.B. N = 4 for cong. and N = 6 for prel. for the phoneme score). Significant differences are indicated with a black line and * $p < .05$.

Table 4

Relation of Phoneme Score and P300 Latency and Amplitude

Phoneme score	**P300 Latency**	**N2P3 amplitude**	**P3N3 amplitude**
Congenital	r = -.77, p = .45	r = .63, p = .57	r = .83, p = .38
Prelingual	r = .39, p = .44	r = -.32, p = .54	r = -.34, p = 52
Postlingual	r = -.12, p = .75	r = .23, p = .55	r = .55, p = .13
All groups	r = -.31, p = .22	r = .03, p = .92	r = .17, p = .49

Table 4: Correlations (r) and p-values (p) for the P300 latency, N2P3 amplitude and P3N3 amplitude in relation to phoneme score for the total group of CI users (N = 18) and the congenital (N = 3), prelingual (N = 6) and postlingual (N = 9) groups seperately.

Correlations with other variables

To indicate the effects of the independent variables age, auditory deprivation, CI use, onset of deafness and age of implantation, on the dependent variables phoneme score, P300 latency and N2P3 and P3N3 peak-to-peak amplitudes, correlations between the dependent and independent variables were analyzed using Pearson's r correlation. This has been done for the total group, as for the three groups separately.

Age

The correlation of the independent variable age and the dependent variables shows, a significant positive correlation for the P300 latency was found. Thus, an increase of age means an increase of the latency. Secondly, a significant negative correlation was found for the N2P3 peak-to-peak amplitude, i.e. P300 amplitude decreases with age. When looking at the different groups, negative significant correlations for the P3N3 peak-to-peak amplitude for the congenital and postlingual groups were found. In contrast to the prelingual group, the congenital and postlingual groups were significantly negatively correlated with age for P3N3 peak-to-peak amplitudes; for the prelingual group scores were negatively correlated with age. With increasing age, P300 latency increased with decreasing N2P3 amplitude (see Table 5).

Table 5

Relations of Phoneme Score, P300 Latency and Amplitude and Variable 'Age'

Age	P3 Latency	N2P3 amplitude	P3N3 amplitude	Phoneme score
Congenital	r = .21, p = .86	r = -.97, p = .15	**r = -0.99*, p = .04**	r = -0.79, p = .21
Prelingual	r = .64, p = .17	r = -.31, p = .55	r = -.45, p = .37	**r = -.76, p = .05**
Postlingual	r = .50, p = .17	r = -.54, p = .14	**r = -.67, p = .05**	r = -.25, p = .52
All groups	**r = .49, p < .01**	**r = -.52, p < .01**	r = -.50, p = .21	r = -.28, p = .23

Note. Pearson's r correlations (r) and p-values (p) for the dependent variables P300 latency, N2P3 amplitude and P3N3 amplitude in relation to variable 'age' for the three groups and the total group of CI users.

Auditory deprivation

For the variable auditory deprivation, a significant negative correlation is found for the phoneme score for all groups and for the prelingual group, meaning that phoneme scores decrease with increasing time of auditory deprivation (see Table 6).

Table 6

Relations of Phoneme Score, P300 Latency and Amplitude and Variable 'Auditory deprivation'

Auditory deprivation	P300 Latency	N2P3 amplitude	P3N3 amplitude	Phoneme score
Congenital	r = -.15, p = .90	r = -.99, p = .08	r = -0.91, p = .27	r = .54, p = 46
Prelingual	r = .38, p = .46	r = -.42, p = .41	r = -.01, p = .99	**r = -.75, p = .05**
Postlingual	r = .36, p = .34	r = -.34, p = .38	r = -.11, p = .89	r = .25, p = .52
All groups	r = .37, p = .13	r = -.35, p = .15	r = -.09, p = .73	r = -.52*, p = .02

Note. Pearson's r correlations (r) and p-values (p) for the dependent variables P300 latency, N2P3 amplitude and P3N3 amplitude in relation to variable 'auditory deprivation' for the three groups and the total group of CI users.

CI use

No significant correlations were found between the time of CI use (variable 'CI use') and the dependent variables (see Table 7).

Table 7

Relations of Phoneme Score, P300 Latency and Amplitude and Variable 'CI use'

CI use	P300 Latency	N2P3 amplitude	P3N3 amplitude	Phoneme score
Congenital	r = .91, p = .27	r = -.40, p = .74	r = -.64, p = .55	r = -.92, p = .08
Prelingual	r = .02, p = .97	r = -.38, p = .45	r = -.36, p = .49	r = .53, p = .22
Postlingual	r = .21, p = .59	r = .08, p = .85	r = -.03, p = .93	r = -.26, p = .50
All groups	r = -.01, p = .98	r = .23, p = .36	r = -.13, p = .61	r = .05, p = .84

Note. Pearson's r correlations (r) and p-values (p) for the dependent variables P300 latency, N2P3 amplitude and P3N3 amplitude in relation to variable 'CI use' for the three groups and the total group of CI users.

Onset deafness

The variable 'onset deafness' is not significantly correlated with the four variables on the level of the total group. Significant negative correlations were found for the P3N3 peak-to-peak amplitude (see Table 8), for the prelingual and postlingual group, meaning that an increase of onset of deafness results in a decrease of P3N3 amplitude.

Table 8

Relations of Phoneme Score, P300 Latency and Amplitude and Variable 'Onset Deafness'

Onset deafness	P300 Latency	N2P3 amplitude	P3N3 amplitude	Phoneme score
Congenital	r = -.16, p = .90	r = .98, p = .11	r = .99, p = .07	r = .68, p = .32
Prelingual	r = .61, p = .20	r = -.09, p = .86	**r = -.89, p = .01**	r = .30, p = .52
Postlingual	r = .15, p = .70	r = -.38, p = .31	**r = -.71, p = .03**	r = -.40, p = .29
All groups	r = -.23, p = .37	r = -.23, p = .36	r = -.35, p = .15	r = .42, p = .06

Note. Pearson's r correlations (r) and p-values (p) for the dependent variables P300 latency, N2P3 amplitude and P3N3 amplitude in relation to variable 'onset deafness' for the three groups and the total group of CI users.

Age of implantation

The variable 'age of implantation' shows a significant negative correlation for all the groups for the N2P3 amplitude. This means that a higher age of implantation leads to a decrease in the N2P3 amplitude. For the separate groups, a negative significant correlation was found for the phoneme score for the prelingual group. Thus, an increase of the age of implantation leads to a decrease of the phoneme score of the prelingual group (see Table 9).

Response differences deviant stimulus 1000 Hz and 2000 Hz

Comparison frequencies for all groups

To investigate whether larger differences in frequency of the deviant to the standard stimulus (i.e. 2000 Hz instead of 1000 Hz) would lead to a difference of P300 characteristics, a Paired-samples T-test was used. Analyses show no significant difference for the P300

characteristics for the total group (P3 latency (t (17) = .90; p = .38); N2P3 amplitude (t (17) = -1.29 ; p = .21); P3N3 amplitude (t (17) = -.14; p = .89), see Table 10 and Figure 14.

Table 9

Relations of Phoneme Score, P300 Latency and Amplitude and Variable 'Age of Implantation'

Age of implantation	**P3 Latency**	**N2P3 amplitude**	**P3N3 amplitude**	**Phoneme score**
Congenital	r = -.18, p = .89	r = -.99, p = .10	r = -.90, p = .29	r = -.58, p = .42
Prelingual	r = .41, p = .42	r = -.42, p = .40	r = -.07, p = .90	**r = -.74, p = .05**
Postlingual	r = .36, p = .34	r = -.51, p = .17	r = -.58, p = .10	r = -.12, p = .77
All groups	r = .21, p = .41	**r = -.49, p = .04**	r = -.33, p = .19	r = -.24, p = .30

Note. Pearson's r correlations (r) and p-values (p) for the dependent variables P300 latency, N2P3 amplitude and P3N3 amplitude in relation to variable 'age of implantation' for the three groups and the total group of CI users.

Table 10

The P300 Outcomes for the Different Deviant Stimuli for the Total Group

	1000 Hz	**2000 Hz**
P300 latency	388.6 (62.9)	377.6 (47.9)
N2P3 amplitude	17.0 (6.2)	17.8 (7.8)
P3N3 amplitude	12.9 (6.1)	12.9 (4.3)

Note. The values of the P300 latency (ms), N1P2-, P2N3- and P3N3 peak-to-peak amplitude (μV) and phoneme score (%) for the two deviant stimuli (1000 Hz and 2000 Hz) for the total group of CI users (N = 18 for 1000 Hz, N = 19 for 2000 Hz).

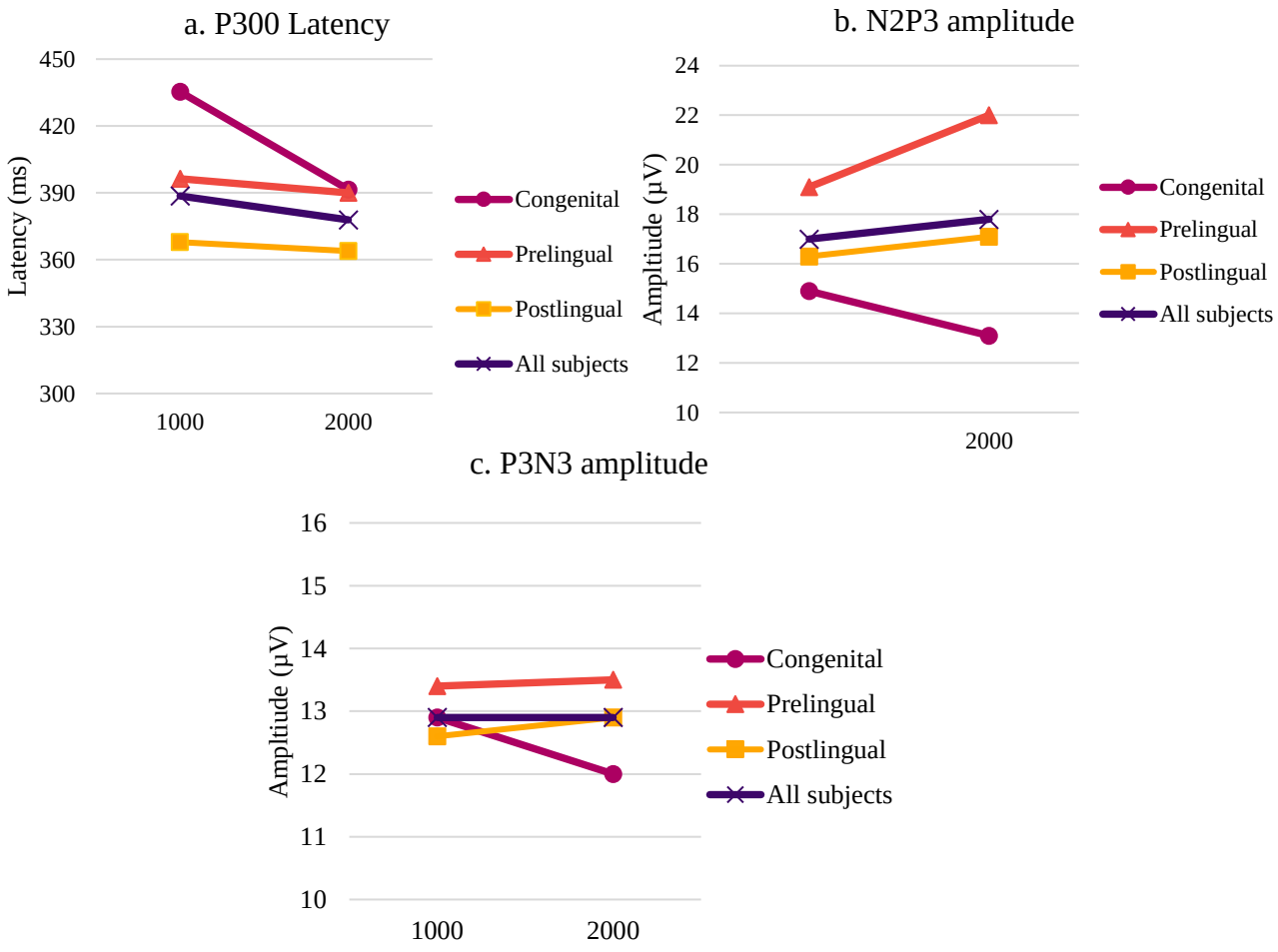
Comparison frequencies for the congenital, prelingual and postlingual groups

To determine whether the P300 latencies for each of the three groups differ from one another, the amplitudes of the N2P3- and P3N3 for the deviant stimuli of 1000 Hz versus 2000 Hz, a Paired-samples T-test is used. The results show no significant difference for all

four different variables for the congenital (P3 latency (t (2) = .66; p = .58); N2P3 amplitude (t (2) = -1.07 ; p = .40); P3N3 amplitude (t (2) = -.02; p = .98), prelingual (P3 latency (t (5) = .54; p = .61); N2P3 amplitude (t (5) = -.83 ; p = .44); P3N3 amplitude (t (5) = -.05; p = .96), and postlingual groups group (P3 latency (t (8) = .28; p = .79); N2P3 amplitude (t (8) = -.75 ; p = .48); P3N3 amplitude (t (8) = -.12; p = .88).

Figure 14

The P300 Outcomes for the Deviant Stimuli for the CI groups



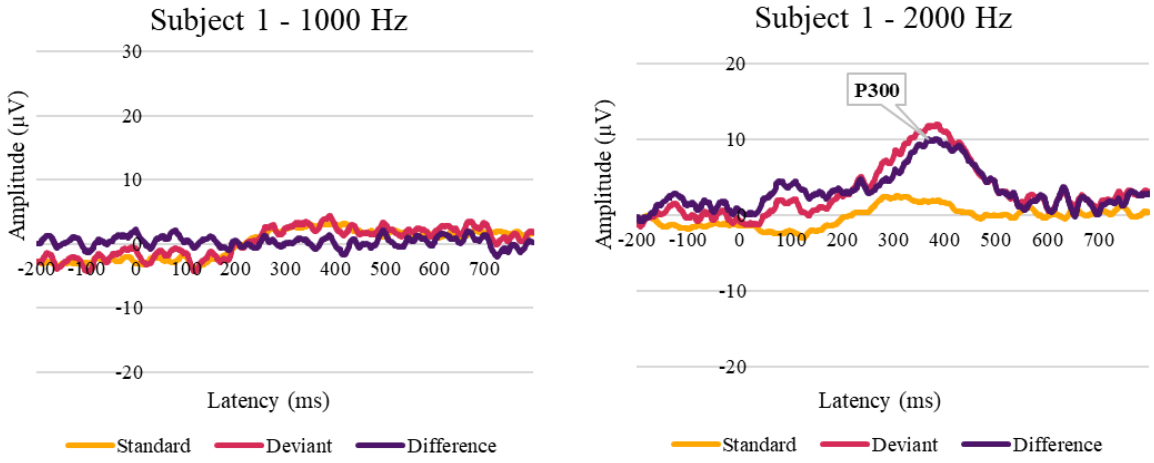
Note. Outcomes for the a. P300 latency (ms); b. N2P3 peak-to-peak amplitude (µV); c. P3N3 peak-to-peak amplitude (µV) and d. N1P2 peak-to-peak amplitude (µV) for the two deviant stimuli 2014 (left) and 2023 (right). N = 18 for 1000 Hz (cong. = 3, prel. = 6, postl. = 9) and N = 17 for 2000 Hz (cong. = 4, prel. = 6, postl. = 9). *p < .05.

Salient results of single case

A notable finding pertains to subject 1, who uniquely showed no P300 response to deviant stimulus of 1000 Hz, yet a detectable P300 was observed for the deviant stimulus at 2000 Hz (see Figure 15).

Figure 15

Responses to the Different Frequencies of the Deviant Stimuli of Subject 1



Note. The response waves for the measurement of the deviant stimulus of 1000 Hz (left) and 2000 Hz (right) for prelingual subject 1. The standard wave corresponds to the neural response to the standard stimulus (500 Hz).

Discussion

In this research, the goal was to investigate the cortical auditory neural plasticity of adult CI users over time. Besides the longitudinal comparison between 2014 and 22023, the discussion includes differences between CI groups, the relationship between speech perception and P300 characteristics and the impact of various variables on the P300. The study concludes by providing recommendations for future research and an overall conclusion.

Research questions

Longitudinal comparison

Our hypothesis posits that deaf CI users show plasticity, reflected in a change of the cognitive P300 potential, as a measure of auditory discrimination and an increase in phoneme

score as a measure of perception. The results revealed a significant decrease in P300 latency and an increased P3N3 peak-to-peak amplitude for 2023 compared to 2014 (Figure 2). Previous studies have consistently reported shorter latencies in P300 (elicited by pure tones) with prolonged CI use (Kelly et al. 2005, Sasaki et al. 2009). These findings suggest that, over the years of CI use, the speed of processing auditory input increases within the auditory cortex. However, no significant difference was found for the N2P3 peak-to-peak amplitude, making it challenging to draw conclusions about neural activity in the auditory cortex. Nonetheless, the data tentatively suggests that the time of CI use contributes to the increase of neural activity. A larger sample size could provide more robust insights. For the phoneme score, no significant difference was found between the measurements of 2014 (74.3%) and 2023 (71.6%). While Figure 4 indicates a slight decrease in speech recognition (measured by the current task), it wasn't substantial enough to reach significance. Based on the hypothesis, an improvement of speech recognition would have been expected, a topic that will be addressed later in the discussion. The postlingual group exhibited a statistically significant decrease in P300 latency (396 ms in 2014 vs. 367 ms in 2023, Figure 4), suggesting faster neural conduction regarding the increase of CI use.

Two prelingual subjects, 14 and 15, were previously tested in 1998 and 2014 (and in 2005 for subject 15). Subject 14 exhibited a consistent pattern of P300 latency throughout the past 25 years, whereas the amplitude increased substantially in 2023 opposed to 2014 (Figure 5 and Table 2). However, the P300 amplitude is quite variable throughout measurements between 1998 and 2014. Moreover, subject 15 showed a variable pattern of P300 latencies, in which the latency increased seriously in 2023 compared to 2014 (resp. 434,0 ms and 389,0 ms). However, Figure 6 shows a plateau for the P300, spanning from 360 ms till 440 ms. This caused uncertainty in precisely identifying the P300 marker, which makes this marker less reliable. Furthermore, the amplitude increases throughout the years, as can be seen in Figure

6. Overall, the outcomes for the latencies do not demonstrate an improvement in the neural processing speed, whereas the amplitudes suggest a rise in neural activity with the increase of the use of the CI over 25 years.

Differences between groups

For P300 latency, a significant difference exists between the congenital and control groups, as well as between the prelingual and control groups, with controls demonstrating significantly shorter latencies. This aligns with Ghiselli et al. (2020), who also observed prolonged latencies in prelingually deaf individuals compared to controls. The postlingual group did not show significant prolonged latencies compared to the controls (resp. 367 ms vs. 333 ms). Some earlier studies (o.a. Henkin et al. (2008), Grasel et al. (2018)) reported similar P300 latency results between normal-hearing individuals and CI users, as reported by Amaral et al. (2023). These findings suggest that (postlingual) CI users may achieve central auditory pathway maturation with increased hearing experience, reaching a level similar to that of normal-hearing people. Furthermore, no significant prolonged latencies were observed between the congenital and prelingual groups, possibly due to both groups comprising prelingually deaf individuals (onset of deafness before age of 3;0 years). The most plausible explanation for this finding is the small and varied sample sizes used in the study.

Contrary to expectation, the P2N3 and P3N3 peak-to-peak amplitudes were not significantly smaller for the pathological groups compared to the control group, which could again be attributed to small and varies samples sizes. Consequently, based on the present findings of the neural responses (latency and amplitude), there seems to be no significant difference in the neural activity of the auditory cortex between the CI groups.

For the phoneme score, the percentages were significantly higher for the postlingual group than for the prelingual and congenital. So when onset of deafness occurs after the age of 3;0 years (postlingual subjects), speech recognition was better than of those an onset before

3;0 years (i.e. congenital/prelingual individuals). This aligns with Arndt et al.'s (2023) recent study comparing speech recognition in congenital/prelingual and postlingual young CI users.

Correlation with phoneme score

Unlike our hypothesis and various other recent studies (a.o. Groenen et al. (2001), Graset et al. 2018; Jacquemin et al. (2019)), no significant correlation can be found between the phoneme score and the P300 latency ($r = -.31$, $p = .22$), whereas a significant correlation was found in 2014 ($r = .66$, $p = .003$). However, the phoneme scores of 2014 and 2023 exhibit a significant and strong correlation for the P300 latencies ($r = .89$, $p < .001$). The most likely reason for this difference is the variation in sample size: the group of 2014 had twice as many participants as the current subject group, making it more difficult to identify significant correlations. Nevertheless, the auditory cortex still shows plasticity in cortical auditory responses, which is not observed in the speech perception test. This could imply that speech audiometry is not sensitive enough to evaluate neural differences in for this group of CI users. Another reason for this discrepancy could be that cortical neural objective measure reflect different neural processes than needed for speech audiometry.

Furthermore, concerns about the ecological validity and reliability of speech audiometry arise from factors such as the controlled testing environment (quiet setting and lack of situational context) and the measurement capturing only a snapshot of speech perception. Considering these factors, it is plausible that a significant correlation between speech perception and the P300 characteristics exists, but was not observed in this measurement. To address this, a more extended investigation is recommended, like including additional speech-related questionnaires and the input of a speech therapist.

Influence of the five variables

This section will emphasize the key correlations between the variables (age, auditory deprivation, CI use, onset of deafness and age of implantation) and P300 characteristics. The variable 'age' showed moderate, yet statistically significant correlations for P300 and N2P3 amplitude. Previous studies also indicated a decrease in P300 amplitude and increase in P300 latency with age among normal-hearing individuals (o.a. Schiff et al. (2008), Juckel et al. (2012), Bourisly (2016)). The variable 'auditory deprivation' showed a medium, but significant negative correlation with the phoneme scores. This implies that increased years of auditory input are associated with improved speech perception, aligning with previous research (Strøm-Roum et al., 2012). Consequently, it is critical that deaf people receive a CI as soon as possible after the loss of their hearing ability. The variable 'CI use' does not have a significant impact on the cortical neural responses. However, Kelly et al. (2005) observed decreased latencies and increased amplitudes with prolonged CI use, which is also supported by the comparison between 2014 and 2023, where improved P300 variables were found after more years of CI use. Therefore, the nonsignificant effect is likely due to an external factor (small group size) rather than an accurate reflection of reality.

Difference 1000 Hz and 2000 Hz

The last comparison involved examining different frequencies of the deviant stimulus: 1000 and 2000 Hz. The hypothesis posited that differentiating the 2000 Hz stimulus from the standard 500 Hz stimulus would be less challenging, which might result in shorter latencies and higher amplitudes. Nevertheless, except for one subject (subject 1, see Figure 15), no significant differences were found in response to the different deviant stimuli, as illustrated in Figure 14. Notably, Grasel et al. (2018) also didn't report a significant difference for P300 characteristics between different deviant stimuli for CI users. The fact that subject 1 did show a different response, might be explained by the individual frequency resolute of the CI

electrode mapping. The allocation of the response to the 1000 Hz stimulus may occur on the same electrode as the 500 Hz standard stimulus, whereas the 2000 Hz stimulus could be assigned to another neighboring electrode, which may explain the inability of discriminating of the 500 and 1000 Hz difference.

Suggestions for further research

This research attempted to give an insight of the plasticity of CI users over time. Like in every study, some methodological limitations occurred. However, a couple more ideas to improve the current study can be pointed out. First of all, the stimuli used in this study consisted of pure tones, a common choice in P300 research. However, using pure tones also has a negative side: these pure tones are artificial sinusoids and less representable for speech rather than speech/phoneme contrasts. This compromises the experiment's ecological validity. Furthermore, Perez (2016) demonstrated that, despite better reproducibility for pure tone stimuli, P300 amplitudes were more robust when using stimuli compared to pure tones. For future investigations, it would be advisable to incorporate speech contrasts alongside to pure tones to evoke P300 responses. This approach would enable the observation of neural activity of the CI users, triggered by a more representable input for everyday life.

Secondly, for this study, the control group was derived from the control subjects examined in the study of 2014, due to logistical and temporal constraints. In order to verify the current accuracy of this data, three individuals with normal-hearing were tested to ensure they align with the norms of the control group, which was confirmed. Ideally, the subjects and controls should be tested within the same time frame. Another important aspect to point out, is the representativeness of the current group of CI users. The existing group experienced satisfaction and substantial benefits from their CIs, this may not fully reflect the worldwide CI population. To draw more generalizable conclusions, future research on neural cortical plasticity should involve a more representative CI user group. Additionally, further research

could focus on constructing a predictive model for the outcomes after CI implantation. This model might explore factors such as age, onset of deafness, cause of deafness, the P300 latency and amplitude, as well as environmental and cognitive factors (e.g. social environment). A large-scale linear regression analysis on a representative group of CI users, could help identify the most influential factors of outcomes after CI implantation, potentially surpassing the 80% variance that is explained by now (Anderson et al. (2019)).

Conclusion

In conclusion, after nine more years of CI use, the auditory cortex of adult CI users shows signs of neural plasticity. Although not consistently statistically significant, a general trend of decreased P300 latencies and increased amplitudes with prolonged CI use were found. The lack of improvement of speech recognition, whereas neural plasticity indeed was found, might be attributed to the unsensitivity of the speech audiometry for neural plasticity. This may suggest to include objective electrophysiological assessment in practice, to investigate the improvement of the CI users' ability to adapt.

Previous research indicates that, in comparison to the congenital- and prelingual groups, the postlingual group of CI users exhibits better neural responses and speech recognition. However, the present study did not identify significant between-group differences in P300 latencies and amplitudes, whereas an increase in phoneme score indeed was found for the postlingual group. The lack of significant differences between groups for the P300's latencies and amplitudes can most likely be attributed to the small and varied sample sizes of the group. Overall, the evaluation of auditory cortical potentials seems to be a valuable tool for assessing long-term neural adaptation in CI users.

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Appendix A

Table A1

Demographics of the CI Users per Group

Group	Age	Onset deafness	Age at implantation	CI use	Auditory deprivation
Congenital					
(N = 4)	*M* = 61;1,	*M* = 0;2	*M* = 42;6	*M* = 18;7	*M* = 42;4
	SD = 4;11	*SD* = 0;4	*SD* = 7;11	*SD* = 8;7	*SD* = 7;0
	Range = 53;9 - 64;8	*Range* = 0;0 - 0;8	*Range* = 33;5 - 46;5	*Range* = 13;1 - 31;3	*Range* = 33;5 - 49;3
Prelingual					
(N = 7)	*M* = 41;3	*M* = 2;2	*M* = 17;4	*M* = 24;1	*M* = 15;1
	SD = 10;8	*SD* = 0;10	*SD* = 16;6	*SD* = 7;11	*SD* = 16;8
	Range = 31;1 - 59;7	*Range* = 1;5 - 3;0	*Range* = 3;7 - 44;8	*Range* = 13;9 - 32;11	*Range* = 2;2 - 43;3
Postlingual					
(N = 9)	*M* = 51;3	*M* = 18;7	*M* = 29;5	*M* = 21;10	*M* = 10;10
	SD = 13;7	*SD* = 11;1	*SD* = 15;5	*SD* = 6;3	*SD* = 10;8
	Range = 26;10 - 67;8	*Range* = 5;2 - 35;0	*Range* = 7;8 - 50;1	*Range* = 12;5 - 30;7	*Range* = 2;3 - 32;1

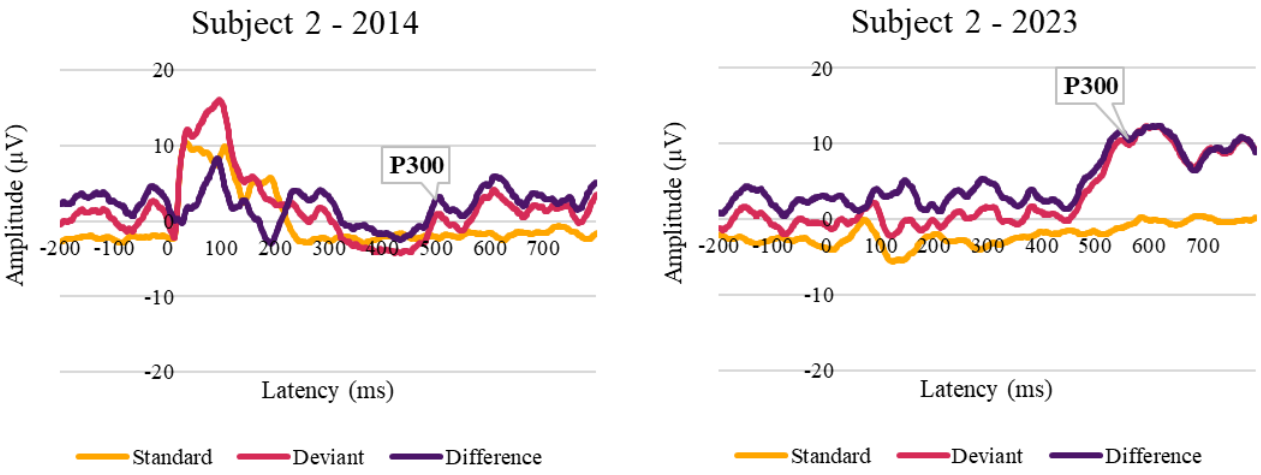
Note. Means, standard deviations and ranges of the demographic information for the congenital, prelingual and postlingual CI users.

Appendix B

Appendix B contains the individual comparisons of the neural response waves for the measurements of 2014 and 2023 of the subjects that have not been discussed yet.

Figure B1

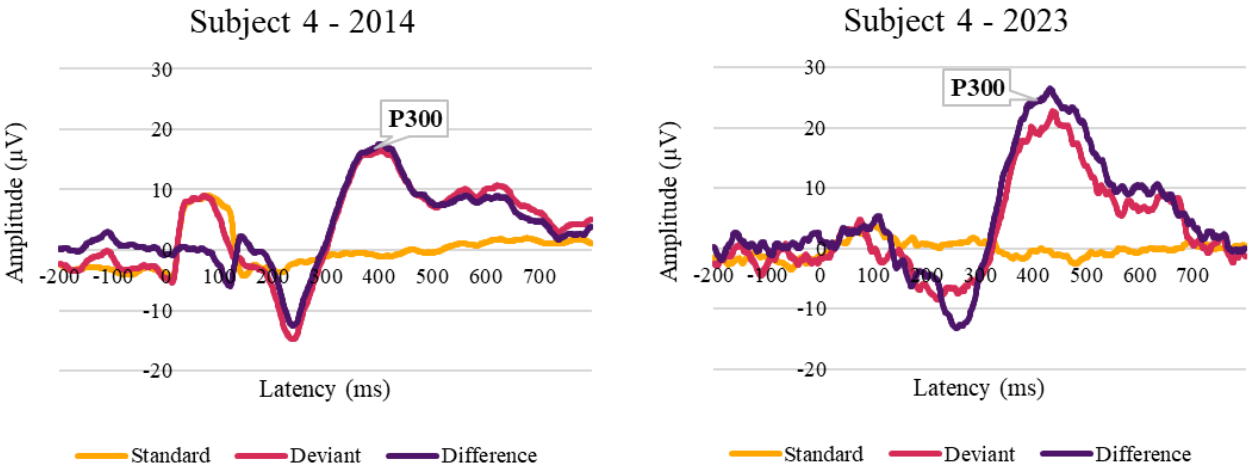
Cortical Neural Response Waves of Subject 2



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 2. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter. The big peak around 100 ms represent an artefact of the sound stimulus.

Figure B2

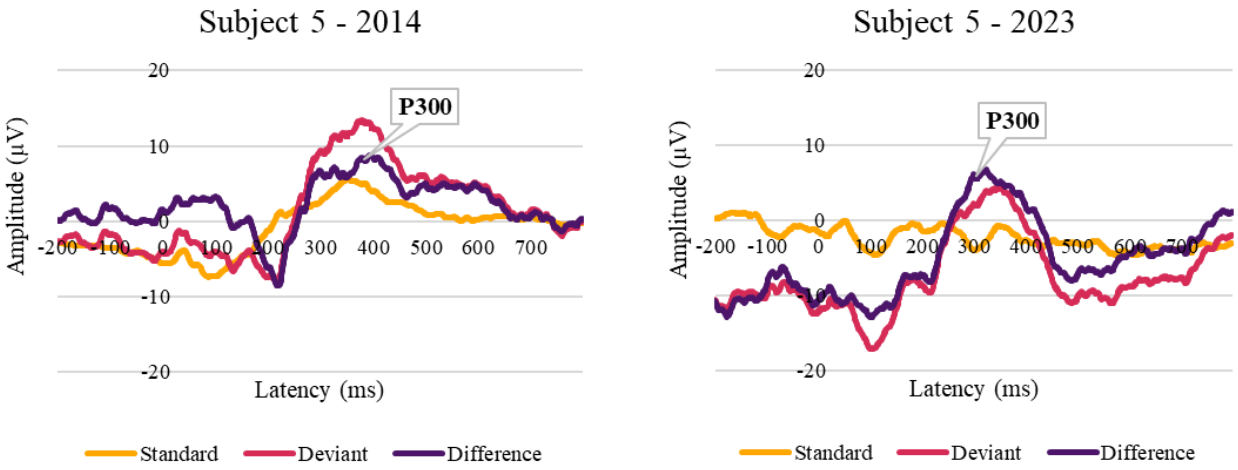
Cortical Neural Response Waves of Subject 4



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 4. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter.

Figure B3

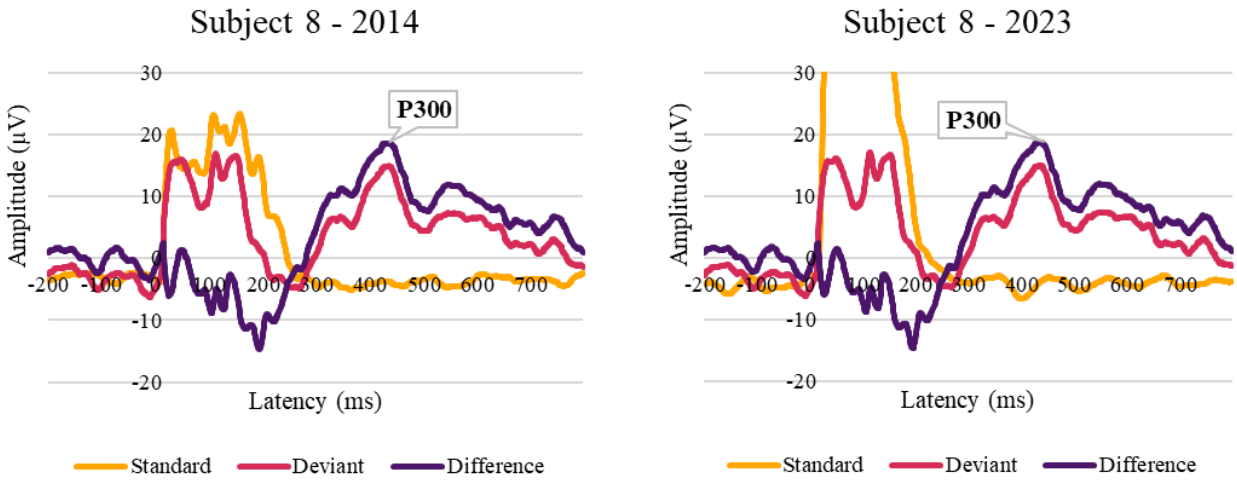
Cortical Neural Response Waves of Subject 5



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 5. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter.

Figure B4

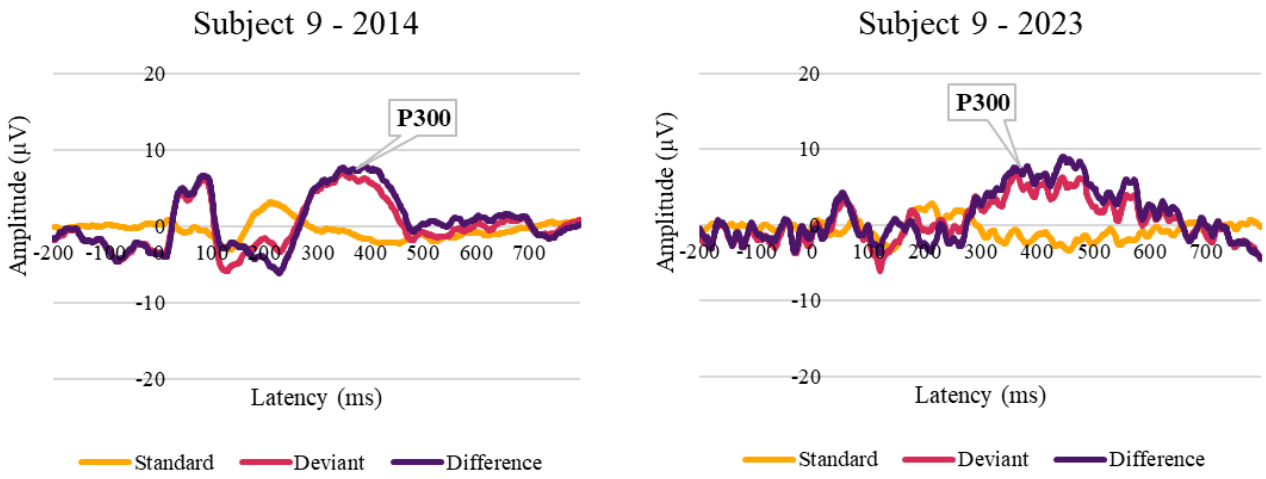
Cortical Neural Response Waves of Subject 8



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 8. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter. The big peak around 100 ms represent an artefact of the sound stimulus.

Figure B5

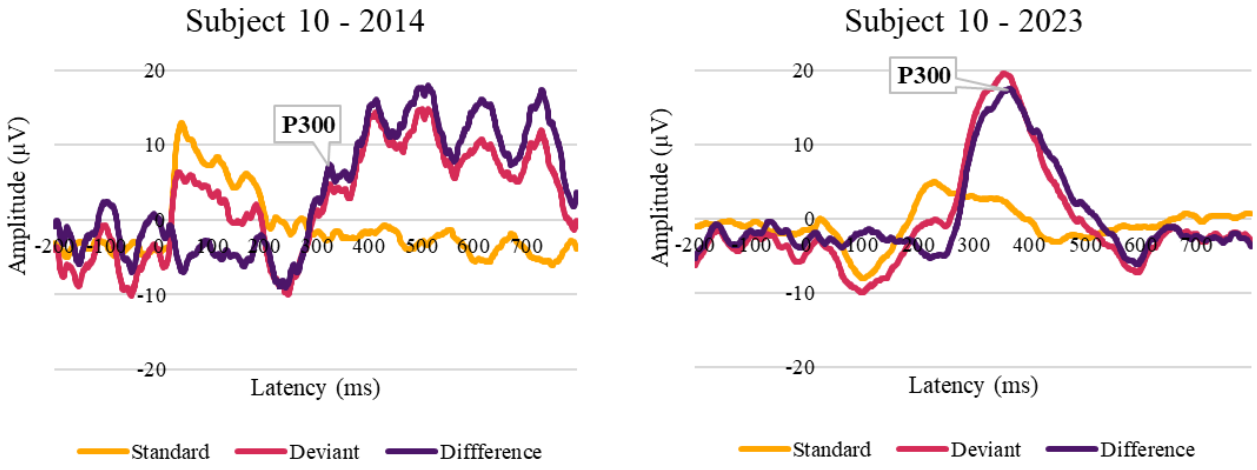
Cortical Neural Response Waves of Subject 9



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 9. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter. The big peak around 100 ms represent an artefact of the sound stimulus.

Figure B6

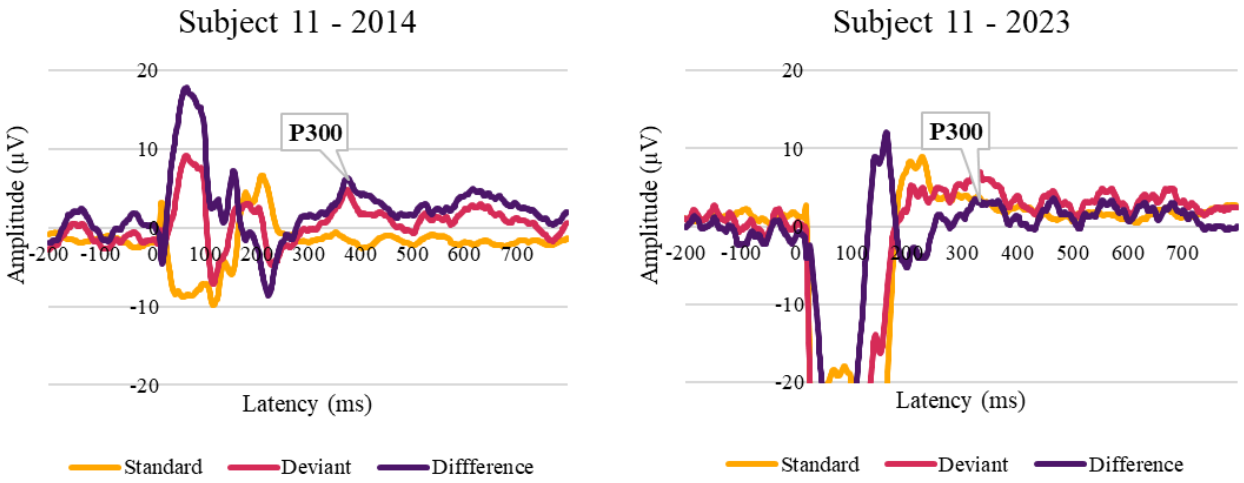
Cortical Neural Response Waves of Subject 10



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 10. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter. The big peak around 100 ms represent an artefact of the sound stimulus.

Figure B7

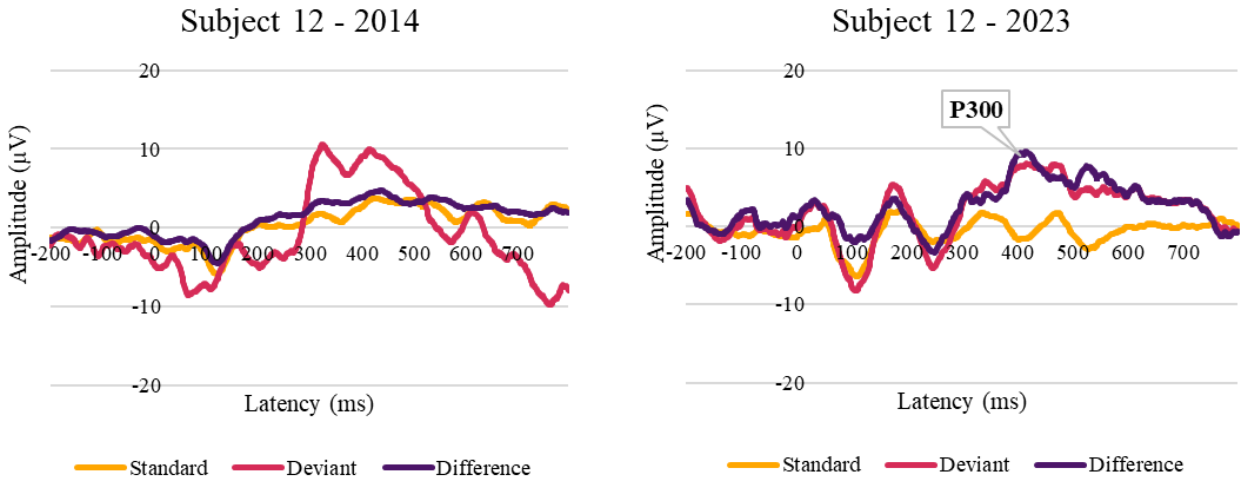
Cortical Neural Response Waves of Subject 11



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 11. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter. The big peak around 100 ms represent an artefact of the sound stimulus.

Figure B8

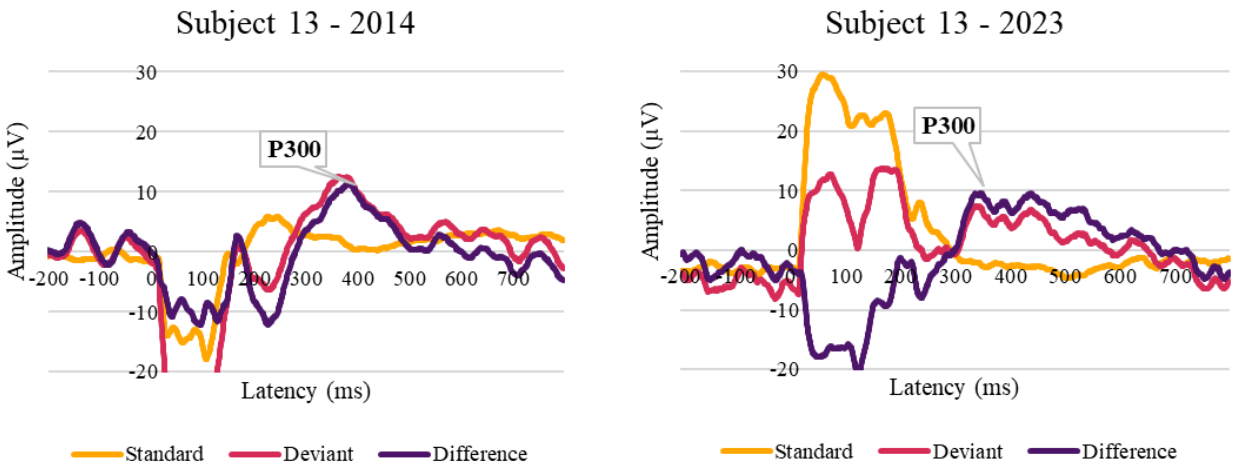
Cortical Neural Response Waves of Subject 12



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 12. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter.

Figure B9

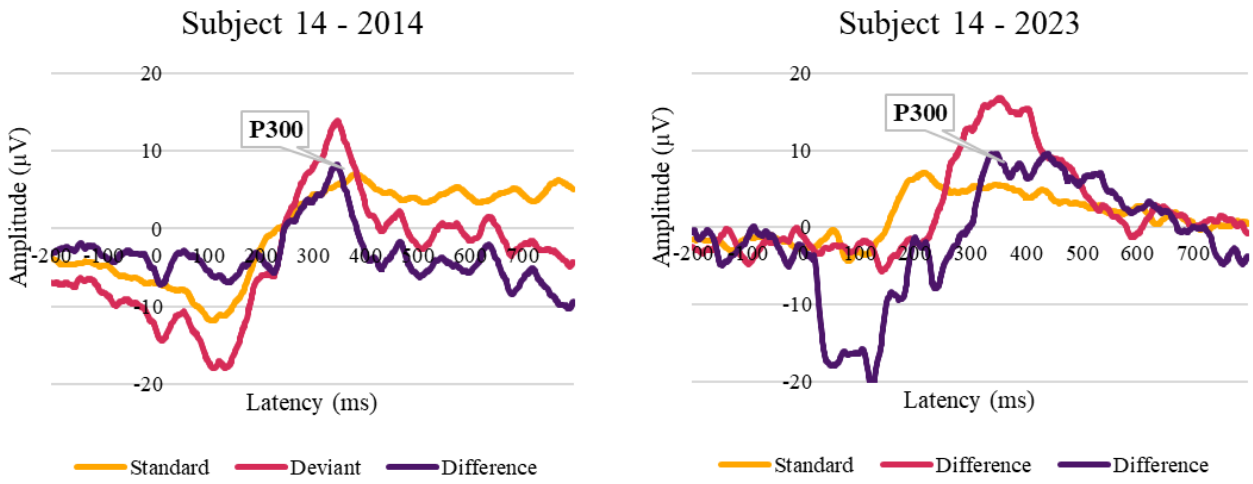
Cortical Neural Response Waves of Subject 13



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 13. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter. The big peak around 100 ms represent an artefact of the sound stimulus.

Figure B10

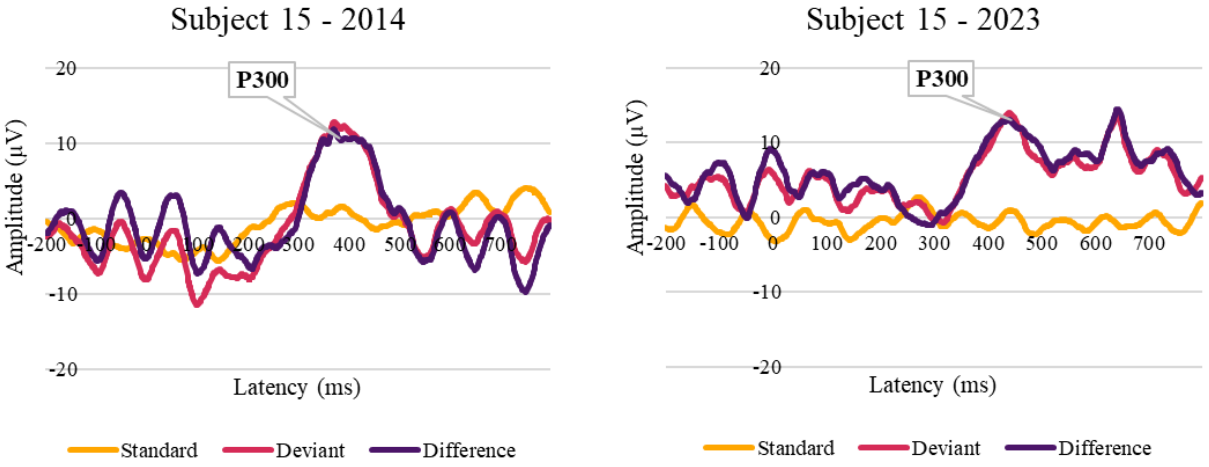
Cortical Neural Response Waves of Subject 14



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 14. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter. The big peak around 100 ms represent an artefact of the sound stimulus.

Figure B11

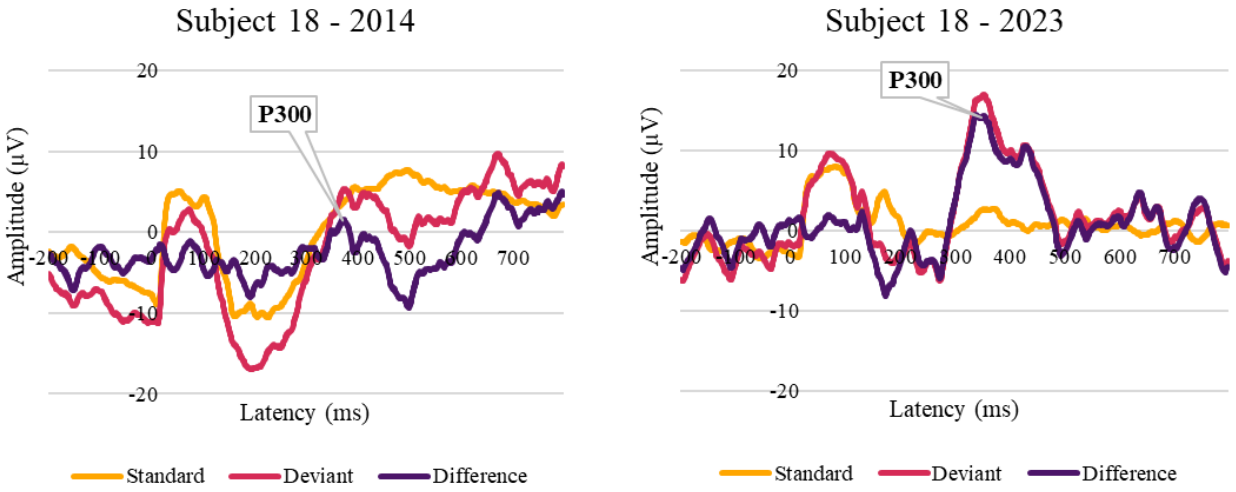
Cortical Neural Response Waves of Subject 15



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 15. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter.

Figure B12

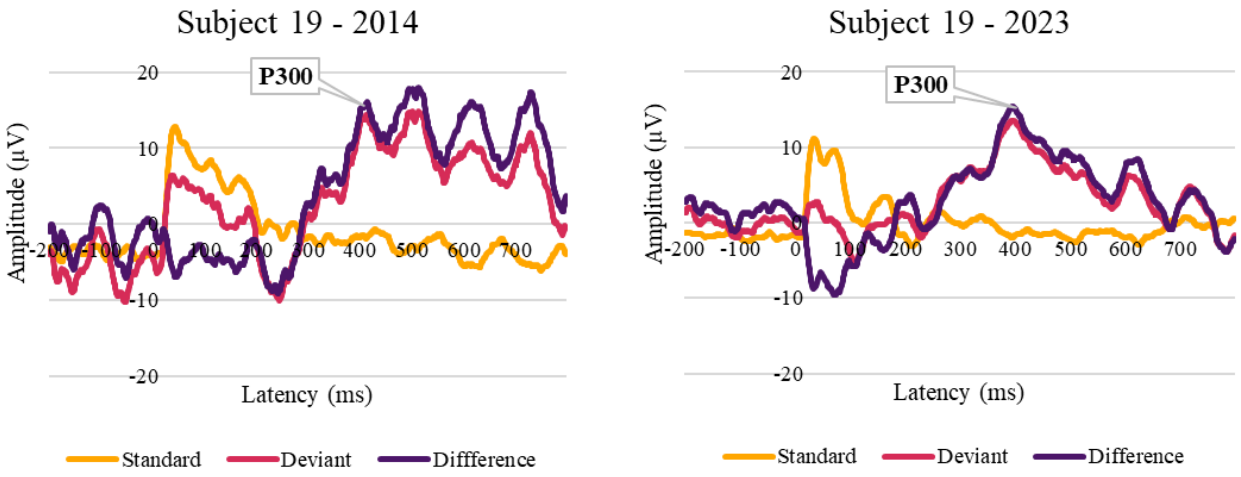
Cortical Neural Response Waves of Subject 18



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 18. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter. The big peak around 100 ms represent an artefact of the sound stimulus.

Figure B13

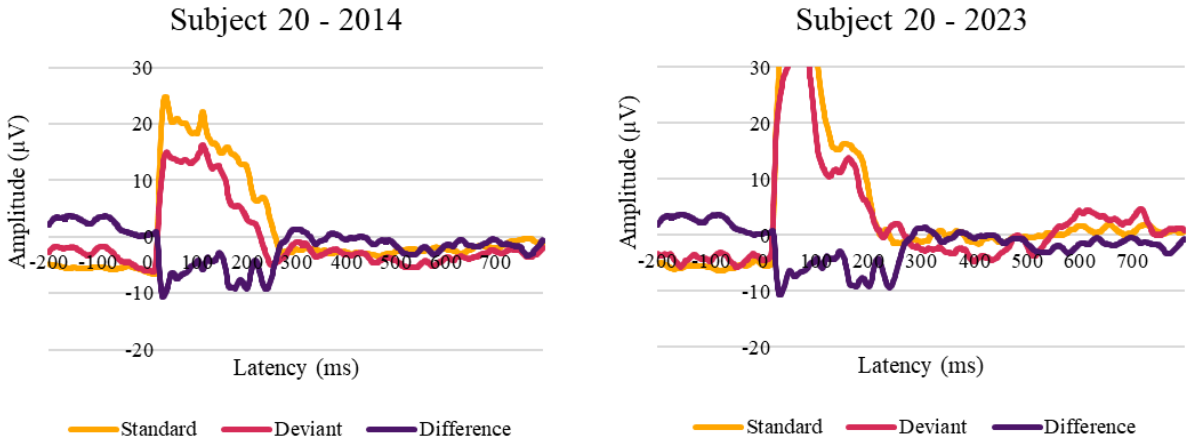
Cortical Neural Response Waves of Subject 19



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 19. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter. The big peak around 100 ms represent an artefact of the sound stimulus.

Figure B14

Cortical Neural Response Waves of Subject 20



Note. The response waves for the measurement of 2014 (left) and 2023 (right) for prelingual subject 20. The standard wave corresponds to the neural response to the standard stimulus (500 Hz), the deviant wave to the deviant stimulus (1000 Hz) and the difference wave the results of subtracting the former from the latter. The big peak around 100 ms represent an artefact of the sound stimulus.