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Vowel processing in Italian pediatric cochlear-implant users: A behavioral and neurophysiological study

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Contents

Abbreviations and symbols

Abbreviations

ABR	Auditory Brainstem Responses
AEP(s)	Auditory Evoked Potentials
Ampl.	Amplitude
ATR	Advanced Tongue Root
AUC	Area Under the Curve
BAEPs	Brainstem Auditory Evoked Potentials
Bnd	Bound
CAEP(s)	Cortical Auditory Evoked Potentials
CI(s)	Cochlear implant(s)
Conf. int.	Confidence Interval
D	different
dB	Decibel
E.d.	Euclidean Distance
EEG	Electroencephalogram / Electroencephalographic
ENT	Ear, Nose, and Throat (hospital department)
ERPs	Event-Related Potentials
F	Female
FA	False Alarm (rate)
FAT	Frequency Allocation Table
fMRI	functional Magnetic Resonance Imaging
FUL	Featurally Underspecified Lexicon
Gnd	Ground
H	Hit (rate)
Hem.	Hemisphere
HL	Hearing Level
Hz	Hertz
IDR	Input Dynamic Range
ICA	Independent Component Analysis
ISI	Interstimulus interval
Lat.	Latency
LLAEPs	Long-latency AEPs
M	Male

Max	The highest value of the descriptive statistical analysis
Min.	The lowest value of the descriptive statistical analysis
MMN	Mismatch Negativity
MLAEPs	Middle-latency AEPs
Ms	millisecond(s)
N1/N1m	Negative ERP/ERF response with peak latency of around 100
NH	normal-hearing
P / p	probability
P1	Positive ERP response with peak latency of around 100
PET	Positron Emission Tomography
Ref	Reference
RT(s)	Reaction Time(s)
S	same
s.d.	standard deviation
SDT	Signal Detection Theory
S. E.	Standard Error
Sig.	Significance
SLI	Specific Language Impairment
SNHL	Sensorineural Hearing Loss
SOA	Stimulus Onset Asynchrony
SPL	Sound Perceived Level
Stat.	Statistical
V1	First vowel in a vowel sequence
V2	Second vowel in a vowel sequence

Symbols

μV	Microvolts
α	Statistical alpha level (alternatively confidence level or significance level)
x^2	Chi-squared

Riassunto in Italiano

Gli impianti cocleari (IC) multicanale ripristinano parzialmente la sensazione uditiva nei bambini affetti da ipoacusia neurosensoriale congenita a livello bilaterale. Se l'IC viene chirurgicamente inserito prima del compimento di 3.5 anni, l'IC ha buone possibilità di ripristinare la sensazione uditiva, permettendo così ai bambini sordi di percepire e di discriminare sia i suoni linguistici che quelli ambientali e, più raramente, anche quelli musicali, soprattutto in assenza di rumore di sottofondo.

Precedenti studi su bambini *italiani* portatori di IC unilaterale si sono concentrati sulle abilità uditive generali e sull'intelligibilità del parlato dei bambini sordi [cf. Colletti et al. 2005, 2011, 2012; Scorpecci et al. 2012; Martines et al. 2013], sulla percezione e sulla produzione del linguaggio (*receptive and expressive language*) [cf. Colletti et al. 2005, 2011, 2012; Santarelli et al. 2009; Volpato 2011; Caselli et al. 2012], ricorrendo esclusivamente a test logopedici somministrati a livello attentivo. In base alle nostre conoscenze, gli unici studi ERPs condotti su bambini italiani con IC hanno monitorato la percezione della musica [cf. Vecchiato et al. 2011] e l'elaborazione di stimoli tonali [cf. Burdo et al. 2006] a livello corticale. Inoltre, gli studi precedenti appena citati si sono concentrati prevalentemente su bambini italiani che sono stati sottoposti alla chirurgia per l'inserimento dell'IC dopo 3.5 anni, ossia al di fuori del periodo di massima plasticità delle vie uditive [cf. Burdo et al. 2006; Santarelli et al. 2009; Caselli et al. 2012; Scorpecci et al. 2012], mentre solo pochi studi hanno monitorato bambini impiantati entro i 3.5 anni [cf. Colletti et al. 2005, 2011, 2012; Vecchiato et al. 2011; Volpato 2011; Martines et al. 2013]. Dunque, il presente lavoro si differenzia dagli studi precedenti condotti su bambini italiani con IC dal momento che si tratta del primo studio che indaga l'elaborazione di vocali naturali sia a livello comportamentale (attentivo), mediante test di categorizzazione e di discriminazione vocalica, che a livello neurofisiologico (automatico, a livello della corteccia uditiva), mediante gli ERPs uditivi che sono considerati i correlati neurali dei processi di detezione, categorizzazione e discriminazione dei suoni linguistici (e non linguistici).

Moltissimi studi hanno, invece, investigato l'elaborazione di singole suoni linguistici e di coppie di suoni linguistici a livello corticale in bambini con IC che apprendono l'inglese, l'ebraico, il tedesco, il finlandese, il croato, ecc. Il presente lavoro si differenzia dagli studi precedenti per i seguenti motivi. Per prima cosa, questo studio si concentra sull'elaborazione corticale delle vocali, mentre precedenti studi neurofisiologici hanno monitorato prevalentemente l'elaborazione corticale delle consonanti [cf. Kileny et al. 1997; Beynon et al. 2002; Singh et al. 2004; Sharma et al. 2002abc, 2005, 2007; 2009; Gilley et al. 2008; Henkin et al. 2008; Munivrana & Mildner 2013; Ortmann et al. 2013] e solo raramente quella delle vocali [cf. Kileny et al. 1997; Beynon et al. 2002; Henkin et al. 2008; Munivrana & Mildner 2013; Ortmann et al. 2013]. In secondo luogo, in questo lavoro i soggetti pediatrici vengono confrontati con stimoli vocalici elicitati naturalmente e poi adeguatamente normalizzati per renderli acusticamente stabili ed omogenei, senza inficiarne la 'genuinità', mentre la maggior parte degli studi ERPs precedenti hanno fatto ricorso a stimoli (semi)sintetici [cf. Beynon et al. 2002; Sharma et al. 2002abc, 2005, 2007; 2009; Singh et al. 2004; Gilley et al. 2008; Munivrana & Mildner 2013] e solo raramente si sono avvalsi di stimoli naturali [cf. Kileny et al. 1997; Henkin et al. 2008; Ortmann et al. 2013]. In fine, precedenti studi su bambini *non italiani* portatori di IC hanno studiato l'elaborazione di vocali e consonanti ricorrendo agli ERPs uditivi, che monitorano l'elaborazione automatica dei suoni linguistici a livello corticale, senza affiancare a questi ultimi l'uso di test comportamentali che monitorassero a livello cosciente, ossia tramite l'emissione di una 'risposta', l'elaborazione dei suoni linguistici. Un'eccezione in tal senso è rappresentata dal recente lavoro di Ortmann et al. (2013) su bambini tedeschi con IC.

Il presente studio si avvale di stimoli linguistici naturalmente elicitati (vocali) e solo minimamente normalizzati per gettare luce sia sull'elaborazione delle singole vocali (/u/, /i/, /ɛ/, /ɔ/, /a/) che delle coppie di vocali e delle coppie di vocali (/u/-/u/, /i/-/i/, /ɛ/-/ɛ/, /ɔ/-/ɔ/, /a/-/a/, as well as /u/-/i/, /i/-/u/, /ɛ/-/i/, /i/-/ɛ/, /ɔ/-/a/, /a/-/ɔ/), sia a livello comportamentale (attentivo) che a livello neurofisiologico (automatico), in un gruppo di bambini sordi italiani portatori di IC unilaterale. Questi bambini hanno ricevuto l'IC ad un'età compresa fra 2.1 e 4.4 anni ed usano l'IC da almeno 2 anni (*range*: 2.4 – 8.1 anni). A livello comportamentale, ai bambini sono stati somministrati dei test di categorizzazione e di discriminazione vocalica. A livello neurofisiologico, invece, è stata registrata l'attività EEG mentre i bambini guardavano un cartone animato senza audio e, al posto dell'audio, venivano presentate loro le vocali in sottofondo. Dall'attività EEG acquisita sono state estratte le componenti P1, N1 e MMN che indicizzano la detezione, la categorizzazione e la discriminazione degli stimoli uditivi, sia di tipo linguistico che di tipo non linguistico, a livello neurale. Le *performances* dei bambini con IC sono state confrontate con quelle di un gruppo di bambini normoacusici (NH) *matchato* in base all'età dei bambini con IC. Questo studio ha anche esplorato se, e in che misura, alcuni fattori esterni fossero eventualmente suscettibili di influire sull'elaborazione delle vocali nei bambini con IC. Questi fattori sono: i) il timbro vocalico; ii) le caratteristiche articolatorie delle vocali (codificate acusticamente da F1 ed F2); iii) la maggior vs. minor distanza Euclidea che caratterizza le coppie di vocali; iv) la differente specificazione delle vocali in termini di tratti folonogici e, più in particolare, la direzionalità del cambiamento nella stessa fra la prima e la seconda vocale di ciascuna coppia; v) la maggior vs. minor precocità con cui avviene la chirurgia; e vi) il maggior vs. minor periodo di uso dell'IC.

I principali risultati del presente studio sono i seguenti. Il primo risultato è che la principale differenza emersa fra il livello comportamentale e quello neurofisiologico consiste nel fatto che i bambini con IC incontrano delle difficoltà nell'elaborazione delle coppie di vocali a livello comportamentale, ma non a livello neurofisiologico; al contrario, per quanto riguarda l'elaborazione delle singole vocali, i bambini con IC incontrano delle difficoltà a livello neurofisiologico, ma non a livello comportamentale. Il secondo risultato è che, a livello neurofisiologico, i bambini con IC risultano avere delle difficoltà a livello uditivo, ma non a livello cognitivo. In effetti, sebbene i bambini con IC siano meno precisi di quanto dovrebbero nella detezione e nella categorizzazione delle singole vocali, che sono processi uditivi, essi non incontrano alcuna difficoltà nella discriminazione delle coppie di vocali, che è un processo cognitivo. Il terzo risultato è che né l'età alla chirurgia né il periodo di uso dell'IC influiscono in alcun modo sull'elaborazione delle vocali a livello comportamentale. Tuttavia, a livello neurofisiologico, può succedere che i bambini che hanno ricevuto l'IC prima di 3.4 anni e/o che lo usano da almeno 5.8 anni riescano ad elaborare le singole vocali e le coppie di vocali in maniera più efficace e/o più accurata. Gli altri fattori esterni studiati, ossia il timbro vocalico, le caratteristiche articolatorie delle vocali, la distanza Euclidea che caratterizza le coppie di vocali e la differente specificazione delle vocali in termini di tratti fonologici, invece, non influiscono in maniera significativa sull'elaborazione delle vocali né a livello comportamentale né a livello neurofisiologico.

Summary in English

Multichannel cochlear implant (CI) devices partially restore the auditory sensation in children affected by congenital, bilateral, and severe-to-profound sensorineural hearing loss, thus enabling them to perceive and discriminate speech and environmental sounds, and rarely musics as wells, especially in the absence of background noise, provided that CI surgery takes place during the sensitive period for maturation of the auditory pathways, which is presumed to end at 3.5 years.

Previous studies on Italian pediatric CI users investigated the general auditory abilities as well as the speech intelligibility [cf. Colletti et al. 2005, 2011, 2012; Scorpecci et al. 2012; Martines et alii, 2013] together with receptive and expressive language [cf. Colletti et al. 2005, 2011, 2012; Santarelli et al. 2009; Volpato 2011; Caselli et al. 2012] in deaf children wearing unilateral CI devices, by using the usual tests administered by speech therapists. To the best of our knowledge, there are only two ERP studies on Italian CI children: the study by Vecchiato et al. (2011) investigates music perception, whereas the one by Burdo et al. (2006) explores processing of tones, both at the cortical level. Another limitation of previous studies on Italian CI children is that only half of them concentrates on children implanted ealy in their life, i.e. prior to 3.5 years [cf. Colletti et al. 2005, 2011, 2012; Vecchiato et al. 2011; Volpato 2011; Martines et al. 2013], while the remaining half of them focuses on deaf children receiving their unilateral CI too late, i.e. after the age of 3.5 years [cf. Burdo et al. 2006; Santarelli et al. 2009; Caselli et al. 2012; Scorpecci et al. 2012]. As compared to the above-mentioned studies on Italian pediatric CI users, the present study is the first one that investigates detection, categorization, and discrimination of speech sounds (e.g., vowels) in early-implanted children by jointly recurring to behavioral measures, administered consciously, and to neurophysiological measures, administered automatically, to better investigate the processing of speech sounds.

Previous studies investigated detection, categorization, and discrimination of speech sounds, both consonants and vowels, at the cortical level (automatically) in CI children exposed to languages other than Italian, such English, German, Finnish, Hebrew, Croatian, and Finnish. Out of these studies, some focused on early-implanted children [cf. Munivrana & Mildner 2013; Ortmann et al. 2013], while others focused on late-implanted children [cf. Kileny et al. 1997; Beynon et al. 2002; Singh et al. 2004; Henkin et al. 2008], or even on both early- and late-implanted children [cf. Sharma et al. 2002abc, 2005, 2007; 2009; Gilley et al. 2008]. Despite achieving some interesting and crucial findings about cortical processing of speech sounds in CI children, these studies present some methodological limitations. First, they usually rely on (semi)synthetic, rather than on natural, stimuli. Second, they recurred only to neurophysiological measures (e.g., the auditory ERPs) without combining them with behavioral measures (e.g., tests of categorization and discrimination of speech sounds). As compared to the above-mentioned studies, the present research introduces two methodological innovations. First, it relies on natural speech stimuli, only minimally normalized. Second, it combines the use of behavioral measures (e.g., tests of categorization and discrimination of speech sounds, administered attentively) with the use of neurophysiological measures (e.g., the EEG recording for subsequent extraction of the auditory ERPs). By combining behavioral and neurophysiological measures, the present study aims at achieving a more complete picture on vowel processing in Italian CI children.

By using natural speech stimuli (e.g. vowels), only minimally normalized, this study aims at investigating processing of single vowels (e.g., /u/, /i/, /ɛ/, /ɔ/, /a/) as well as vowel pairs (e.g., /u/-/u/, /i/-/i/, /ɛ/-/ɛ/, /ɔ/-/ɔ/, /a/-/a/, as well as /u/-/i/, /i/-/u/, /ɛ/-/i/, /i/-/ɛ/, /ɔ/-/a/, /a/-/ɔ/) at the behavioral (e.g., conscious) and at the neurophysiological (e.g., automatic) levels in a group of deaf Italian children implanted during the sensitive period for central auditory maturation (range of age at surgery: 2.1 – 4.4 years) and who had been using their CI for at least 2 years (range of duration of CI stimulation: 2.4 – 8.1 years). At the behavioral level, tests of vowel detection and of vowel categorization were administered. At the neurophysiological level, the EEG activity was passively recorded when children were watching a silent movie while hearing vowel stimuli on the background. Subsequently, the P1, N1, and MMN responses of the auditory ERPs are the neural correlates of (speech) sound detection, categorization, and discrimination, in turn, were extracted. The vowel processing performance of the CI children will be compared against the performance exhibited by a group of normal-hearing (NH) children matched for biological age with the CI children. This study also investigated whether, and to what extent, some external factors were able to constrain vowel processing at the behavioral and neurophysiological level in CI children. These factors are the following ones: i) vowel quality (e.g., high vs. front vs. back); ii) the articulatory characteristics of the five vowels (e.g., /u/, /i/, /ɛ/, /ɔ/, /a/) acoustically codified by the values of F1 and F2; iii) the larger vs. smaller Euclidean distance characterizing the vowel pairs; iv) the different distinctive feature specification and, more particularly, the direction of change in the distinctive feature specification between the first and the second vowel of each pair; v) the earlier vs. later age at surgery; and vi) the longer vs. shorter duration of CI use.

The main findings of the present study are the following ones. First, the main difference between the behavioral and the neurophysiological levels of processing in CI children consists in the fact that the processing of vowel pairs is partially impaired for accuracy only at the behavioral level, whereas the processing of single vowels is partially impaired for accuracy, and rarely delayed, only at the neurophysiological level. Second, at the neurophysiological level, CI children are impaired at the auditory, not at the cognitive, level. In fact, in spite of typically being less accurate in detection and categorization of single vowels, CI children are not impaired in the processing of vowel pairs. Third, age at surgery and duration of implant stimulation are irrelevant for behavioral vowel processing, whereas they constrain cortical vowel processing, although not systematically: deaf children implanted before 3.4 years and/or who had been using their CI for at least 5.8 years may process single vowels as well as vowel pairs faster and more accurately. Vowel quality, the articulatory characteristics of the five vowels, the Euclidean, and the direction of change in the distinctive feature specification, on the other hand, turn out to be irrelevant in constraining vowel processing either at the behavioral and at the neurophysiological level.

CHAPTER 1

Introduction

1.1 Introduction

This chapter starts with the declaration of the topics of the present study (cf. 1.2). Subsequently, the aims (cf. 1.3) and the importance (cf. 1.4) of the study are stated. Finally, the structure of this dissertation is presented, by resuming the main points addressed in each chapter (cf. 1.5).

1.2 Topics of the study

To understand language in everyday communicative situations, individuals must be able to categorize and discriminate speech sounds varying in frequency, intensity, and temporal characteristics. Frequencies (e.g., formants) are crucial for the accurate perception of vowels and consonants, since the formant values are strictly correlated to the movements of the articulators in the oral cavity. In the case of vowels, the values of the first two formants (F1 and F2) are of crucial importance, since F1 is a correlate of tongue body height on the vertical axis, while F2 is a correlate of tongue body advancement on the horizontal axis.[e.g., Ladefoged 2001]. The importance of frequencies for perception of speech sounds and, more generally, for language comprehension, is evident in subjects affected by sensorineural hearing loss (SNHL) who use unilateral cochlear implant (CI) devices. In fact, because of the often degraded and incomplete signal delivered by CI devices, CI users are usually able to hear, but they are not always able to categorize and discriminate speech sounds, thus encountering difficulty in understanding language, especially in the presence of background noise [cf. Moore 1996].

By using natural speech stimuli (e.g. vowels), only minimally normalized, this study aims at investigating processing of single vowels as well as of vowel pairs at the behavioral (e.g., conscious) and at the neurophysiological (e.g., automatic) levels in a group of deaf children implanted during the sensitive period for central auditory pathways’ maturation (range of age at surgery: 2.1 – 4.4 years) and who had been using their CI for at least 2 years (range of duration of CI stimulation: 2.4 – 8.1 years). The vowel processing performance of the CI children will be compared against the performance exhibited by a group of normal-hearing (NH) children matched for biological age with the CI children.

This study is devoted to the behavioral and cortical processing of vowels, rather than consonants, for two reasons. First, vowels are marked by acoustically and articulatory stable features, which emerge at a physiological level, as a consequence of the speech phonation processes (e.g., Ladefoged 2001, Albano Leoni & Maturi 2003, among many others). Second, vowels are mastered earlier and more accurately as compared to diphthongs and consonants by CI children. Additionally, vowel production improves relatively soon after CI surgery, thus suggesting the relative ease of production of vowels as compared to other classes of speech sounds [cf. Serry & Blamey 1999; Blamey et al. 2001; Van Lierde et al. 2005; Horga & Liker 2006].

1.3 Aims of the study

This study aims at throwing light on the processes of detection and categorization of single vowels as well as of discrimination of vowel pairs in CI as compared to NH children, on the one hand, as well as in deaf children implanted earlier vs. deaf children implanted later in their life, on the other hand.

This research wants to understand whether, to what extent, and at what level CI children are impaired or lag behind their NH peers for detection and categorization of single vowels as well as for discrimination of vowel pairs, both at the behavioral (e.g., conscious) and at the neurophysiological (e.g., automatic) levels. This study also aims at clarifying whether, to what extent, and at what level deaf children implanted later are likely to lag behind deaf children implanted earlier in their life for detection and categorization of single vowels as well as for discrimination of vowel pairs. Both behavioral measures, i.e. the task-oriented categorization and discrimination tests administered to children, and neurophysiological measures, i.e. the recording of the Electroencephalographic (EEG) activity when children were looking at a silent movie while hearing vowel sounds in the background, for subsequent extraction of the P1, N1, and MMN responses of the auditory Event-Related Potentials (ERPs). This study also investigates whether, and to what extent, some external factors were able to constrain vowel processing at the behavioral and neurophysiological level in CI children. These factors are the following ones: i) vowel quality (e.g., high vs. front vs. back); ii) the articulatory characteristics of the five vowels (e.g., /u/, /i/, /ɛ/, /ɔ/, /a/) acoustically codified by the values of F1 and F2; iii) the larger vs. smaller Euclidean distance characterizing the vowel pairs; iv) the different distinctive feature specification and, more particularly, the direction of change in the distinctive feature specification between the first and the second vowel of each pair; v) the earlier vs. later age at surgery; and vi) the longer vs. shorter duration of CI use.

By investigating the processes of vowel detection, categorization, and discrimination, this study aims at casting light on the following aspects: i) whether the systematic CI use, together with an adequate logopedic rehabilitation, promotes the maturation of the central auditory pathways (from the ear to the auditory cortex), by limiting the degree of cortical reorganization; ii) whether the brain areas involved in the processing of speech sounds are more or less the same in CI and NH children; iii) whether the degree of activation of the brain areas is comparable or reduced in CI and NH children.

1.4 Importance of the study

This study will represent an important contribution in the field of speech sound processing by pediatric CI users in general and, more particularly, by Italian pediatric CI users.

Previous studies on Italian pediatric CI users investigated the general auditory abilities together with the speech intelligibility [cf. Colletti et al. 2005, 2011, 2012; Scorpecci et al. 2012; Martines et al. 2013] as well as receptive and expressive language [cf. Colletti et al. 2005, 2011, 2012; Santarelli et al. 2009; Volpato 2011; Caselli et al. 2012] in deaf children wearing unilateral CI devices, by using the usual tests administered by speech therapists. Rather, previous studies did not focused on the abilities exhibited by CI children in categorization and discrimination of speech sounds. To the best of our knowledge, there are only two ERP studies on Italian CI children: the study by Vecchiato et al. (2011) investigates music perception, whereas the one by Burdo et al. (2006) explores processing of tones, both at the cortical level. Another limitation of previous studies on Italian CI children is that only half of them concentrates on children implanted early in their life, i.e. prior to 3.5 years [cf. Colletti et al. 2005, 2011, 2012; Vecchiato et al. 2011; Volpato 2011; Martines et al. 2013], while the remaining half of them focuses on deaf children receiving their unilateral CI too late, i.e. after the age of 3.5 years [cf. Burdo et al. 2006; Santarelli et al. 2009; Caselli et al. 2012; Scorpecci et al. 2012]. As compared to the above-mentioned studies on Italian pediatric CI users, the present study is the first one that investigates detection, categorization, and discrimination of speech sounds (e.g., vowels) in early-implanted children by jointly recurring to behavioral measures, administered consciously, and to neurophysiological measures, administered automatically.

Previous studies investigated detection, categorization, and discrimination of speech sounds, both consonants and vowels, at the cortical level (automatically) in CI children exposed to English, German, Finnish, Hebrew, Croatian, Dutch, Finnish, and so on. Out of these studies, some focused on early-implanted children [cf. Munivrana & Mildner 2013; Ortmann et al. 2013], while others focused on late-implanted children [cf. Kileny et al. 1997; Beynon et al. 2002; Singh et al. 2004; Henkin et al. 2008], or even on both early- and late-implanted children [cf. Sharma et al. 2002abc, 2005, 2007; 2009; Gilley et al. 2008]. Despite achieving some interesting and crucial findings about cortical processing of speech sounds in CI children, these studies present some methodological limitations. First, they usually rely on (semi)synthetic, rather than on natural, stimuli. Second, they recur only to neurophysiological measures (e.g., the auditory ERPs) without combining them with behavioral measures (e.g., tests of categorization and discrimination of speech sounds). As compared to the above-mentioned studies, the present research introduces some methodological innovations, since it relies on natural speech stimuli, only minimally normalized, and since it combines the use of behavioral measures (e.g., tests of categorization and discrimination of speech sounds, administered attentively) with the use of neurophysiological measures (e.g., the EEG recording for subsequent extraction of the auditory ERPs). By combining behavioral and neurophysiological measures, the present study aims at achieving a more complete picture on vowel processing in Italian CI children.

1.5 Dissertation structure

This dissertation consists of ten chapters and it is structured as follows.

Chapter 1 introduces the topics, the aims, and the importance of the present study, especially as compared to previous studies on CI children. It stresses the methodological features differentiating the current study from previous studies. A report on the dissertation structure closes the first chapter.

Chapter 2 presents the reader with the most important concepts recurring throughout the study. First, he physiology of the auditory system, from the ear to the auditory cortices, the functional asymmetries in the auditory cortices of both hemispheres, and the concept of neural traces are presented. Then, the principles and functioning of the Electroencephalography and the different components of the Auditory Evoked Potentials are addressed, with special attention to those ERP components which are of interest in the study, i.e. the P1 response which is the neural correlate of sound detection, the N1 response which is the neural correlate of sound categorization, and the MMN response which is the neural correlate of sound discrimination. Finally, the maturational patterns and the values of P1, N1, and MMN in adults and children are presented, as reported in previous ERP studies.

Chapter 3 states the main aspects related to hearing loss. First, the different degrees of hearing loss as well as SNHL are introduced. Second, the characteristics and the functioning of multichannel CI devices are addressed. Third, electrical hearing as conveyed by CI devices, is addressed in great detail by pointing out that it fails to capture the pitch, loudness, and spectral shape of complex sounds as compared to natural hearing. Fourth, binaural vs. monaural hearing is briefly considered as well. Fifth, sensitive periods in the development of brain and behavior are discussed. Sixth, we review previous studies on the effect of earlier vs. later age at surgery on cortical processing of (speech) sounds in CI users, and the subsequent cortical reorganization when CI surgery takes place too late. Seventh, we give a summary of previous ERP studies on processing of linguistic and non-linguistic sounds in early-implanted and late-implanted children exposed to languages other than Italian. Eight, the effect of duration of CI stimulation on cortical processing of speech sounds is addressed. Ninth, we summarize previous studies on Italian CI children, evaluating their general auditory abilities, their speech intelligibility, and their receptive and expressive language, but not their processing of vowels at the behavioral or cortical level. Finally, previous studies on the acoustic vowel space of CI users, both in perception and in production, are considered.

Chapter 4 deals with the subjects, the materials, and the methods. First the characteristics of the pediatric CI users (n = 8) and of the NH children (n = 9) are presented. It is worth pointing out that the CI children selected had received their unilateral CI during the sensitive period for central auditory maturation and, therefore, they may be considered as ‘early-implanted children’. It is also worth observing that these children have been benefiting from a CI stimulation of at least 2 years and may, therefore, be regarded as ‘experienced CI users’. Then, the materials are described in great detail. Finally the behavioral and the neurophysiological measures adopted are introduced, by explaining how data were collected, stored, and analyzed. In this chapter, the Euclidean distance, the acoustic and articulatory characteristics of the Italian vowels, as well as their phonological representation in the neural trace are addressed. Some considerations concerning the joint use of behavioral and neurophysiological measures when exploring vowel processing in pathologic children close this chapter.

Chapter 5 copes with the aims, the hypotheses, and the expectations of the study. More particularly, we advance some predictions concerning behavioral and cortical processing in CI as compared to NH children, as well as in early-implanted vs. late-implanted children.

Chapter 6 presents the results of the behavioral study concerning frequency (as indicated by the percentages) and accuracy (as indicated by the *d’* values) in correct categorization of single vowels and in correct discrimination of same- and different-vowel pairs in CI as compared to NH children. The possible influence played by vowel quality, the Euclidean distance, age at surgery, and duration of CI stimulation on behavioral vowel processing is explored as well.

Chapter 7 deals with the first results of the neurophysiological study concerning concerning the time interval required for vowel processing, the accuracy, and the size of neuronal activation taking place during vowel processing, as suggested by the ERP latency, amplitude, and area, in turn. More specifically the detection (as indicated by the P1 response) and the categorization (as suggested by the N1 response) of single vowels as well as the processing of vowel pairs (as indicated by the MMN response) are examined in CI as compared to NH children. Furthermore, the brain area activation (as shown by the scalp topography), the degree of involvement of the different brain areas (as represented by the response strength), and the hemisphere lateralization (as suggested by the scalp distribution) of the ERP responses are investigated as well.

Chapter 8 explores the possible influence played on the ERP values of latency, amplitude, and area by external factors such as vowel quality, the Euclidean distance, the direction of change in the distinctive feature specification, age at surgery, and duration of CI stimulation.

Chapter 9 resumes the main results achieved throughout the study and provides an interpretation for them. The main results are the following ones. First, vowel detection and categorization tend to be partially impaired in CI children as compared to NH children only at the cortical level, mostly for accuracy and only rarely for the time interval needed. Second, discrimination of vowel pairs tends to be partially impaired in CI children as compared to NH children only at the behavioral level, both for frequency and for accuracy. When comparing deaf children implanted earlier with deaf children implanted later, vowel processing is only minimally affected by age at surgery (range: 2-1 – 4.4 years), only at the neurophysiological level. In other words, deaf children receiving their unilateral CI before the age 3.4 are likely to process vowels faster as compared to children receiving their CI later. When comparing children benefiting from a longer CI use with children benefiting from a shorter CI use, vowel processing appears only minimally affected by duration of CI stimulation (range: 2.4-8.1 years). This means that deaf children who have been using their CI for at least 5.8 years are likely to process vowels faster and/or more accurately relative to those children who have been using their CI for a shorter period.

Finally, **chapter 10** presents the conclusion, the clinical importance of the study, as well as its limitations and the factors accounting for the high variability of language outcomes in deaf children wearing unilateral CI devices.

CHAPTER 2

Processing of (speech) sounds in the auditory cortices: from the Electroencephalography to the auditory Event-Related Potentials

2.1 Introduction

This chapter reviews the current theoretical understanding of the processing of (speech) sounds in the auditory cortices in humans, both in adults and in pediatric subjects. Some fundamental concepts and assumptions which will be recalled throughout the whole research are presented in this chapter, such the physiology of the auditory system, from the ear to the auditory cortex (cf. 2.2), the principles and functioning of the Eletroencephalography (cf. 2.3), the different components of the Auditory Evoked Potentians (cf. 2.4), categorization of the auditory Event-related Potentials (e.g., the P1, the N1, and the MMN responses) evoked by non-linguistic and linguistic sounds (cf. 2.5), as well as their maturational patterns and characteristics in adults (cf. 2.5) and children (cf. 2.6) as reported in previous ERP studies. Finally, a summary closes this chapter (cf. 2.7).

2.2 Physiology of the auditory system

In humans, the auditory system consists of the ears (cf. 2.2.1), the auditory nerve, which is adjacent to the coclea, and the ascending auditory pathways which terminate in the contralateral auditory cortex.(cf. 2.2.2). The neural traces of the speech sounds are assumed to be stored in the auditory cortex (cf. 2.2.3). Functional asymmetries have been shown to characterize the auditory cortices in the left as compared to the right hemisphere (cf. 2.2.4).

2.2.1 The ear

The human ears can be splitted into into three main parts: the outer ear, the middle ear, and the inner ear (cf. Figure 1). First, the *outer* ear is formed by the ear shell (or pinna) and the external ear canal; it conducts the acoustic sound waves to the middle ear. The tympanic membrane separates the outer ear from the middle ear. Second, the *middle* ear consists of three ossicles (the malleum or hammer, the incus or anvil, and the stapes or stirrup). The vibration of the tympanic membrane sets these three ossicles into motion, with the stapes resting on the oval window leading directly to the fluid-filled cochlea. The task of the middle ear consists in amplifying the speech frequencies and in increasing the efficiency of energy transmission of the acoustic sound waves, so that the sound energy can get from the air-filled external world to the fluid-filled cochlea. The oval and round windows separate the middle from the inner ear. Finally, the *inner* ear consists of the cochlea, which receives mechanical waves and transforms them into neural (i.e. electrical) signals that are transported by the auditory neural pathways and that finally lead to perception in the auditory cortex.

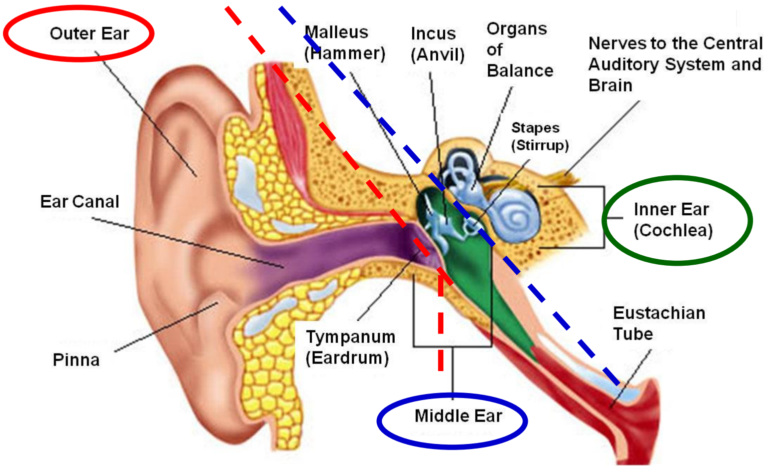

Figure 1. Cutaway of the human ear. Figure retrived and adapted from http://www.lyrichearing.com/hearing-aid-blog.

The ear is anatomically fully developed before birth: the outer ear reaches adult size when the child is 8 years old, while the middle ear reaches the adult size in the period around birth. Finally, the inner ear reaches its full size before birth (i.e. at five months of gestation) [cf. Rubel 1984; cf. also Schauwers 2006: 100-101].

The cochlea is a snail-shaped, bony structure (cf. Figure 2). Inside this bony structure there is a tunnel, called modiolus, with a total length of 35 mm. The tunnel is divided by two membranes (e.g., the Basilar membrane and the Reissner’s membrane) into three parts (e.g., the scala *timpani*, the scala *media*, and the scala *vestibuli*).

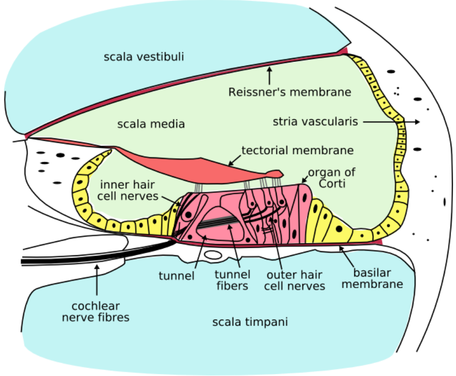

Figure 2. A cross section of the cochlea. Figure from http://hendrix2.uoregon.edu/~dlivelyb/phys152/l9.html).

The beginning of the cochlea is referred to as the base, while its ending is known as the apex. The cochlea is tonotopically organized, in that the basilar membrane reacts best to higher frequencies at the base, while the basilar membrane reacts to lower frequencies at the apex (cf. Figure 3).

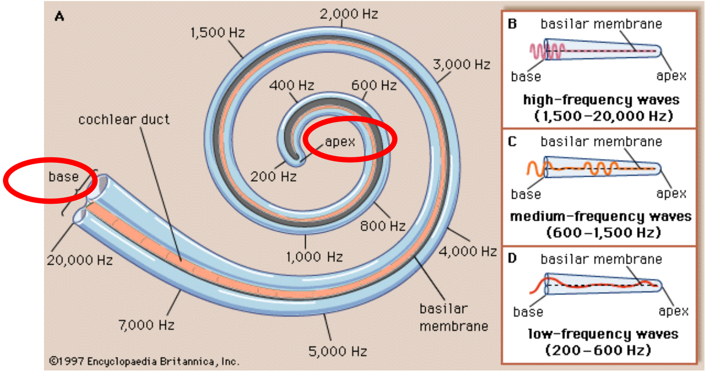

Figure 3. The tonotopic organization of the coclea. Figure adapted from http://www.ifd.mavt.ethz.ch/research/group_lk/projects/cochlear_mechanics.

The anatomical structure of the basilar mebrane is known as the Organ of Corti: it contains the auditory sensory cells (also called hair cells or receptor cells), the supporting cells, and the peripherical endings of the auditory nerve (cf. Figure 4). The inner hair cells (about 3,000) are located as a single row along the basilar membrane: their surface contains sensory hairs and the tips of the tallest hair cells are embedded in the tectorial membrane. The base of the interior hair cells connects to about 10 afferent nerve endings, which form the cochlear nerve and transmit the auditory information to the brain and the central nervous system. The cochlear nerve runs from the modiolus (e.g., the internal tunnel inside the cochlea) to the cochlear nucleus in the brainstem [cf. , among many others, Schauwers 2006: 103].

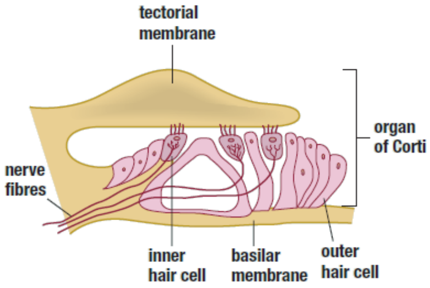

Figure 4. The organ of Corti. Figure from http://michaelsoud.wikispaces.com/Different+Frequencies+and+the+Sound+Shadow.

Sound is transmitted through the middle ear into the fluid-filled coclea. Vibration of the oval window displace the fluid inside the cochlea and the Basilar membrane moves upwards and downwards. In response to sinusoidal stimulation, the movement of the basilar membrane takes the form of a traveling wave from the base toward the apex [cf. Govaerts 2002, among many others]. The envelop of the traveling wave presents a maximal amplitude at a specific point along the basilar membrane and this point crucially depends on the stimulus frequency (cf. Figure 3 above). Hiw-frequency sounds produce a maximum displacement of the Basilar membrane near the base of the cochlea, whereas low-frequency sounds produce a maximum displacement near the apex of the cochlea [cf. Schauwers 2006: 104-105, among many others].

The inner hair cells located in the region of the membrane displacement will be deflected to elicit a receptor potential that will elicit action potentials in the afferent nerves. These action potentials will be sent from the cochlea to the brain. In the brain, numerous relay stations (i.e. groups of neurons) receive these signals and decode them in order to cause a sensation or a conscious perception in the auditory cortex (cf. Figure 5).

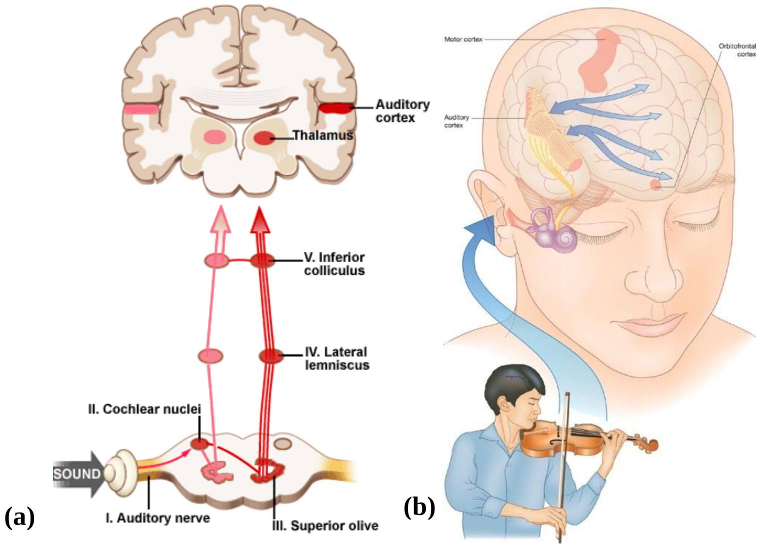

Figure 5. The auditory pathways (a). Figure from http://www.cochlea.org/en/spe/auditory-pathways-2.html).The processing of sound waves (b). Figure from http://www.nature.com/nature/journal/v434/n7031/fig_tab/434312a_F1.html.

2.2.2 The auditory cortex

The auditory nerve, which is adjacent to the coclea (cf. Figure 1 above), terminates in the contralateral auditory cortex. The auditory cortex is a very complex structure and it is located in the superior portion of the temporal lobe of each hemisphere, bilaterally in the Heschl's gyrus, right above the ears (cf. Figure 6).

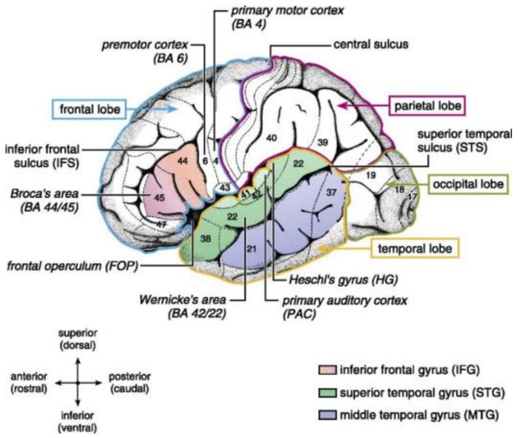

Figure 6. Left view of the main regions of the human auditory cortex. Figure from Friederici et al. (2011).

The auditory cortex represents the most central stage in the processing of auditory information along the auditory pathways. Although the auditory cortex has a number of subdivisions, a broad distinction can be made between the primary auditory cortex and the secondary auditory cortex (cf. Figure 7).

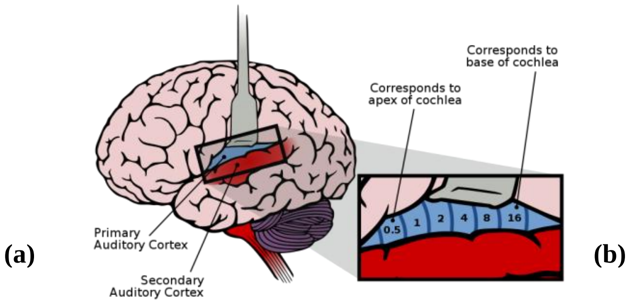

Figure 7. The human auditory cortex: diagram showing the brain in the left lateral view (a). The tonotopic organization is given in kHz (b). Figure from http://commons.wikimedia.org/ wiki/File: Auditory_Cortex_ Frequency_Mapping.svg.

The primary auditory cortex consists of the Brodmann's areas 41 and 42, while the secondary auditory cortex consists of the auditory association area (e. g., Brodmann area 22) (cf. Figure 6 above). The function of the primary auditory cortex is to process sounds and it is crucial for understanding language: it receives point-to-point input from the ventral division of the medial genicolate complex of the thalamus, which it is thought to process auditory input at a very basic level with little, if any, distinction between the right and left hemispheres (cf. discussion in 2.2.4). The belt areas of the auditory cortex receive more diffuse input from the medial geniculate complex and, therefore, they are less precise in their tonotopic organization. The neurons in the primary auditory cortex are organized tonotopically, as in the cochlea (cf. Figure 3 above), in the sense that the neurons in the auditory cortex react best to specific frequencies. At one end of the auditory cortex, neurons react best to low frequencies, and at the other end, they react to high frequencies. Thus, a lesion to a certain area of the primary auditory cortex is likely to cause a loss of certain frequency perception. However, it is worth pointing out that the cochlea has already decomposed the acoustical stimulus when it reaches the auditory cortex (cf. Purves et al. 2001). Finally, the auditory association area (e.g., Brodmann areas 42 and 22) are involved in the interpretation of sounds.

2.2.3 The neural traces of speech sounds

The neural traces of speech sounds are assumed to be assemblies of cortical cells forming the memory traces for learned cognitive representations relative to speech sounds [cf. Näätänen 2001]. Although knowledge of speech sound representation in the auditory domain is stille sparse [cf. Obleser et al. 2004] and even though no consensus has so far been reached either about the content stored in the neural traces of speech sounds or about how this content is coded, in some previous studies [cf. Eulitz & Lahiri 2004; Cornell et al. 2011; Scharinger et al. 2012], the neural traces of speech sounds have been implicitly assumed to consist of information concerning the phonological representation of speech sounds in terms of appropriately specified (e.g., either as [+] or as [-]) distinctive features (e.g., [+HIGH] or [-HIGH]) or of present (e.g., [HIGH]) vs. absent (e.g., [-]) distintive features. When adopting the usual (e.g. full) specification approach, the neural traces of vowels are assumed to contain the correct specification of the phonological features [HIGH], [LOW], [BACK], [ROUND], and [ATR] (cf. 4.3.4 for detailed discussion). Additionally, the neural traces are thought to be conceptualized in a manner enabling them to identify the invariant phoneme-identity code amongst wide acoustic variation [cf. Näätänen 2001; Näätänen et al. 1997, 2007; Pulvermueller & Shrytov 2006].

The formation of the neural traces of speech sounds (with adequate distintive feature specification) in the child auditory cortex can only be driven by speech input [e.g., Cheour et al. 2000], delivered either naturally (as in the case of NH subjects) or electrically (as in the case of successful CI users). More specifically, the auditory pathways appear to extract the spectral frequencies, which are relevant for linguistic categorization from the ongoing acoustic-phonetic input. In the case of vowels, which are of particular interest here, the first two formants (e.g., F1 and F2) are of crucial importance for vowel categorization (cf. Lindblom & Sundberg 1971; Kent 1997; Stevens 1999). The value of F1 relates to tongue body height along the vertical axis, with the high vowels (e.g., /u/ and /i/) being characterized by lower F1 values as compared to mid (e.g., /ɛ/ and /ɔ/) and low (e.g., /a/) vowels. The values of F2, relate to tongue body place of articulation along the horizontal axis, with front vowels (e.g., /ɛ/ and /i/) being characterized by higher F2 values as compared to back vowels (cf. /a/, /ɔ/, and /u/) (cf. 4.3.4 for a comprehensive discussion about Salento Italian vowels).

After extraction of the spectral frequencies (e.g., F1 and F2 values) from the ongoing acoustic-phonetic input, the neural traces of speech sounds are activated [cf. Näätänen, 2001; Näätänen et al. 1997, 2007; Pulvermueller & Shrytov 2006], where the spectral frequencies are coded in terms of distintive features, with adequate specification as [+] or as [-] [cf. Eulitz & Lahiri 2004; Cornell et al. 2011; Scharinger et al. 2012]. Finally, as suggested in 9.9, the adequate distintive feature specification contained in the neural traces of speech sounds is put into practice (or realized) by individuals by activating the corresponding configurations of the vocal organs, which have been naturally acquired, in the case of NH children, but which have been learned during linguistic training and oral rehabilitation by CI children.

2.2.4 Functional asymmetries in the auditory cortex and hemisphere specialization

Functional asymmetries have been shown to characterize the auditory cortices: if the left auditory cortex has a greater temporal sensitivity, the right auditory cortex has a greater spectral sensitivity [cf. Zatorre et al. 2002; Dorsaint-Pierre et al. 2006]. These functional asymmetries have been grounded on anatomical asymmetries, in that the anatomical structures of the auditory cortices appear larger [cf. Geschwind & Levitsky 1968] and longer [cf. von Economo & Horn 1930; Penhume et al. 1996, 2003] in the left relative to the right hemisphere, as well as a greater number of larger cells, with more heavily myelinated axons and greater interconnectivity were found in the left as compared to the right hemisphere [cf. Seldon 1981ab, 1982; Hulster & Gazzaniga 1996]. These differences characterizing the left as compared to the right auditory cortex at the anatomical and cellular levels are assumed to be responsible for a more efficient processing of rapidly changing temporal information, which is relevant for speech sound processing, thus indicating that certain aspects of speech decoding depend critically on the left auditory cortex and, more generally, of the left hemisphere [cf. Zatorre et al. 2002; Dorsaint-Pierre et al. 2006].

Equal involvement of both hemispheres in detection (as indicated by P1) and categorization (as suggested by N1) of isolated speech sounds delivered binaurally had been frequently reported either in NH adults [cf. Binder et al. 2000; Hickok & Poeppel 2000; Zatorre et al. 2002] or in NH children [cf. Sharma et al. 1997; Čeponiene et al. 2001, 2005, 2008; Gilley et al. 2005; Bruder et al. 2010; for exceptions, see Golding et al. [2006], thus suggesting that the earlier stages of processing depend on core auditory areas at the bilateral level (cf. also 9.10). In the case of monaural stimulation in NH adults, on the other hand, greater cortical activity was reported in the hemisphere contralateral to the stimulated ear [cf. Wolpaw & Penry 1977] during processing of non-linguistic stimuli [cf. Hine & Debener 2007], thus indicating that activity in the auditory cortex is typically lateralized [cf. Jancke et al. 2002].

During processing of pairs of native speech sounds, as indicated by MMN, the left auditory cortex has been reported to be more deeply committed in right-handed NH adults [cf. Mazoyer et al. 1993; Dehaene et al. 1997; Kim et al. 1997; Shafer et al. 2004] and in NH children [cf. Dehaene-Lambertz & Dehaene 1994; Csepe 1995; Dehaene-Lambertz & Baillet 1998; Dehaene-Lambertz 2000], although not regularly [for adults, cf. Näätänen, 2001; Pulvermüller & Shyrov 2006; for children, cf. Novak et al. 1989; Molfese & Burger-Judish 1991; Csepe 1995; Shestakova et al. 2002; Sharma M. et al. 2006; Bruder et al. 2010], especially when speech sounds are placed in a grammatical context [cf. Shtyrov et al. 2005], or when subjects are attending to the auditory stimuli [cf. Imaizumi et al. 1997]. During processing of non-native speech sounds, on the other hand, both hemispheres appeared equally committed [cf. Shestakova et al. 2003; Rinker et al. 2010; Bruder et al. 2010; Davids et al. 2011]. The higher degree of commitment of the left hemisphere during processing of speech sounds is assumed to depend on the presence of the long-term memory traces of native phonemes [cf. Näätänen, 2001; Näätänen et al. 1997, 2007; Pulvermueller & Shrytov 2006] (cf. also the discussion in 2.2.3).

2.3 From the Electroencephalography to the Auditory Evoked Potentials

The human cerebral cortex is a folded layer of about 2 or 3 mm of thickness and with a total surface area of roughly 1600 cm^2. This layer is composed of about 1010 highly interconnected neurons that compose the grey matter. Each neuron receives as inputs to its dendrites and cell body around 103 to 105 connections or synapses, which are specialized interfaces consisting of a cleft between a presynaptic and a postsynaptic neuron. Finally, synapses deliver electric currents from other cortical neurons and deeper brain structures such as the cerebellum [cf. Nunez 2006; Manca 2014].

The brain generates two types of electrical activity: i) the action potentials reflecting transfer of information within a neuron (e.g., intra-cellular potentials) and ii) the post-synaptic potentials reflecting transfer of information between two or more neurons (e.g., extracellular potentials). The Electroencaphalographic (EEG) signal originates from the latter even though its exact origins are still not completely understood. The duration of the posts-ynaptic current is of the order of about 10 milliseconds, which favours temporal summation of the fields, as compared to the one-millisecond action potentials.

However, an electrode placed at the scalp cannot detect electrical changes in a single neuron, either because the potentials are small in magnitude due to the low extracellular resistance, or because there is a considerable distance from the cell to the scalp surface. Brain’s electrical potential recordings can be detectable thanks to the specific structure of a relatively large population of brain cells i.e., the pyramidal cells, which all have the same relative orientation and polarity. In the cerebral cortex, pyramidal cells tend to be oriented perpendicularly to the surface of the cortex; the net effect of dendritic currents in an assembly of pyramidal cells is the origin of the macroscopically detected EEG signals (cf. Nunez 2006).

The synchronization of pyramidal cells and the summation of the dipoles created of thousands of neurons create an electrical potential detectable at the scalp. Hereby, by attaching a pair of electrodes to the surface of the scalp and by connecting them to an amplifier, the output of the amplifier shows a variation in voltage over time. The electrical potential is then conducted through the brain tissue, enters the membranes surrounding the brain i.e. the cerebrospinal fluid and it continues through the skull to appear finally at the scalp (cf. Figure 8; see Manca 2014).

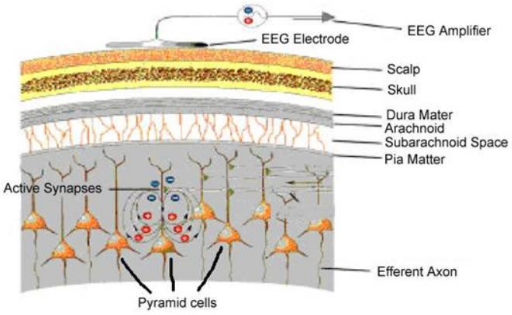

Figure 8: Head’s section. Figure adapted from Aguiar et al. (2000).

The post-synaptic potentials, which are the generators of the extracellular potential field recorded with an EEG system, are marked by a small amplitude (e.g., in the range between 0.1 and 10 uV) and by a large interval of time (e.g., in the range between 10 and 20 ms). In some brain regions, especially in subcortical structures, the neurons are arranged with the cell bodies clustered in the centre and dendrites reaching out in all directions. In such as an arrangement, known as a closed field configuration (opposite to the open field in which pyramid cells are organized), it is highly unlikely for the signal to be picked up by scalp electrodes (cf. Rugg & Coles 1995; see also Manca 2014).

The EEG system and, more specifically, the long-latency responses of the Auditory Evoked Potentials (AEPs) can be used to explore the functioning of the auditory cortices when they are engaged in speech perception processes. The EEG automatically measures brain activity while the subjects is typically performing a task to direct his/her attention away from the target (e.g., typically auditory or visual) stimuli. For example, when studying automatic speech sound perception in the auditory cortex, subjects are usually asked to watch a silent movie in order to direct their attention away from the auditory stimuli.

The EEG signal is captured from 32, 64, or 128 scalp electrodes, typically arranged according to the 10:20 system [cf. Jasper 1958] (cf. Figure 8), it is amplified with EEG amplifiers, and it is recorded by means of an EEG recording software, by using a bandpass filter and a sampling rate adequate for the purposes of the recording session (cf. Figure 9 and Figure 10).

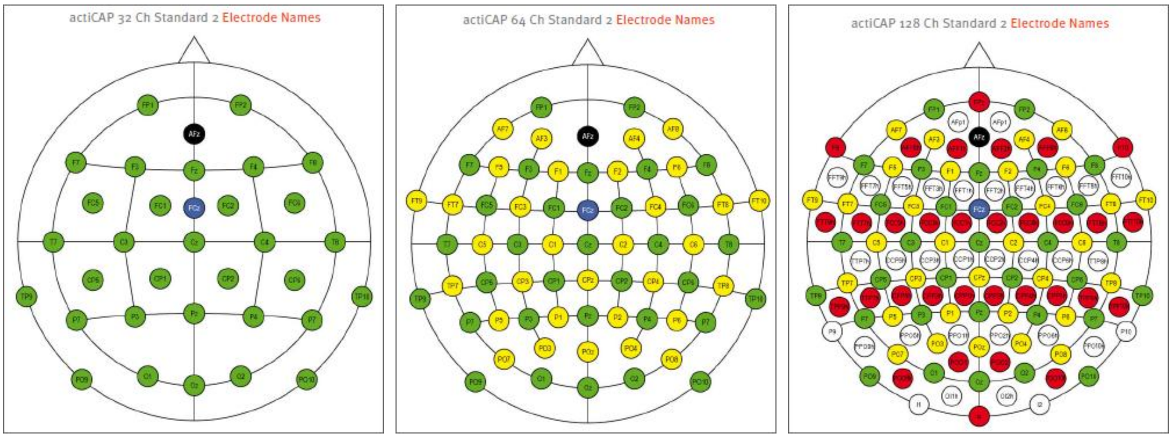

Figure 8. Standard 32, 64, and 128 electrode layout of the Acticap System (BrainProducts).

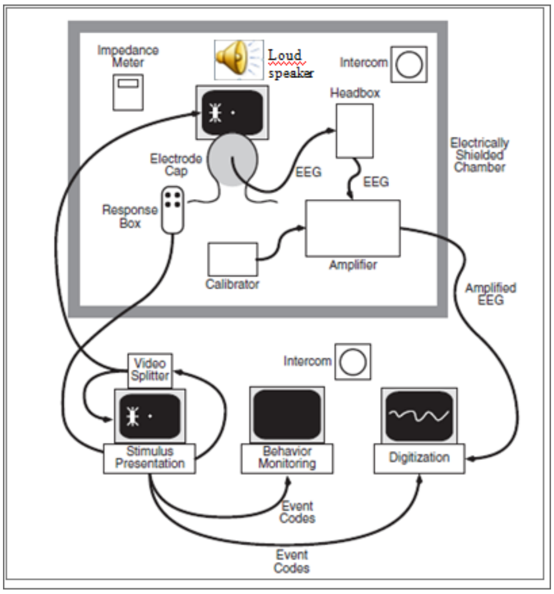

Figure 9: Major components of a typical ERP recording system. Figure from Luck (2005).

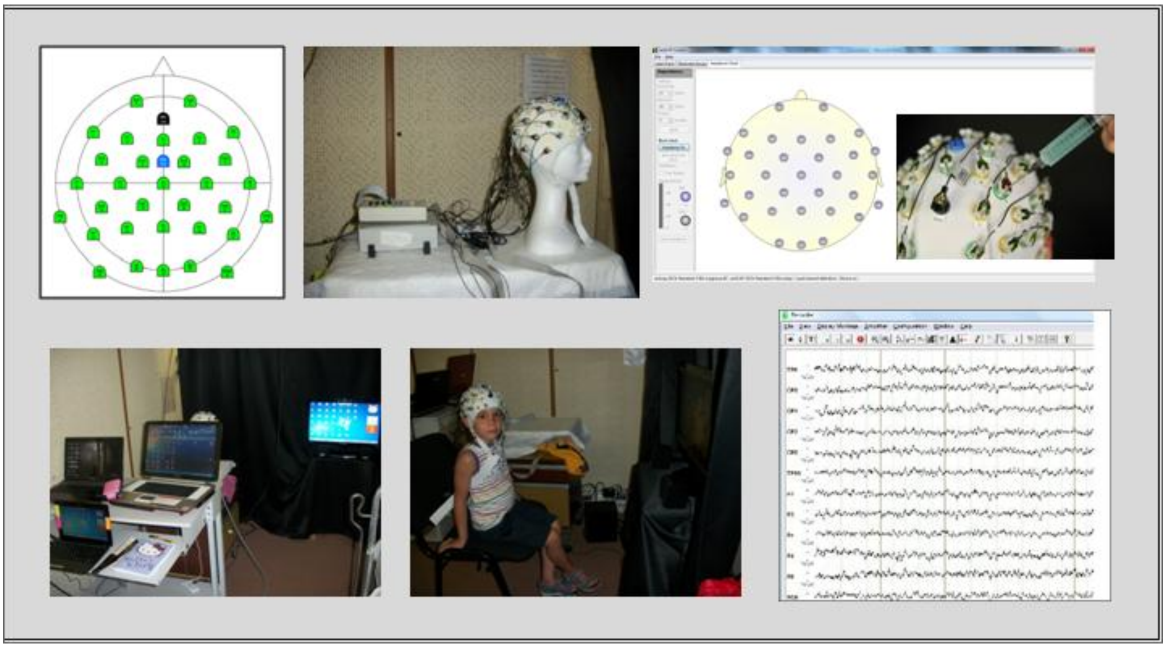

Figure 10. Representation of an actual EEG session

The recorded EEG signal contains different kinds of information concerning the brain activity (e.g., the auditory and visual activity) as well as other types of activity (e.g., eye and muscle movements as well as skin potentials). Before being able to search for the peaks of interest in the recorded EEG signal, it has to be pre-processed through the Independent Component Analysis (ICA) to separate most artifacts from the genuine EEG activity. Then the EEG signal is re-referenced, segmented, baseline-corrected, and residual artifacts are then eliminated. Finally, the EEG signal undergoes averaging (cf. Figure 11) and a convenient filtering to eliminate residual skin potentials and muscle activity, among others, without eliminating the true EEG activity of interest (cf. Figure 12).

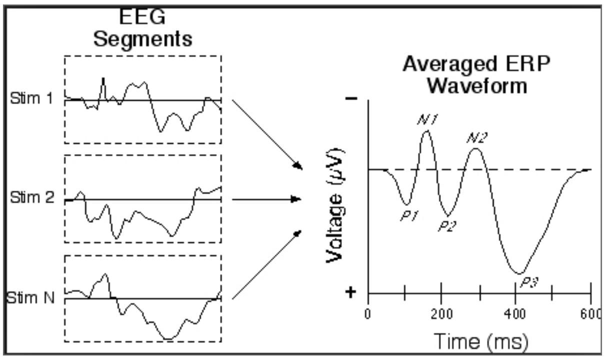

Figure 11: Averaging of EEG segments. Figure from Luck (2005).

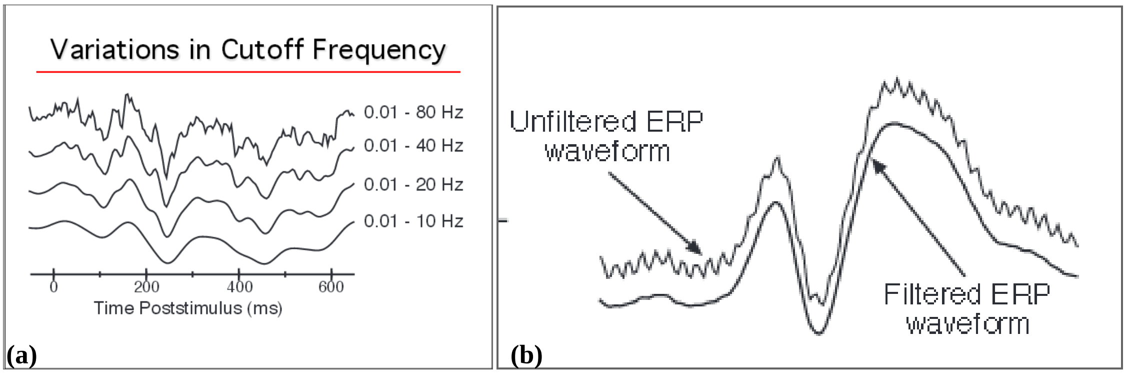

Figure 12: Variations in cutoff frequency (a): the original waveform (top), low-pas filter ~ 40Hz (second from top), low-pass filter ~20Hz (third from top), low-pass filter ~ 10 (third from top). From an unfiltered to a filtered ERP waveform (b). Figures from Luck (2005).

Only at this point, one can look for the peak of interest. In the present research, we concentrated on the activity automatically induced in the brain by the auditory stimuli, i.e. on the long-latency components of the AEPs.

The main advantages of the EEG technique are represented by its high temporal resolution, by its non-invasiveness, and by the fact that it is low cost as compared to other neurophysiological techniques, such as PET or fMRI (cf. Luck 2005). Since changes in the brain’s electrical activity occur very quickly, extremely high time resolution is required to determine the precise moments at which these electrical events take place. The EEG technology can accurately detect brain activity at a high temporal resolution, millisecond–by-milliseconds, giving a picture of what happens in the brain during its activation (cf. Gratton et al. 2001), and thus the possibility to observe functionally distinct processes at different locations.

However, despite its excellent time resolution, one of the main disadvantages of using the EEG system is that it provides poor information at a spatial level. Contrary to other devices, such as the haemodynamic measures which have a spatially resolution in the millimeter range (for a review, see Huettel et al. 2009), the localization of specific neuronal patterns cannot be directly estimated by using EEG only. Because of the fluid bone and skin that separate the electrodes from the actual electrical activity, signals tend to be smoothed and rather noisy. The signal detected by a single electrode indeed, is the result of the activation of hundreds of thousands of neurons spatially distributed into the brain and thus, defining the loci of the neuronal activity from scalp voltage topography is very difficult by exploiting EEG measurements alone (cf. Luck 2005). Nevertheless, thanks to more advanced techniques, more accurate estimates of the signal source is now available and can contribute to clarify the locus of the phenomenon investigated.

2.4 Auditory Evoked Potentials: *Short-*, *middle-*, and *long-latency* responses

Auditory evoked potentials are objective measures that can provide detailed information concerning the functioning of the central auditory pathways, starting from the cochlea (in the inner ear) and traveling along the auditory nerve fiber by passing through a number of nuclei (e.g., ipsilateral cochlear, superior, inferior, and medial geniculate) before reaching the contralateral auditory cortex, as shown in Figure 13.

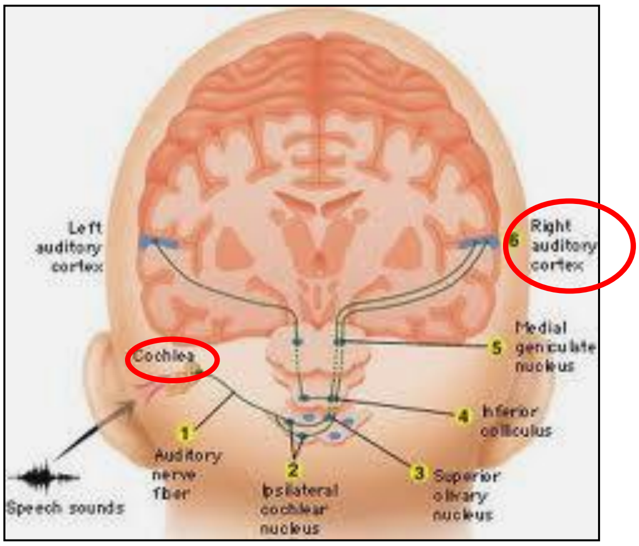

Figure 13. A simplified version of the unilaterally excited auditory pathwats, starting from the left coclea and terminating into the right auditory cortex. Figure adapted from Calhoum (2008).

AEPs are electrical responses recorded in the auditory nervous system in response to a stimulus (e.g., pure tones, clicks, musics, speech sounds). The electrical activity evoked by the stimuli is recorded via electrodes placed on the scalp and then amplified (cf. 2.3). AEPs can be recorded at various stages along the auditory pathways: they are usually classified as short-, middle-, and long-latency evoked potentials, depending on the delay between the stimulus presentation and the evoked electrical signal [e.g., McPherson & Ballachada 2000; Burkard & Secor 2002]. The Auditory Brainstem Responses (ABR) occurr during the first 10 ms after auditory stimulus presentation. Therefore, they are classified as short-latency AEPs, and they are often abridged as BAEPs. The Middle Latency Responses (MLR) occur between 10 and 50 ms subsequent to auditory stimulus presentation. They are often abridged as MLAEPs. The cortical auditory evoked potentials (CAEPs) occur at least 50 ms after auditory stimulus presentation and they are usually known as auditory Event-Related Potentials (henceforth ERPs). See Figure 14.

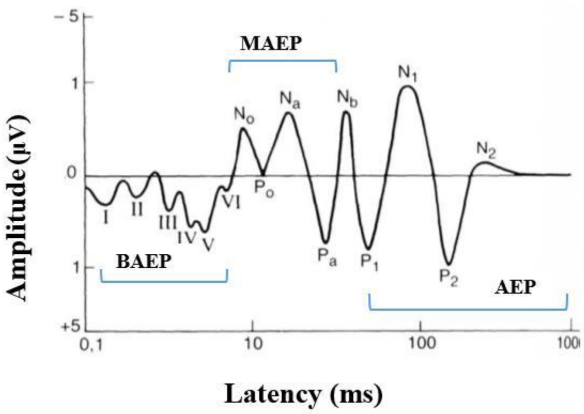

Figure 14. Short- (e.g., BAEP), middle- (e.g., MLAEP), and long-latency (LLAEP) auditory evoked potentials. Figure adapted from Hillyard et al. (1993).

When comparing the ABR, the MLR, and the ERP responses, some differences emerge. First, the ABR responses have their generators along the brainstem as well as the MLRs have their generators in the thalamus and auditory cortex, while the ERP responses have their generators only (or, at least, predominantly) in the auditory cortices. Second, the ABR responses can be evoked only with non-linguistic stimuli, whereas the ERPs are evoked both by non-linguistic and linguistic stimuli [cf. Souza & Tremblay 2006; Stapells 2009). Having their generators in the auditory cortices and being evoked by linguistic sounds, auditory ERPs are more suited to investigate the neural perception and the processing of speech sounds at the highest level along the auditory pathways and, therefore, they are more indicative of whether and how the neural signals are reaching the auditory cortex.

2.5 Categorization and values of the auditory ERPs at the cortical level

The peaks of the auditory ERPs are defined according to their polarity (e.g., positive [P] or negative [N]) as well as their latency. Thus, P1 (also referred to as P100) is a peak with positive polarity occurring at about 100 ms after the stimulus onset (cf. Souza & Tremblay 2006; Martin et al. 2008, among others).

Auditory ERPs have their generators (predominantly) in the auditory cortices: they occur between 50 and 300 ms after the auditory stimulus onset. The values of the auditory P1, N1, and MMN reponses provide information regarding the timing (via peak latency, measured in ms), the sensitivity and accuracy (via peak amplitude, measured in μV), and the size of neuronal activation (via area under the MMN curve, measured in ms*uV]) during speech sound processing [cf. Beauchemin & De Beaumont, 2005; Martin et al. 2008]. The peak latency, measured in milliseconds (ms), describes the neural conduction time to the site of excitation or, in other words, the time it takes for the sound to travel through the peripheal auditory system to the place of excitation in the central auditory system. The peak amplitude, measured in microvolts (uV), indicates the strength of the response [cf. Souza & Tremblay

2006; Martin et al. 2008, among others]. In the present study, the peak latency and amplitude will be monitored for the P1, the N1, and the MMN responses.

The area under the curve (measured in ms*μV), on the other hand, is usually monitored only for MMN [cf. Beauchemin & De Beaumont, 2005]. It has to be pointed out that, to the best of our knowledge, only a few ERP studies focused on the MMN area value beside the MMN amplitude value [cf. Sharma A. et al. 1993; McGee et al. 1997; Sussman et al. 2004; Sussman 2007; Petermann et al. 2009; Davids et al. 2011; Neuhoff et al. 2012], to get more reliable MMN values. The reason that lead previous studies to concentrate on the MMN area as well are the following two. First, as compared to P1 and N1, the MMN is a small-amplitude (range: approximately from -0.5 to 5 uV) response [cf. Sharma A. et al. 2006; Duncan et al. 2009; Garrido et al. 2009]. Second, MMN elicited by the same stimuli for different participants at the same electrode site may have the same amplitude, but a different width, or the same width coupled with a different amplitude [cf. Sharma A. et al. 2004; Beauchemin & De Beaumont 2005]. The MMN area is argued to be a more reliable measure than a time point estimate of peak amplitude and it is likely to provide the researcher with additional pieces of information beside MMN amplitude [cf. Sharma A. et al. 1994; McGee et al. 1997].

The voltage maps of ERPs in a given window around the ERP peak convey information concerning the response displacement on the scalp (via scalp topography) and the higher or lower degree of brain area activation (via response strength). Finally, the degree of hemisphere involvment during speech sound processing may be inferred by jointly studying the ERP values over the two hemispheres separately as well as the scalp distribution of the ERP responses on the voltage maps.

All these ERP values (e.g., the peak latency, amplitude, and area) and characteristics (e.g., the scalp topography, the response strength, and the scalp distribution) need to be examined to achieve a full picture concerning cortical processing of (speech) sounds in humans.

Among the many components of the auditory ERPs, the present research will examine the following three: the P1, the N1, and the MMN responses. The first two are auditory obligatory responses, whereas the third one is a discriminative (or “cognitive”) response. All of them are maximal over the fronto-central region of the scalp, in the sense that they reach their maximal amplitude over fronto-central scalp electrode sites [cf. Sams et al. 1985; Giard et al. 1990].

2.5.1 The obligatory responses: P1 and N1

In adults’ ERP waveforms, the P1 response is the first positive peak occurring approximately 50 ms after the stimulus onset, whereas the N1 response is the first negative peak occurring between 90 and 150 ms after the stimulus onset [cf. Purdy et al. 2001; Wunderlich & Cone-Wesson 2006]. The ERP waveforms in adults are typically dominated by the N1 response, which presents a larger amplitude as compared to the P1 response.

The P1 response is known to generate from the thalamo-cortical projections to the auditory cortex at the bilateral level [cf. Sharma et al. 2005, 2007, 2009; Shatma & Dorman 2006; Kelly et al. 2005; Dorman et al. 2007; Martin et al. 2008 and references cited therein]. The N1 response has multiple generators in the primary and secondary auditory cortices at the bilateral level [Vaughan & Ritter 1970; Martin et al. 2008; Näätänen et al. 2012 and references cited therein].

To evoke the P1 and N1 responses, the auditory presentation of a single (and the same) sound needs to be repeated in time. When evoked by non-linguistic sounds, P1 is the neural correlate of detection of the non-linguistic stimulus onset, whereas N1 is the neural correlate of extraction of the acoustic (e.g, temporal and spectral) features which are relevant for categorization of the non-linguistic stimulus.

When P1 and N1 are evoked by linguistic sounds, they are the correlated of different processes concerning speech sound processing at the cortical level. The P1 response indicates detection of speech sounds (either vowels or consonants) at the cortical level and; especially in those subjects who had experienced, or who are experiencing, a period of auditory deprivation, the P1 response is regarded as a marker for the maturation of the central auditory pathways [cf. Sharma et al. 2002, 2005b, 2007, 2009; Gilley et al. 2008; for a review, Sharma & Dorman 2006].

The N1 response if the correlate of cortical extraction of the acoustic-phonetic features which are relevant for linguistic categorization [cf. Pulvermüller & Shyrov 2006; Näätänen et al. 2011]. When N1 has been evoked by vowels, it indicates cortical extraction of the acoustic-phonetic features (e.g., the formant values) which are relevant for linguistic categorization. The N1 is particularly sensitive to sound audibility and salience [cf. Martin et al. 1997]. Furthermore, the N1 response of the ERPs (as well as its magnetic counterpart, the N1m) has been shown to be modulated by the vowels' spectral properites in that different vowels elicit differential values of latency and amplitude of the N1 and of the N1m [cf. Roberts et al. 2000, 2004; Obleser et al. 2003, 2004; Titinen et al. 2005; Pulvermüller & Shyrov 2006; Rinne 2006; Näätänen et al. 2011; Scharinger et al. 2011, 2012; Manca 2014: 75-78]. A recent study by Manca (2014) on the modulation exerted by the spectral characteristics of the Salento Italian vowels on the latency and the amplitude values of the N1 response in adult NH speakers has reported findings consistent with a significant modulation of the N1 values depending on the vowels' spectral characteristics. As for the N1 latency, /a/ and /u/ elicited a later response as compared to /ɛ/, /i/, and /ɔ/. With respect to the N1 amplitude, /u/ and /i/ elicited a greater amplitude with respect to /a/, /ɛ/, and /ɔ/ [cf. Manca 2014: 75-78]. In languages other than Italian, a consistent modulation of the N1m values depending on the vowels' spectral characteristics has been reported as well. First, the back vowels /o/ and /u/ were found to elicit later N1m responses than non-back vowels, thus suggesting that N1m latency inversely traks F1 [cf. Roberts et al. 2000, 2004, and Titinen et al. 2005 for English vowels; cf. Obleser et al. 2004 for German vowels; cf. Scharinger et al. 2011 for Turkish vowels]. Second, the high vowels /i/ and /u/ turned out to elicit later N1m responses than non-high vowels, thus revealing a significant interaction of tongue body height and tongue place of articulation [cf. Obleser et al. 2004 for German vowels; Scharinger et al. 2011 for Turkish vowels]. Third, as far as non-back vowels are concerned, the low vowel /a/ elicited a significantly faster response than the mid-high vowel /e/ as well as /e/ elicited a significantly faster response than the high vowel /i/ [cf. Obleser et al. 2003]. Fourth, as for N1m amplitude, it appeared to inversely track both F1 and F2, by increasing with decreasing formant valuesm in that the largest N1m amplitudes were observed for the high back vowel /u/ [cf. Scharinger et al. 2011 for Turkish vowels].

The auditory P1 and N1 components are obligatory (or exogenous) responses of the ERPs, since their elicitation is solely (or, at least, predominantly) dependent on the acoustic/physic characteristics of the external auditory stimulus and on the integrity of the central auditory system. Thus, P1 and N1 are auditory responses, i.e. they are more "low-level" as compared to the MMN (cf. 2.5.2) [cf. Pulvermueller & Shtyrov 2006].

To conclude, the presence of the auditory responses in the ERP waveforms indicates that the stimuli have successfully ascended the auditory pathways and, for this reason, the auditory stimuli have (presumably) been heard.

2.5.2 A cognitive response: the MMN

The MMN response is a neural indicator of a deviance detection automatically observed in the auditory scene [cf. Sussman et al. 2013]. It is usually studied by recurring to the standard oddball paradign, where a frequent (called "standard") stimulus is randomly replaced by a rare (called "deviant") stimulus (cf. Naatanen et al. 2001).[1] The frequent occurrence of the standard sound forms the basis of deviance detection, provided that the auditory stimulus regularities (e.g., the spectral and temporal features) have been extracted from the ongoing repetitive acoustic input. MMN is only elicited when a "new" sound is detected (e.g., the deviant stimulus) as violating at least one regulatiry of the preceding auditory sequence (e.g, the one formed by the standard stimuli) [cf. Sussman et al. 2003, 2013].

In previous work by Näätänen and colleagues [cf., among many others, Näätänen 1990, 2001; Näätänen et al. 2001, 2007, 2010, 2011, 2012; Pulvermueller & Shtyrov 2006; Winkler 2007], the MMN elicitation is assumed to consist of the following steps. First, the standard sound creates a central sound representation, corresponding to the repetitive aspects (e.g., the spectral and temporal features) extracted from the incoming auditory input and maintained in the auditory system. Second, the deviant sound creates a percept corresponding to the auditory regularities, i.e. to those auditory features characterizing both the deviant and the standard sound, as well as to the auditory irregularities, i.e. to those auditory features differentiating the deviant from the standard. Third, the MMN is automatically (e.g., in the absence of attention) elicited when the cortical representation of the deviant sound is compared against the cortical representation of the standard sound, and the different spectral and/or temporal features differentiating the deviant from the standard sound are automatically observed at the cortical level. In other words, it is the automatic recognition of a "mismatch" in the specification of the temporal and/or spectral features between the deviant and the standard which crucially determines automatic elicitation of the MMN response.

In the traditional view, starting from the earliest works by Näätänen and colleagues [cf., among many others, Näätänen 1990, 2001; Näätänen et al. 2001, 2007, 2010, 2011, 2012; Pulvermueller & Shtyrov 2006; Winkler 2007], the MMN has been regarded as an index of: i) a change detection in the auditory scene and, thus, as an index of the auditory feature discrimination; ii) the existence and activation of the memory traces representing the auditory regularities characterizing both the standard and the deviant as well as the auditory irregularities differentiating them; iii) the short-term (or sensory or echoic) auditory memory and, consequently, as an index of intact auditory memory capacities.

MMN can be elicited even in the absence of the participant's attention as well as it does not necessarily require subjects to be engaged in a task or to be alert during its elicitation, which makes it particularly useful in the assessment of pediatric [cf. 2.6.2; cf. Nelson et al.

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[1] For studies using modified version of the standard oddball paradigm by presenting one standard and many deviants in the same block of stimuli, cf. Petermann et al. (2009), Putkinen et al. (2012), Totppa et al. (2012), among many others.

2008 for a review], impaired, but cognitively normal [cf. Chapter 3; cf. Nelson et al. 2008; Duncan et al. 2009 for review], or pathologic [cf. Chaoter 3; cf. Lang et al. 1995; Kujala et al. 2007; Duncan et al. 2009; Näätänen et al. 2012] subjects [cf. Näätänen et al. 2011, 2012 for a review].

If MMN elicitation has so far been interpreted as indicating detection of a feature change in the auditory scene as well as of activation of the memory trace corresponding to the two isolated speech stimuli passively heard, the MMN absence, on the other hand, does not necessarily mean that the auditory feature differentiating the deviant from the standard has not been discriminated. Building on this evidence, Sussman and colleagues have started proposing that MMN elicitation in itself cannot serve as an objective index of auditory feature discrimination, since MMN is highly context-dependent [Sussman et al. 2003, 2008, 2013].

For Sussman and colleagues, the basis for MMN elicitation is represented by the (adequate) formation of the cortical representation of the auditory regularities occurring in the standard. The key factors influencing deviance detection in the auditory scene are: i) cortical extraction of the standard regularities from the ongoing acoustic-phonetic input, and ii) cortical representation of these regularities in memory [cf. Sussman et al. 2003, 2013]. Building on this view, MMN can be used to assess not only the irregulatiries occurring in stimulation, but also the auditory regularities extracted from the acoustic input sequence and represented in the auditory system in the short-term memory. Sussman and colleagues suggest that, rahter than as a simple auditory feature discriminator, MMN represents the outcome of a series of processes that precede deviance detection (e.g., the aditory stream segregation during which the brain detects when the deviant occurs) and is reflective of the larger auditory context [Sussman et al. 2003, 2013]. In the present research, we will extend the definition of MMN proposed by Sussman et colleagues by contextualizing it for the processing of speech sounds.

Along the lines of the a few previous studies [Eulitz & Lahiri 2004; Sussman et al. 2003, 2013], here we would like to interpret the presence of the MMN response evoked during the automatic processing of speech sounds as indicating recognition of acoustic-phonetic (i.e., with pronounced formants) speech sounds as a native phoneme (i.e., as meaningfull linguistic sounds) in the hearer's native language. More precisely, we would take the MMN response to signal the successful extraction and representation of the auditory regularities characterizing the standard speech sound (e.g., its acoustic spectral and temporal features) as well as the auditory irregularities characterizing the deviant speech sound (e.g., the acoustic and spectral features differentiating the deviant from the standard) at the cortical level in the auditory system. Henceforth, MMN would be an index of memorization, rather than a simple index of auditory feature discrimination, as well as an index of the fact that the phoneme's neural traces have developed in the auditory cortex.

Following Näätänen (2001) and Eulitz & Lahiri (2004), among others, we assume that the standard speech sound creates a central sound representation, corresponding to their neural trace stored in the auditory cortex. Neural traces are assemblies of cortical cells forming the memory trace for learned cognitive representations relative to the automatically processed speech sounds at the cortical level. The neural traces of speech sounds convey information about the vowel phoneme's phonological representation in terms of distintive features. As soon as the deviant speech sound is automatically heard, it creates a percept corresponding to its neural trace stored in the auditory system. Third, the MMN is automatically elicited when the phonological representation of the deviant speech sound, which is part of the vowel's neural trace, is compared against the phonological representation of the standard speech sound, and the different specification for a single phonological feature or for a couple of phonological features is automatically observed at the cortical level.[2]

The MMN has traditionally been detected on the classical differential waveform obtained by subtracting the grand-averaged waveform of the standard stimulus from the grand-averaged waveform of the deviant (e.g., deviant minus standard difference wave, cf. Figure 15). In adults' ERP waveforms, the MMN is the first negative deflection of the differential waveform: it typically peaks between 100 and 250 ms from stimulus onset and its peak is of between -0.5 and 5 uV [cf., among many others, Näätänen 1990, 2001; Näätänen et al. 2001, 2007, 2010, 2011, 2012; Pulvermueller & Shtyrov 2006; Winkler 2007].

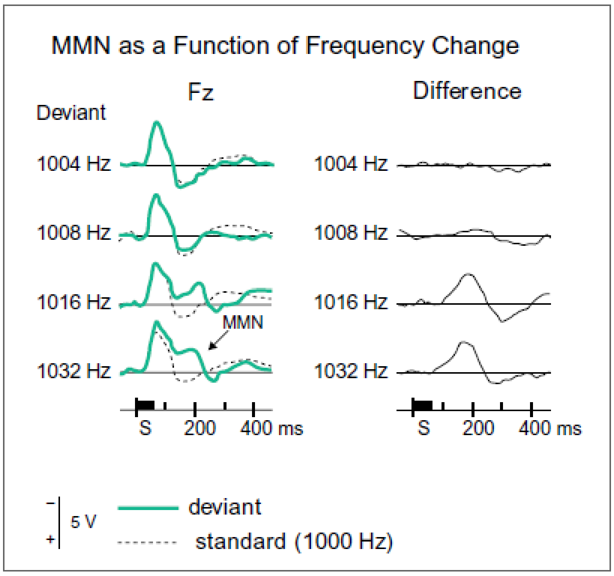

Figure 15. (Left) Frontal (Fz) event-related potentials (ERPs) (averaged across subjects) to randomized 1000 Hz standard (80%, black line) and to deviant (20%, green line) stimuli of different frequencies (as indicated on the left side). (Right) The difference waves obtained by subtracting the standard stimulus ERP from that of the deviant stimulus for the different deviant stimuli. Subjects were reading a book. Figure from Naatanen et al. (2007).

The MMN is known to get contribution from (at least) two intracranial processes: (i) a bilateral supratemporal process generating the supratemporal MMN component in the primary and secondary auditory cortices, which is believed to be a neural correlate of brain activity related to change detection; and (ii) a predominantly right hemispheric frontal process generating the frontal MMN subcomponent in the frontal cortex, which is thought to be related to the involuntary attention switch caused by auditory change [cf. Alho 1986, 1995; Giard et al. 1990; Escera et al. 1998, 2001; Rinne et al. 2000; Näätänen & Michie 1979; Näätänen et al. 1997, 2007, 2012; Kujala et al. 2007; Martin et al. 2008 oppure for reviews, cf. Giard 1990; Alho 1995; Deovell 2007].

The MMN values are known to vary in relation to many parameters [cf. Naatanen et al. 2007 for a review]. They may vary in relation to the magnitude of deviance between the standard and the deviant stimuli: in the case of stimuli characterized by a high magnitude of deviance, discrimination gets easier and, as a consequence, MMN latency decreases and

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[2] In language characterized by rich vowel systems, i.e., such as French, German, or English, a single phonological feature is able to differentiate two vowel phonemes. In languages such as Salento Italian, which consist of no more than five vowel phonemes, on the other hand, at least two phonological feature differentiate two vowels (cf. discussion in 4.3.4).

MMN amplitude increases; in the case of stimuli characterized by a low magnitude of deviance, on the other hand, discrimination gets more difficult and, consequently, MMN latency increases and MMN amplitude decreases [Sussmann et al. 1998; Novitski et al. 2004; Näätänen et al. 2007; Dinces et al. 2009]. However, this does not hold systematically [Horvàth et al. 2008]. Additionally, the MMN parameters may also vary in relation to the type of the eliciting stimuli, i.e. linguistic vs. non-linguistic stimuli (cf. 2.2.4). During processing of pairs of native speech sounds, the left auditory cortex has been reported to be more deeply committed in right-handed NH adults [cf. Mazoyer et al. 1993; Dehaene et al. 1997;], Kim et al. 1997; Shafer et al. 2004], as signaled by shorter MMN latencies and/or enhanced MMN amplitudes recorded in correspondence of the scalp areas on the left hemisphere. However, this does not systematically holds [cf. Näätänen, 2001; Pulvermüller & Shyrov 2006]. MMN left-lateralization is more frequent when speech sounds are placed in a grammatical context [cf. Shtyrov et al. 2005], or when subjects are attending to the auditory stimuli [cf. Imaizumi et al. 1997]. The higher degree of commitment of the left hemisphere during processing of speech sounds is assumed to depend on the presence of the long-term memory traces of native phonemes [cf. Näätänen, 2001; Näätänen et al. 1997, 2007; Pulvermueller & Shrytov 2006]. See also discussion in 2.2.3 above.

The auditory MMN is a discriminative (or endogenous) response of the ERPs, since its elicitation requires the subjects to have the ability to discriminate between acoustic changes in the stimulus sequences, rather than being simply triggered by physical differences between two auditory stimuli (cf. Purdy et al. 2001, 2005; Mazza & Turatto 2005: 9; Pulvermueller & Shtyrov 2006; Wunderlich & Cone-Wesson 2006; Martin et al. 2008). Thus, MMN is considered as a cognitive response which correlates with higher-order perceptual processes underlying stimulus discrimination and as indicator of normal central auditory processing at the level of the auditory cortex [Pulvermüller & Shyrov 2006; Näätänen et al. 2011; Sussman et al. 2013], whereas P1 and N1 are auditory responses, i.e. they are more “low-level” as compared to MMN (Pulvermueller & Shtyrov 2006). The MMN is the earliest negative cognitive component that can be observed in an ERP trace [cf. Alho et al. 1990].

2.6 Maturation of the ERP waveforms in typically-developing children

In the following, we will first review some previous studies on the cortical maturation of the auditory P1 and N1 responses (cf. 2.6.1) and then of the cognitive MMN response (cf. 2.6.2) in typically-developing children.

2.6.1 The P1 and N1 responses

The ERP waveforms in typically-developing children are dominated by the P1 response, which occurs between 100 and 300 ms after the auditory stimulus onset [cf. Sharma & Dorman 2006]. The N1 response, on the other hand, is not completely mature until the adolescence, since its generators continue to mature from childhood until adolescence [cf. Mäkela & Hari 1992; Mäkela & McEvoy 1996; Sharma et al. 1997; Gilley et al. 2005; Wunderlich et al. 2006; Sussman et al. 2008].

When comparing maturation of the P1 and N1 responses in the ERP waveforms of infants (age range: 1 – 4 years), young children (age range: 4 – 6 years), school-age children (age range: 6 – 12 years), adolescents (age range: 13-18 years) and adults (age range: 18-25 years), some clear differences emerge. The ERP latencies appeare significantly shorter in adults as compared to all children, both when ERPs had been evoked by non-linguistic [cf. Wunderlich et al. 2006; Sussman et al. 2008] and by linguistic [cf. Sharma et al. 1997, 2002a; Gilley et al. 2005] sounds (cf. Figure 16).

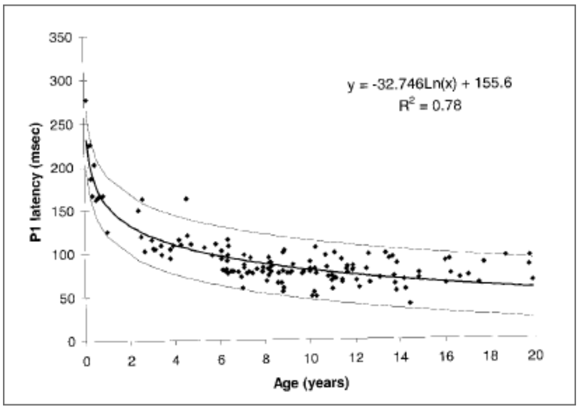

Figure 16. P1 latencies vs. age function in NH children. Superimposed to the raw data is the line showing the best fit as well as the 95% confidence interval. Figure from Sharma et al. (2002a).

With respect to the ERP amplitudes, the amplitude of P1 decreases with age, while that of N1 increases with age, both when ERPs had been evoked by non-linguistic [Wunderlich et al. 2006; Sussman et al. 2008] and by linguistic [Sharma et al. 1997, 2002a; Gilley et al. 2005] sounds (cf. Figure 17 and Figure 18).

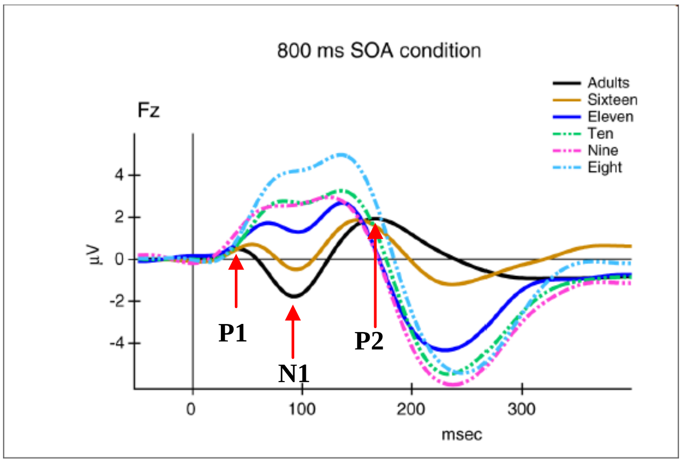

Figure 17. The longest SOA condition (= 800ms) is shown for all age groups to illustrate the major maturational changes of the ERP waveforms. Observe the decrease in P1 latency along with the increase in P2 latency as the N1 component emerges from within the byphasic, dominant positive peak of che child waveforms. Figure adapted from Sussman et al. (2008).

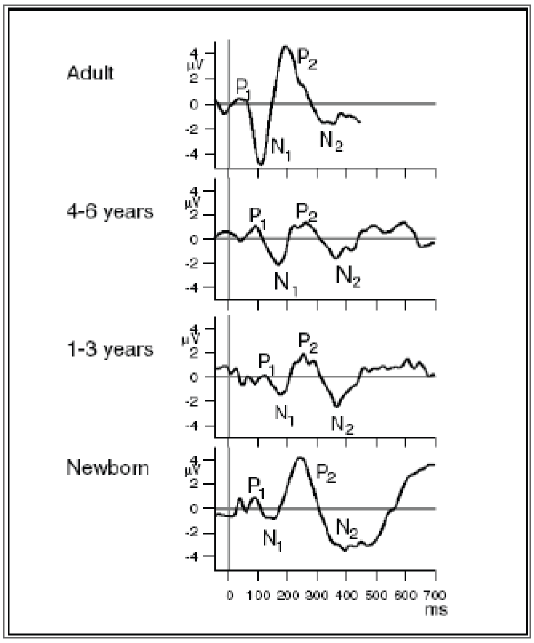

Figure 18. Maturation of auditory ERPs from newborn through to infant, child, and adult waveforms. ERP latency decreases with maturity, as does P1 amplitude. The N1 and P2 amplitudes decrease. Figure from Wunderlich & Cone-Wesson (2006).

The maturational changes reported by previous studies in NH children of various ages are consistent with the general development of the central nervous system. The decrease seen in the latencies of all ERP responses reflects the maturation of structures in the cochlea, auditory nerve, and brainsteam up to the audtiroy cortex: an increase in neural condution velocity due to intensive myelination in the brainstem and auditory nerve as well as an increase and in synaptic density in the auditory cortex [cf. Huttenlocher et al. 1982; Eggermont 1998; for reviews, see Thomas & Crow 1994; Mercuri et al. 1997]. Furthermore, the changes reported in the amplitudes and dominancy of P1 and N1 support the notion that these peaks have different neural generators, which are located in the thalamo-cortical sites for P1, but in the primary auditory cortex for N1 [cf. Sharma et al. 1997, 2002a; Sharma & Dorman 2006; Wunderlich et al. 2006].

2.6.2 The MMN response

The MMN is the first negative deflection of the difference signal between the cortical responses to the deviant and the standard stimuli. In adults, it typically peaks between 100 and 250 ms from stimulus onset and its peak is of about 5uV[cf., among many others, Näätänen 1990, 2001; Näätänen et al. 2001, 2007, 2010, 2011, 2012; Pulvermueller & Shtyrov 2006; Winkler 2007].

MMN tends to peak somewhat later in children, both when MMN had been evoked by non-liguistic [cf. Shafer et al. 2000; Peterman et al. 2009; Lovio et al. 2009] and by linguistic [cf. Lovio et al. 2009] sounds, although not regularly [for non-linguistic sounds [cf. Csepe 1995; Ceponiene et al. 1998; for linguistic sounds, cf. Shestakova et al. 2002].

Contrary to other ERP components, such as the N1 response, the MMN response is mature by birth and it can be obtained at a very early age, as reported by Alho et al. (1990) for full-term infants, Cheour et al. (1996) in pre-term infants, Pang et al. (1998) in 8-month olds.

As compared to other ERP components, such as the P1 and N1 responses, the MMN is developmentally quite stable in terms of latency and amplitude: there are no huge differences between adults and school-children for the MMN latency and amplitude [cf. Csepe 1995; Ceponiene et al. 1998; Shestakova et al. 2002]. In infants, on the other hand, the MMN latency tends to be somewhat longer (e.g., between 200 and 400ms), while the MMN amplitude might be smaller in infants as compared to school-age children [Aaltonen et al. 1987; Cheour et al. 1997], but it rapidly increases between the age of six months and one year [Cheour et al. 1998].During processing of pairs of native speech sounds, the left auditory cortex has been reported to be more deeply committed in right-handed NH children [Dehaene-Lambertz & Dehaene 1994; Dehaene-Lambertz & Baillet 1998; Dehaene-Lambertz 2000; Csepe 1995], although not regularly [cf. Novak et al. 1989; Molfese & Burger-Judish 1991; Csepe 1995; Shestakova et al. 2002; Sharma M. et al. 2006; Bruder et al. 2010], especially when speech sounds are placed in a grammatical context [cf. Shtyrov et al. 2005], or when subjects are attending to the auditory stimuli [cf. Imaizumi et al. 1997]. During processing of non-native speech sounds, on the other hand, both hemispheres appeared to be equally committed [cf. Shestakova et al. 2003; Rinker et al. 2010; Bruder et al. 2010; Davids et al. 2011].

2.7 Chapter summary

This chapter presents some important concepts concerning the processing of (speech) sounds in the auditory cortex,. After presenting the physiology of the auditory system, the main auditory ERP components, which are extracted from the EEG activity, are discussed with respect to their categorization and their maturational profile in adults and children.

CHAPTER 3

Sensorineural hearing loss, cochlear implants, electrical hearing, sensitive periods, and previous ERP studies on (speech) sound processing in pediatric CI users

3.1 Introduction

This chapter is devoted to sensorineural hearing loss as well as to its consequences. First, the different degrees of hearing impairment are defined (cf. 3.2), with particular reference to sensorineural hearing loss (cf. 3.3). Second, CI devices are extensively illustrated (cf. 3.4) as well as the differences between electrical hearing, as provided by CI devices to deaf subjects, and acoustic hearing, as naturally provided by the auditory pathways to NH individuals (cf. 3.5). Binaural vs. monoaural hearing is then briefly addressed (cf. 3.6) as well as sensitive periods in the development of brain and behavior (cf. 3.7). Previous studies on CI children are then recalled, both ERP studies on the auditory processing of linguistic and non-linguistic stimuli by CI children exposed to languages other than Italian (3.8) and logopedic studies on CI children exposed to Italian (cf. 3.9). Previous studies on the effect of earlier vs. later age at surgery on the cortical processing of sounds in CI children are then addressed (cf. 3.10), together with cortical reorganization in CI children following the initial auditory deprivation period (cf. 3.11). The effect of duration of CI stimulation on the ERP values is also briefly considered (cf. 3.12). Finally, previous acoustic studies on the vowel spaces of CI users, both in perception and in production, are mentioned (cf. 3.13). A summary closes this chapter (cf. 3.14).

3.2 The hearing impairment

When the processes and mechanisms described in 2.2 do not work as expected, there is the so-called “hearing impairment” (or “hearing loss”): it can be defined as a loss of hearing sensitivity that affects the incoming auditory input by limiting the amount of acoustic information received. The degree of hearing loss can vary from mild to profound (cf. Table 1 as well as Figure 1 and Figure 2).

Scale of hearing loss			
Average threshold level (dB/HL)[3]	Degrees of hearing loss	Performance	Audiogram
Up to 25 dB	NO	No hearing problems. Able to hear whispers.	Figure 1a
26 to 40 dB	MILD	Soft noises are not heard. Understanding speech is difficult in a loud environment.	Figure 1b
41 to 70 dB	MODERATE	Soft and moderately loud noises are not heard. Understanding speech becomes very difficult if background noise is present.	Figure 1c
71 to 90 dB	SEVERE	Conversations have to be conducted loudly. Group conversations are possible only with a lot of effort.	Figure 1d
+ 91 dB	PROFOUND	Some very loud noises are heard. Without a hearing aid, communication is no longer possible even with intense effort.	Figure 1e

Table 1. Degrees of hearing loss. Adapted from Goaerts (2004).

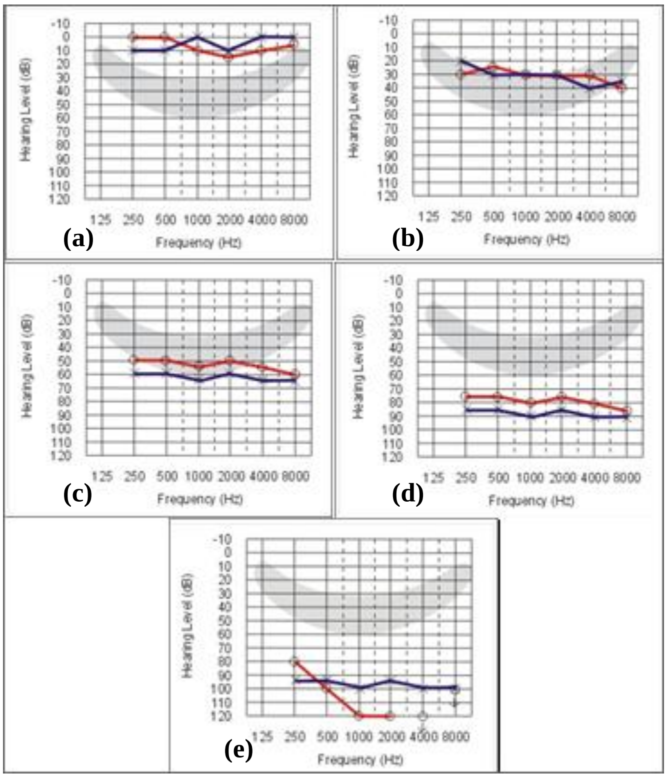

Figure 1: The audiogram in individuals with (a) normal hearing, (b) mild, (c) moderate, (d) severe, and (e) profound hearing loss (retrived from http://www.schooltrain.info/deaf_studies/audiology2/levels.htm). 'X' shows the left ear, while '0' shows the right ear.

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[3] The numerical values indicated in Table 1 are based on the average of the hearing loss in decibel (dB) at the frequencies of 500 Hz, 1000Hz, and 2000Hz in the better ear without amplification.

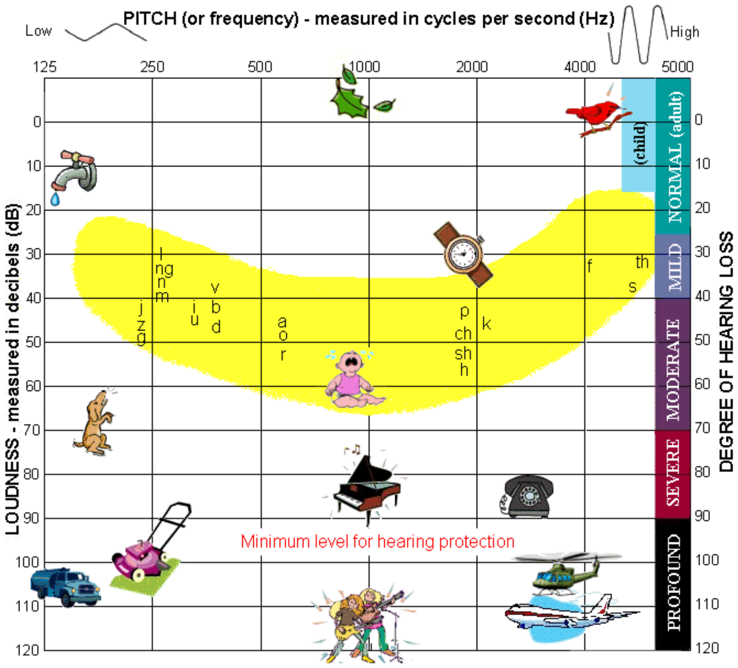

Figure 2: Speech sounds present different loudness and frequency levels. They are recorded on the audiogram as a so-called "speech banana" (retrived from http://www.firstyears.org/lib/banana.htm).

A hearing loss can occur at different stages: i) it is known as 'congenital', if it is present at birth or it is associated with the birth process; ii) it is referred to as 'perinatal', provided that it occurs in the first days or months of life; ii) it is defined as 'acquired' under the condition that it develops later in childhood or adulthood. A further distinction is made between prelingual and postlingual hearing loss. A prelingual hearing loss occurs before the age of 3 years, i.e. before the acquisition of language; congenital, perinatal, and acquired hearing losses can be prelingual. A postlingual hearing loss, on the other hand, occurs after the acquisition of language. Only an acquired hearing loss can be postlingual. According to the place where resides the cause of the hearing loss, it can be classified as 'conductive' or as 'neurosensorial'. If the cause is situated at the level of the outer or middle ear, the hearing loss is defined as conductive. If the anonaly is located in the cochlea, on the other hand, the hearing loss is known as sensorineural [cf. Schauwers 2006, among many others].

3.3 Sensorineural hearing loss

The cause of sensorineural hearing loss (SNHL) at the level of the inner ear resides in a non-functioning cochlea, whose hair cells are virtually always damaged or absent. As a consequence, the link between the middle ear and the auditory nerve is broken (cf. Figure 3). It follows that the incoming auditory input remains blocked at the level of the middle ear, without reaching neither the auditory nerve nor the auditory cortex. Consequently, it can be neither detected, nor categorized, nor interpreted.

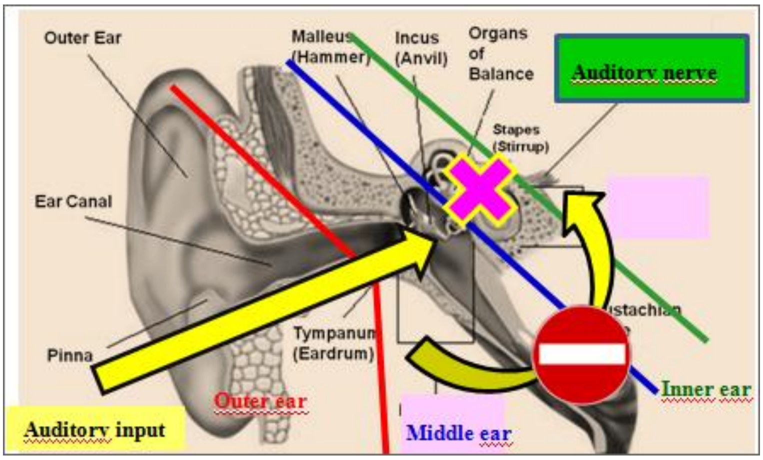

Figure 3: A schematic representation of the consequences of SNHL.

As already made precise in 2.2, the two principal functions of the cochlea consist in amplification and frequency resolution. Individuals affected by congenital, bilateral, and severe to profound SNHL perceive neither speech nor environmental sounds: sounds have to be presented louder in order to be heard by them as well as sounds with neighbouring frequencies sound the same. This latter effect is dramatic, especially for speech sounds. A good amplification and frequency resolution by a functioning cochlea is essential in everyday comunicative situations, since it enables individuals to discriminate between speech sounds, to categorize speech sounds and to produce them through auditory feedback. However, this does not happen in individuals diagnosed by SNHL.

3.4 Cochlear implants

Multichannel cochlear implants (CI) are bionic devices installed into the damaged cochlea, which can partially restore the auditory sensation in individuals affected by severe to profound SNHL, either prelingual or postlingual, at the bilateral level, by capturing the acoustic signal and by transforming it into electrical pulses that directly stimulate the residual fibers of the auditory nerve.

Nevertheless, electrical hearing, as experienced by individuals with SNHL, is different with respect to natural hearing, as experienced by individuals with normal hearing (NH). In natural hearing, auditory sounds pass through the peripheral auditory system (e.g., the outer, middle, and inner ear) before stimulating the auditory nerve, resulting in a signal that travels along the central auditory pathways (cf. 2.2.1) before reaching the auditory cortex (cf. 2.2.2). Multichannel CI devices alter the manner in which the auditory nerve is stimulated: They consist of some internal components, which are surgically placed under the skin (e.g., into the damaged cochlea and within the mastoid bone), as well as of some external components, which are worn behind-the-ear (cf. Figure 4 and Figure 5).

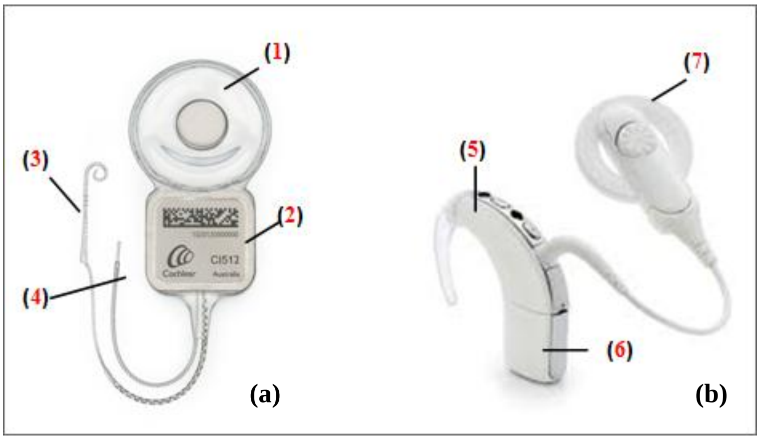

Figure 4: Internal components of a CI (a): (1) receiving coil, (2) implant, (3) 22-electrode array, and (4) ball electrode (retrived from http://funnyoldlife.wordpress.com/tag/cochlear/). External components of a CI (b): (5) microphone, (6) speech processor, and (7) transmitter coil (retrived from http://www.cornerstoneent.com/cochlear-implants-%E2%80%93-hearing-aids-don%E2%80%99t-anymore/).

The external components of the CI (e.g., the transmitter coil, the microphone, the connecting cable, and the speech processor) detect and capture the sound and convey the information to the internal components (e.g., the receiving coil, the implant, and the intracochlear electrode array). The internal components turn acoustic energy in a number of frequency bands into electric pulses at corresponding electrodes to directly provide electrical stimulation to the residual auditory nerve fibers (cf. Figure 5) [cf. Zwolan 2002].

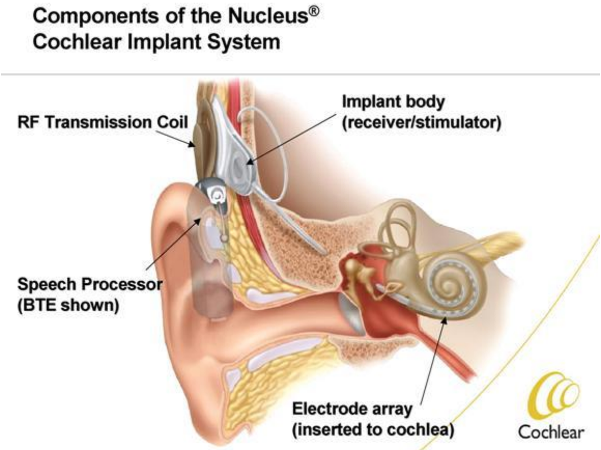

Figure 5: Components of the Nucleus CI surgically implanted under the skin and into the cochlea, as well as worn behind the ear (retrieved from http://nayanb.wikispaces.com/2.3+Hearing+Aids+and+Cochlear+Implants).

The central auditory pathways of children wearing a unilateral CI device are stimulated in a different manner as compared to NH children [cf. Harnsberger et al. 2001; Zeng et al. 2002; Clark 2003; Moore 2003; Rubistein 2004]. In other words, electrical hearing as provided by CI devices induces a pattern of activity that differs from acoustic stimulation as provided by antural hearing. Nonetheless, electrical stimulation mimics the essential coding principles of the cochlea [cf. Dorman & Wilson 2004; Hartman & Kral 2004]. Once the auditory nerve is stimulated by the intracochlear electrodes, the central auditory pathways should presumably proceed as normal, especially in the case of deaf children without additional cognitive impairments, and most CI users learn to interpret artificial, electrical stimulation of the auditory nerve as meaningful speech and non-speech sounds [cf. Zwolan 2002; Wilson & Dorman 2008].

With unilateral CI devices, most CI users manage to differentiate speech sounds snd to interpret the auditory input [cf. Kral & O' Donoghue 2010]. In particular, perception can be fairly well restored under favorable listening conditions (e.g., in the absence of background or concomitant noise) [cf. Harnsberger et al. 2001; Asp et al. 2012; Caldwell & Nittrouer 2012], especially in children receiving their unilateral CI device during the sensitive period for central auditory pathway maturation (cf. 3.8.1, 3.8.2, and 3.10).

3.5 Electrical vs. natural hearing

Although CI devices partially restore auditory sensation in deaf individuals, electrical hearing as provided by a CI device is quite different from normal acoustic hearing. More particularly, the speech signal that reaches the central auditory system after acoustic trasduction through the auditory periphery of NH individuals may be quite different from speech that is electronically trasnformed by a processor and transmitted as electrical pulses along an array of intracochlear electrodes in CI individuals [cf. Ponton et al. 2000; Harnsberger et al. 2001; Zeng et al. 2002; Moore 2003; Rubistein 2004]. More specifically, most current CI devices do not appear to adequately reproduce some aspects (e.g., loudness, spectral shape, and pitch) of complex sounds (e.g., music and speech sounds) [cf. Harnsberger et al. 2001; Zeng et al. 2002; Moore 2003; Rubistein 2004; Torppa et al. 2012 and references cited therein]. Let us discuss these issues more in detail below.

3.5.1 Loudness

In the normal auditory system, the perceived sound level (i.e. loudness) is coded in terms of neural and nerve fiber firing rates. The normal auditory nerve consists of neurons with high spontaneous firing rate (e.g., 61%), neurons with medium spontaneous firing rate (e.g., 23%), and neurons with low spontaneous firing rate (e.g., 16%) [cf. Liberman 1978]. Above a certain sound level, neurons with high and medium spontaneous firing rates no longer respond to increases in sound level wth an increase in firing rate and they are said to be saturated. Neurons with a low spontaneous firing rate, on the other hand, present a firing rate which increases fairly rapidly with increasing sound level, but then their rate of increases slows down. In other words, their firing rates continues to increase gradually with increasing sound level over a wide range of levels, thus resulting in a sloping saturation [cf. Sachs & Abbas 1974]. In response to complex sounds (e.g., speech sounds), nerve spikes tend to be synchronized to the stimulating waveform. Nerve fibers do not necessarily fire on every cycle of the stimulus, but, when spikes do occur, they occur at regular time intervals. For example, if a 500-Hz sinewave has a period of 2 ms, nerve fibers will fire closet o 2, 4, 6, 8, 10 ms, and so on [cf. Moore 2003]. Additionally, the input dynamic range (abbreviated to "IDR") of acoustic hearing, i.e. the range between the detection threshold and the point at which uncomfortabe hearing sensation occurs, is approximately 120dB [cf. Moore 1997; Zeng et al. 2002]. In CIs, sound level is coded by pulse magnitude (e.g., by current), by pulse duration, or by analog current. Increasing stimulating current or pulses leads to increased neural spike rates in the auditory nerve and hence to increate loudness. Parallely, small changes in current or pulse width are believed to lead to large changes in loudness for human implantees [cf. Moore 2003]. The dynamic range of electrical hearing is smaller compared to that of acoustic hearing, i.e. between 30dB (cf. Fourcin et al. 1979) and 60dB (cf. Zeng et al. 2002); however, an IDR of 50-60dB is required in order to achieve optimal phoneme categorization performance in quiet [cf. Zeng et al. 2002]. At this point, some form of compression is essential to map the wide range of input levels into the small usable range of current in CIs. Fast compression would result in a severe reduction of speech intelligibility. The compressors used in CIs vary considerably across different models in the speed of response, although many can be considered as medium-speed compressors [cf. Moore 2003]. Compression may compromise the intelligibility of incoming speech sounds, thus resulting in decreased speech sound categorization and discrimination.

3.5.2 Spectral shape

The perceived quality (or timbre) of complex sounds is partly determined by their spectral shape. In the case of vowels, which are of interest in the present study, each vowel category is characterized by a spectrum with peaks at specific frequencies, called formant frequencies (cf. Lindblom & Sundberg 1971; Kent 1997; Stevens 1999; Ladefoged 2001). The patterning of the formant frequencies plays a crucial role in vowel categorization.

In acoustic hearing, vowel categorization and discrimination depend on the discrimination of formant frequencies and on the frequency analysis performed in the cochlea, where the Basilar membrane behaves like an array of bandpass filters ranging from approximately 50Hz to 20,000Hz, where a given filter respond most strongly to a limited range of frequencies (this range is referred to as the bandwith). Overall, there are approximately 39 independent filters along the cochlea, with 28 (out of 39) independent filters within the frequency range for speech perception. Spectral shape is represented by the relative response across filters along the cochlea [cf. Moore 2003].

In electrical hearing, spectral shape is coded by filtering the incoming signal into several frequency bands and then mapping the filtered signals onto appropriate electrodes. The coding of spectral shape may be poorer in electrical compared to normal hearing for several reasons [cf. Moore 2003]. First, an implanted ear usually has up to 22 intracoclear electrodes (Cochlear Clinical Guidance Document 2010, p. 3). Since the effective number of frequency channels provided by a CI (i.e. up to 22) is less than in a normal ear (i.e. 39), this limits the precision with which information about spectral shape and time can be coded [cf. Moore 2003; Rubistein 2004]. Second, CIs do not stimulate the entire neural population of the cochlea, but only the most basal regions (i.e. about the last 25mm), because the electrode array cannot be inserted completely into the cochlea. Since the most basal locations of the cochlea consist of neurons with higher characteristic frequencies than those stimulated by the same sounds in normal ears, depending on the CI’s depth of insertion in the cochlea, there may be a “mismapping” in the allocation of frequency bands to intracoclear electrodes. For example, the output of a band centered at 1000 Hz may drive an electrode at the 2000 Hz place within the cochlea, thus resulting in spectrally shifted information presented by CIs [cf. Harnsberger et al. 2001; Moore 2003]. Such mismapping can have deleterious effects in the short term [cf. Shannon et al. 1998], although postlingually-deafened CI users may adapt to it with extended CI experience [cf. Rosen et al. 1999]. Third, the implanted cochlea may be characterized by dead regions, i.e. regions of missing neurons [cf. Moore 2001]. It follows that an electrode producing maximum current in a dead region wll give rise to an audible sensation only if the current spreads to an adjacent region with surviving neurons. This produces a second kind of mismapping and may also result in a sort of information overload in the adjacent region [cf. Moore 2003]. Fourth, the Frequency Allocation Table ("FAT") defines the frequency bandwith assigned to each intracochlear electrode: each electrode covers a specific frequency range and a given electrode receives stimulation when its bandwith has the greatest amounth of Energy. Changing the FAT clearly affects sound quality (Cochlear Clinical Guidance Document 2010, p. 15). Depending on the FAT programmed into the CI speech processor and on the individual's ability to discriminate stimulation pulses delivered to different electrodes, CI users may find it quite difficult to identify vowels accurately because formant frequencies, which are important cues for vowel recognition, may not be adequately extracted and delivered by CIs [cf. Harnsberger et al. 2001; Moore 2003]. More particularly, CI users may encounter difficulties in discriminating small differences in the formant frequencies, as in /i/ vs. /e/ or /u/ vs. /o/ [cf. Harnsberger et al. 2001; Henkin et al. 2008] (cf. discussion in 3.13).

3.5.3 Pitch

The pitch evoked by periodic complex sounds is generally very close to the pitch of the fundamental frequency of complex sounds. So, for example, if the complex sound has a repetition rate of 256 Hz per second, its fundamental frequency is 256 Hz. The perception of the pitch of complex sounds in acoustic hearing mainly depends on the frequency of lower resolved harmonics. Crucially, CIs do not convey information about the frequencies of individual harmonics. It follows that the resolution and precision of the pitch perception of complex sounds is much worse for CI users than for NH people [cf. Moore 2003].

3.5.4 Across-channel coincidence

Acoustic hearing also use across-channel coincidence detection to code the sound level, the spectral shape, and the pitch of complex sounds. Different places of the basilar membrane vibrate with different phases. So, when one point is moving upward, a nearby point may be moving downward, etc. The phase response of the basilar membrane varies with sound level, spectral shape and pitch. The phase changes may be detected by the patterns of responses across an array of neurons in the cochlea (the so-called "across-frequency coincidence detectors"), each of which receive inputs from 2 auditory nerve fibers. It is assumed that the conduction time from the instant of spike initiation to the coincidence detector is different for the two input neurons and that this difference varies across coincidence detectors. This kind of coding in not represented in current CIs since it depends on differences in phase response at different points along the basilar membrane [cf. Moore 2003].

3.5.5 Even the best CI user does not hear normally

To sum up, unilateral CI devices, although partially restoring the auditory sensations in congenitally deaf children through electrical hearing, cannot substitute normal hearing. Indeed, the acoustically/phonetically relevant information extracted from incoming speech and delivered by CIs is less precise in terms of acoustic cues (i.e. formant frequencies), loudness, and pitch by comparison with the finer transduction taking place in the human ear, thus frequently leading to incomplete perception of the stimulus features in CI users. Therefore, it has always to be kept in mind that, even the best CI users do not hear normally, since the signal they receive through the stimulation provided by the CI device is degrated, at least to a certain degree.

3.6 Binaural vs. monoaural hearing

Currently, individuals affected by severe to profound SNHL at the bilateral levels typically receive unilateral, rather than bilateral, CI devices. Two normal ears allow NH people a more precise sound localization as well as a finer sound detection and discrimination, especially in less favorable listening conditions, i.e. in the presence of background noise [cf. Davis et al. 1990].

Bilateral cochlear implantation is unlikely to restore to normal the ability to localize sounds and to improve sound detection and discrimination in noise, because it is very unlikely that the intracochlear electrode arrays will be inserted to exactly the same depth in the two ears. It follows that the neurons excited maximally by a given electrode in one ear are not the same with the neurons maximally excited by the specular electrode in the other ear. As a consequence, a misalignment across ears is likely to occur.

Nevertheless, bilateral cochlear implantation enables deaf individuals to achieve some advantages as compared to unilateral cochlear implantation. First, it improves the ability to understand speech in the presence of interfering sounds. Second, it might help to prevent the progressive neural degeneration that would otherwise occur in the non-implanted ear [cf. Tyler et al. 2002; Moore 2003].

To conclude, we would like to observe that the auditory sensation experienced by children with unilateral CI devices is closer to the one experienced by children with a mild hearing loss, rather than to the one experiences by children with unimpaired hearing.

3.7 Sensitive periods in the development of brain and behavior

Sensitive periods are limited periods of development during which the effects of experience on the brain are unusually strong. During sensitive periods, experience instructs neural circuits to process or represent information in a way that is adaptive for the individual. In other words, certain capabilities are readily shaped by experience during sensitive periods. Critical periods represent a special class of sensitive periods. During critical periods, experience provides information that is essential for normal development and that results in irreversibile changes in brain function. Crucially, the adverse effects of atypical experience throughout a critical period cannot be remediated by restoring typical experience later in life [cf. Knudsen 2004].

Although sensitive periods are reflected in behavior, they are primarily a property of neural circuits in the brain. Behavioral measures tend to underestimate the magnitude as well as the persistence of the effects derived by early exposure to experience on neural circuits and, more generally, the importance of critical periods. The reason is that behavior results from the information that has previously been processed through hierarchies of neural circuits in the brain that operate in parallel. Among these circuits, those operating at higher levels in the hierarchy and that still remain plastic tend to obscure irreversibile changes in those circuits operating at lower levels [cf. Knudsen 2004]. Crucially, behavioral performance may improve with subsequent experience and training, even though neural circuits at some level in a pathway have become irreversibly committed to processing information abnormally [cf. Knudsen 2004]. Language acquisition depends on a wide range of specialized sensory, motor, and cognitive skills involving many neural hierarchies. The analyses of phonetics, semantics, grammar, syntax, and prosody are assumed to be accomplished by distinct hierarchies of neural circuits. The functional properties of each of these hierarchies are shaped by experience with language. If the hierarchy underlying semantic processing remains fully plastic throughout life, the hierarchies underlying phonetic, grammar, and syntax contains neural circuits that pass through sensitive periods [cf. Neville et al. 1992; Weber-Fox & Neville 1996; Newport et al. 2001]. Thus, language development involves multiples sensitive periods that affect certain, but not other, aspects of behavior. For this reason, it is only by combining behavioral and neurophysiological measures that one can reconstruct a comprehensive picture concerning the effects of early exposure to a given class of stimuli (i.e. acoustic stimuli) on the behavior and the brain [cf. Knudsen 2004].

Experience during a sensitive period customizes a developing neural circuit to the needs of the individual [cf. Knudsen 2004]. For example, experience calibrates those circuits involved in speech sound processing in humans for the particolar language(s) to which the individual is exposed to [cf. Newport et al. 2001, among many others]. Only specific kinds of stimuli are able to shape a particular neural circuit during the sensitive period. The range of stimuli that is likely to influence a circuit is determined by genetic predispositions built into the nervous system [cf. Knudsen 1999]. Crucially, experience occurring initially during a sensitive period has the unique advantage of shaping the connectivity of a neural circuit. Before a neural circuit has ever been activated strongly, it accomodates with changes. As a result of experience, intense activation of a neural circuit alters its initial state, since synapses participating in driving postsynaptic neurons become strong and less susceptible to further changes due to the insertion of stabilizing proteins and different neurotransmitter receptors. Synapses that do not partecipate in driving postsynaptic neurons, on the other hand, are depressed or even eliminated [cf. Knudsen 2004 and references cited therein]. Although initial experience plays a crucial role in shaping neural patterns of connectivity, subsequent experience has the ability to cause further structural and functional changes that add to initial connectivity patterns, as long as the sensitive period remains open [cf. Knudsen 2004 and references cited therein]. As an example, cortical circuits that process speech sounds can develop the capacity to process speech sounds of different languages with comparable facility provided that the individual learns those languages during the sensitive periods for language acquisition [cf. Doupe & Kuhl 1999; Newport et al. 2001].

A sensitive period ends when the mechanisms that are responsible for the plasticity of a given neural circuit no longer operate or operate with much lower efficiency. The amount of plasticity persisting in a mature circuit varies widely, depending on the neural circuit’s function. As far as language acquisition is concerned, the acquisition of language proficiency in humans is limited to the juvenile lifetime. Afterwards, individuals become unable to acquire a second language and to correctly use the principles of the second language [cf. Lenneberg 1967; Curtis 1977; Newport 1990]. Under conditions of deprivation, a circuit is never activated or never activated strongly, depending on the degree of deprivation. Crucially, deprivation usually leads to consolidation of highly abnormal circuit connectivity and the neurons begin to respond to abnormal patterns of input that otherwise would have been too weak to drive the circuit [cf. Knudsen 2004 and references cited therein]. In the case of language, the sensitive period for maximal plasticity of central auditory pathways which is presumed to end at about 44 months, i.e. 3.8 years (cf. Bishof 2007).

3.8 Previous ERP studies on the processing of auditory stimuli in pediatric cochlear-implant users

Previous ERP studies monitored the cortical processing of a variety of auditory stimuli in pediatric CI users. Processing of both linguistic (e.g., vowels and consonants; cf. 3.8.1) and of non-linguistic (e.g., clicks, tones, and musical stimuli; cf. 3.8.2) sounds was monitored in deaf children implanted either during the period of maximal plasticity of the central auditory pathways (cf. 3.8.1.1 and 3.8.2.1) and once this sensitive period is concluded (cf. 3.8.1.2 and 3.8.2.2).

3.8.1 Cortical processing of linguistic stimuli

The cortical processing of speech sounds, mainly consonants, has been investigated both in early-implanted (< 3.5 years) children (cf. 3.8.1.1) and in late-implanted (> 3.5) children (cf. 3.8.1.2).

3.8.1.1 Children implanted prior to 3.5 years

In deaf children implanted before 3.5 years, detection of speech sounds, as indicated by the P1 response, as well as extraction of the acoustic-phonetic features which are relevant for linguistic categorization, as indicated by N1, have been studied by Munivrana & Mildner (2013) in deaf children implanted prior to 3.5 years. Extraction and representation of the acoustic-phonetic features which are relevant for linguistic categorization, as indicated by the MMN response, has been investigated by Munivrana & Mildner (2013) and Ortmann et al. (2013).

Munivrana & Mildner (2013) used two Croatian syllables (e.g., /ka/ and /te/), whereas Ortmann et al. (2013) recurred to three stimulus pairs (e.g., /bu/$_{\text{std}}$ - /ba/$_{\text{dev}}$, /bu/$_{\text{std}}$ - /bo/$_{\text{dev}}$, and /bu/$_{\text{std}}$ - /pu/$_{\text{dev}}$). The age at surgery, age at testing, and duration of CI use at testing of the CI children monitored are given in Table 2.

Studies	Age at testing	Age at surgery	Duration of CI use	Language learned
Munivrana & Mildner (2013)	8-10 years	3.1 – 4 years	4.1 – 7 years	Croatian
Ortmann et al. (2013)	7 – 19 years	1.2 -4.5 years	6.1 – 15.3 years	German

Table 2. Demographic details of the studies reviewed.

With respect to vowel detection and categorization, Munivrana & Mildner (2013) were able to identify the P1 and the N1 responses in all the CI children monitored. However, the peak latencies were often prolonged as well as their amplitudes were often attenuated in CI as compared to NH children, thus suggesting that CI children took longer to detect and categorize the Croatian syllables as compared to the NH children.

As for vowel discrimination, Ortmann et al. (2013) could identify the MMN response in all the CI children examined. Nevertheless, the MMN of good performers was clearly visible, whereas that of bad performers had attenuated amplitude (cf. Figure 6).

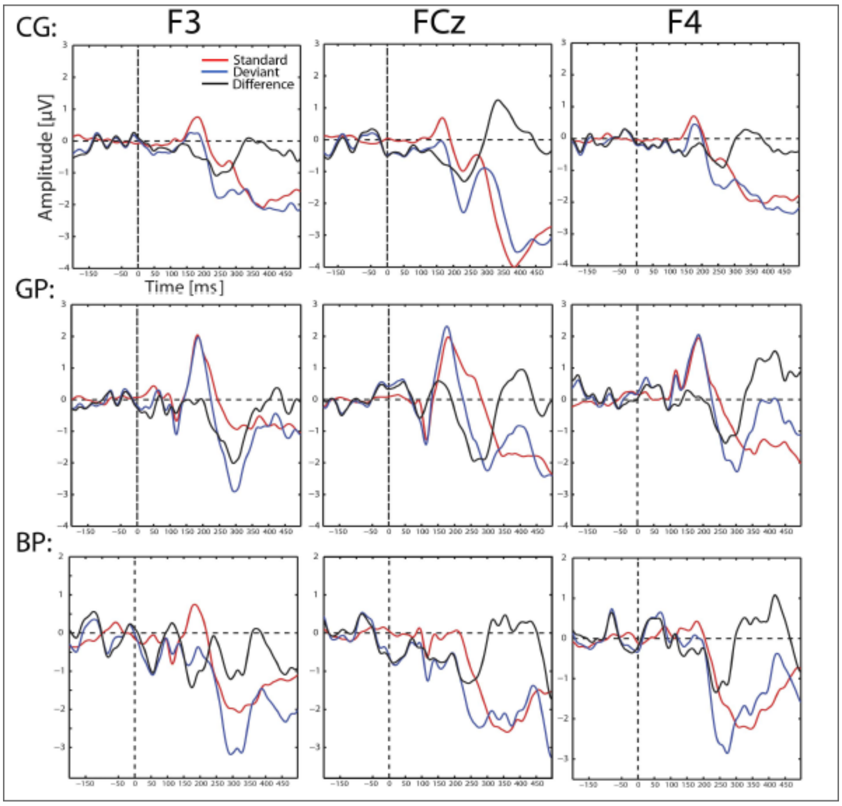

Figure 6. The MMN in Sensor Space. Standards (red), deviants (blue) and their difference waveform (black) are shown at central (FCz) and frontal (F3 and F4) positions for all three groups (CG = control group, GP = good performers, BP = bad performers). Average reference was used. Figure from Ortmann et al. (2013).

To recapitulate for early-implanted children, the studied mentioned so far have provided evidence for largely comparable abilities in the processing of single phonemes and of phoneme pairs in successfully-implanted deaf children and in NH controls, but of better phoneme processing abilities in successfully-implanted deaf children as compared to bad performers.

3.8.1.2 Children implanted after 3.5 years

In deaf children implanted after 3.5 years, detection of speech sounds has been investigated by Singh et al. (2004). Extraction of the acoustic-phonetic features which are relevant for linguistic categorization has been studied by Kileny et al. (1997) and Beynon et al. (2002). Finally, extraction and representation of the acoustic-phonetic features which are relevant for linguistic categorization), as indicated by the MMN response, has been investigared by Singh et al. (2004), whereas involuntary attention switching to changes in speech sounds, as suggested by the P3 response[4], has been investigated by Kileny et al. (1997), Beynon et al. (2002), and Henkin et al. (2008).

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[4] The P3 response, elicited either passively (P3a) or attentively (P3b) is an index of (involuntary) orienting to salient sounds in the environment [cf. Friedman et al. 2001]. Its presence in the ERP waveforms indicate that the feature changes were salient enough to evoked an orienting response.

Kileny et al. (1997) used a vowel place contrast (e.g., /hi:d/-/hu:d/). Beynon et al. (2002) recurred to a vowel contrast where the two vowels differed by place and height (e.g., /i/-/a/) and to a consonantal contrast where the two consonants differed by manner of articulation (e.g., /ba/-/da/). Singh et al. (2004) used a consonantal contrast where the two consonants differed by manner of articulation (e.g., /ba/-/da/). Henkin et al. (2008) recurred to two vowel contrasts differing by place of articulation (e.g., /ki/-/ku/) and height (e.g., /ki/-/ke/), in turn, as well as two consonantal contrast differing by voicing (e.g., /ka/-/ga/) and place of articulation (e.g., /ka/-/ta/), respectively.

The age at surgery, age at testing, and duration of CI use at testing of the CI children monitored are given in Table 3.

Studies	Age at testing	Age at surgery	Duration of CI use	Language learned
Kileny et al. (1997)	4- 12 years	After 3.5 years	0.7 – 7 years	English
Beynon et al. (2002)	≥ 9 years	≥ 5 years	≥ 2 years	Dutch
Singh et al. (2004)	7 – 17 years	2.2 – 15.3 years	1-10 years	English
Henkin et al. (2008).	9.7 – 13.2 years	2.5 – 6.3 years	5 – 9.5 years	Hebrew

Table 3. Demographic details of the studies reviewed

With respect to detection of speech sounds, Singh et al. (2004) identified the P1 response in nearly all the CI children. The latency of P1 was not significantly delayed as well as its amplitude was not significantly reduced as compared to the latency and amplitude values usually found in age-matched NH children (cf. Figure 7).

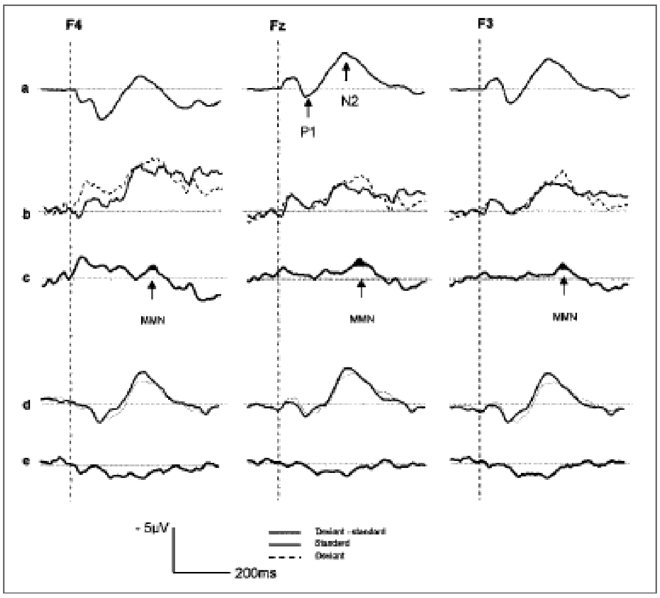

Figure7. Grand average ERPs of CI users recorded at F4, Fz, and F3. (a) Obligatory components in all CI users (*N* = 30), (b) standards and deviants in star performers (*N* = 7), (c) *MMN* revealed by the subtraction waveform in star performers shaded area, (d) standards and deviants in poor performers (*N* = 21), (e) subtraction wave revealing no MMN in poor performers. Figure from Singh et al. (2004).

As for categorization of speech sounds, Kileny et al. (1997) recognized the N1 response in all the CI children. The latency of the N1 peak was found to fall within the expected latency range, whereas its amplitude was often smaller than expected. Beynon et al. (2002) succeeded in identifying the N1 response only in those children with better word recognition performance, but not in those with poor word recognition performance. Nevertheless, the N1 latency was relatively long and the N1 amplitude was significantly attenuated in CI as compared to NH children.

With respect to discrimination of speech sounds, Kileny et al. (1997) detected the MMN and the P3a responses in nearly all the CI children. The latency of MMN and P3a was found to fall within the expected latency range, whereas their amplitude was often attenuated than expected. Beynon et al. (2002) were able to identify the MMN and the P3b responses only in those children with better word recognition performance, although not systematically. When MMN and P3b were present, their latencies were delayed and their amplitudes were reduced in CI as compared to NH children. Singh et al. (2004) could detect the MMN response only in a few children. When MMN was present, its latency was delayed, but its amplitude did not appear reduced in CI children as compared to NH children (cf. Figure 8).

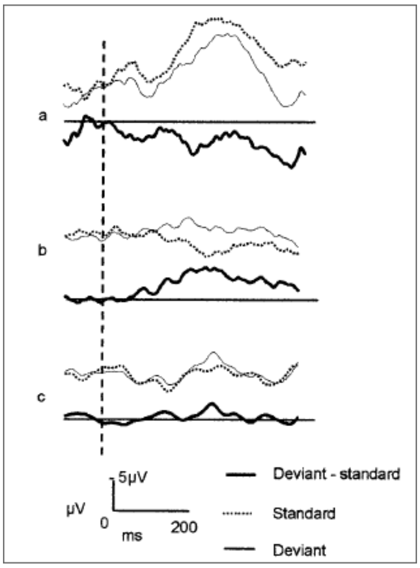

Figure 8. Individual recordings of three patients from Fz. (a) mismatch negativity absent, (b) and (c) mismatch negatività present. Figure from Singh et al. (2004).

Henkin et al. (2008) identified the P3b response in all the CI children examined for the vowel height, the vowel place, and the consonant voicing contrasts, but not systematically for the vowel place contrast. As for P3b latency, the vowel place contrast (e.g., /ki/-/ku/) elicited the shortest latency, whereas the vowel height contrast (e.g., /ki/-/ke/) and the consonantal place of articulation contrast (e.g., /ka/-/ta/) elicited the longest latencies. The P3b latency evoked by the consonantal voicing contrast (e.g., /ka/-/ga/) was longer as compared to the one elicited by the vowel place contrast, but shorter as compared to the vowel height and the consonantal place of articulation contrasts (see Figure 9).

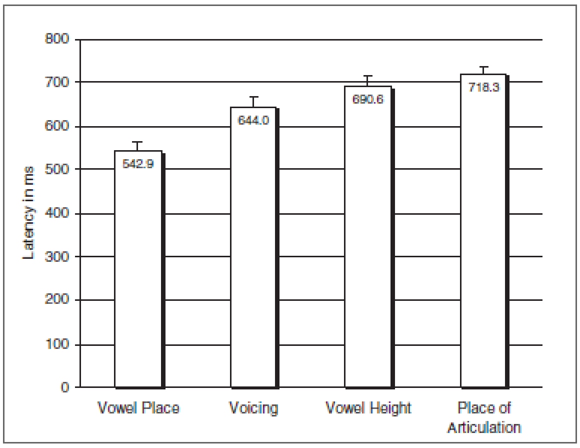

Figure 9. Mean (± Standard Error) P3b latency at the Pz electrode in the different phonetic tasks. Figure from Henkin et al. (2008).

The P3b amplitude evoked by the vowel place contrast was significantly greater than that of the consonantal place of articulation contrast, but it was statistically comparable to that of the consonantal voicing and the vowel height contrasts (cf. Figure 10).

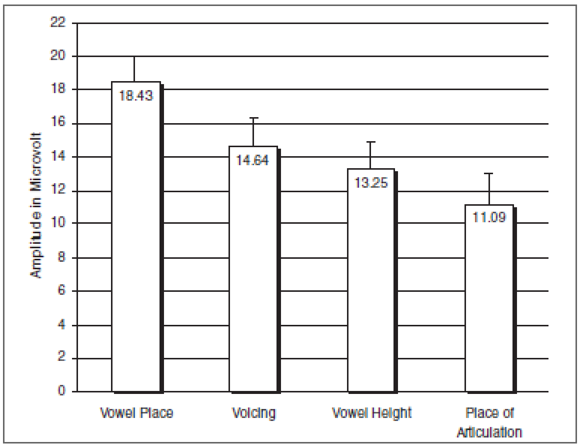

Figure 10. Mean (± Standard Error) P3b amplitude at the Pz electrode in the different phonetic tasks. Figure from Henkin et al. (2008).

Taken together, the findings by Henkin et al. (2008) suggest that, as acoustic-phonetic difficulty increased, the latency of P3 increased as well, but its amplitude decreased.

To sum up, the cortical processing of single speech sounds as well as of pairs of speech sounds was often delayed and less accurate in late-implanted children as compared to NH peers. Additionally, as acoustic-phonetic difficulty increased, the late-implanted CI children took longer to process phonemes as well as they accomplished this automatic 'task' with reduced amplitude.

3.8.2 Cortical processing of non-linguistic stimuli

Cortical processing of non-linguistic sounds has been investigated both in early-implanted (< 3.5 years) children (cf. 3.8.2.1) and in late-implanted (> 3.5) children (cf. 3.8.2.2).

3.8.2.1 Children implanted prior to 3.5 years

In deaf children implanted prior to 3.5 years, detection of non-linguistic sounds has been investigated by Torppa et al. (2012) and Munivrana & Mildner (2013). Extraction and representation of the acoustic features, which are relevant for sound categorization, has been studied by Torppa et al. (2012), whereas involuntary attention switching to change in pairs of non-linguistic sounds has been monitored by Torppa et al. (2012) and Munivrana & Mildner (2013).

The stimuli used by Torppa et al. (2012) were musical sounds differing by magnitude of change in the fundamental frequency, musical instrument, duration, intensity increments and decrements, and presence of a temporal gap. The stimuli employed by Munivrana & Mildner (2013) were tones (e.g., 1000Hz as the standard and 2000Hz as the deviant tones).

The age at surgery, age at testing, and duration of CI use at testing of the CI children monitored are given in Table 4.

Studies	Age at testing	Age at surgery	Duration of CI use	Language learned
Torrpa et al. (2012)	4.1 – 12.6 years	1.2 – 3.1 years	2.10 – 10.8 years	Finnish
Munivrana & Mildner (2013)	8-10 years	3.1 – 4 years	4.1 – 7 years	Croatian

Table 4. Demographic details of the studies reviewed.

As for detection of non-linguistic sounds, Torppa et al. (2012) were able to detect the P1 response in all CI children: the amplitude of P1 was nearly systematically decreased in CI as compared to NH children, whereas the latency of P1 was never delayed in CI relative to NH children, although being shorter in CI relative to NH children in some instances. This last point was interpreted as suggesting differences in sound processing in the auditory cortex following electrical stimulation. Munivrana & Mildner (2013) succeeded in identifying the P1 response in all CI children: its amplitude was not attenuated, while its latency was systematically delayed in CI as compared to NH children.

As far as categorization of non-linguistic sounds is concerned, Munivrana & Mildner (2013) succeeded in identifying the N1 response in all CI children: it was never reduced in amplitude, but it was systematically prolonged in latency.

With respect to discrimination of pairs of non-linguistic sounds, Torppa et al. (2012) managed to identify the MMN and the P3a responses in all CI children: their responses were never prolonged in CI as compared to NH children, but they were often reduced in the former relative to the latter. The reduced amplitude of MMN has been interpreted as suggesting less accurate neural detection of changes of musical instrument, sound duration, and temporal envelope, while the reduced amplitude of P3a has been taken to indicate less accurate involuntary attention switching to changes in musical instrument. Munivrana & Mildner (2013) succeeded in identifying the P3a response in all CI children: on the one hand, its latency was not delayed in CI relative to NH children but, on the other hand, its amplitude was systematically significantly reduced in deaf children.

To conclude, the cortical provessing of single non-linguistic stimuli as well as the processing of pairs of non-linguistic stimuli were likely to be delayed and/or less precise in late-implanted children as compared to NH peers.

3.8.2.2 Children implanted after 3.5 years

In deaf children implanted after 3.5 years, detection of non-linguistic sounds has been investigated by Ponton et al. (2000), Ponton & Eggermont (2001), and Dinces et al. (2009). Extraction of the acoustic-phonetic features which are relevant for sound categorization, as indicated by N1 response, has been explored by Kileny et al. (1997) and Beynon et al. (2002). Extraction and representation of the acoustic features, which are relevant for sound categorization, has been passively investigated by Ponton et al. (2000), Dinces et al. (2009), whereas involontary attention switching to changes in pairs of non-linguistic sounds has been studied by Kileny et al. (1997) and Beynon et al. (2002).

Kileny et al. (1997) used tonal stimuli differing either by loudness (a 1500 Hz tone presented at 75 db SPL as the standard and at 90 dB SPL as the deviant) or by frequency (a 1500 Hz tone as the standard and a 3000 Hz tone as the deviant, both presented at 80 dB SPL). Beynon et al. (2002) employed tonal stimuli differing by frequency (a 500 Hz tone as the standard and a 1000 Hz tone as the deviant). Dinces et al. (2009) used a standard tone (F0 = 500 Hz, intensity = 90 dB SPL, duration = 150 ms, frequency partials = 600, 1200, 1800 Hz) against tonal stimuli differing by duration (50 ms), frequency partials (500, 1000, 1500 Hz), and intensity (75dB SPL).

The age at surgery, age at testing, and duration of CI use at testing of the CI children monitored are given in Table 5.

Studies	Age at testing	Age at surgery	Duration of CI use	Language learned
Kileny et al. (1997)	4- 12 years	After 3.5 years	0.7 – 7 years	English
Beynon et al. (2002)	≥ 9 years	≥ 5 years	≥ 2 years	Dutch
Dinces et al. (2009)	Subject 1: 11.8 years Subject 2: 9.1 years Subject 3: 11.8 years		For all subjects: 1st day of CI use; 1st month of CI use; 3rd months of CI use	English
Ponton et al. (2000) Ponton & Eggermont (2001)	5 – 20 years	After 3.5 years		English

Table 5. Demographic details of the studies reviewed.

With respect to detection of tones, Dinces et al. (2009) investigated this process in three-late implanted children at three time points: during the first day, after the first month, and after 3 months of CI use. Only one out of the three subjects presented the P1 response from the first day of CI use,. Ponton et al. (2000) and Ponton & Eggermont (2001) were able to identify the P1 response in most CI children: its amplitude was larger and its latency was longer in CI as compared to NH children (cf. Figure 11).

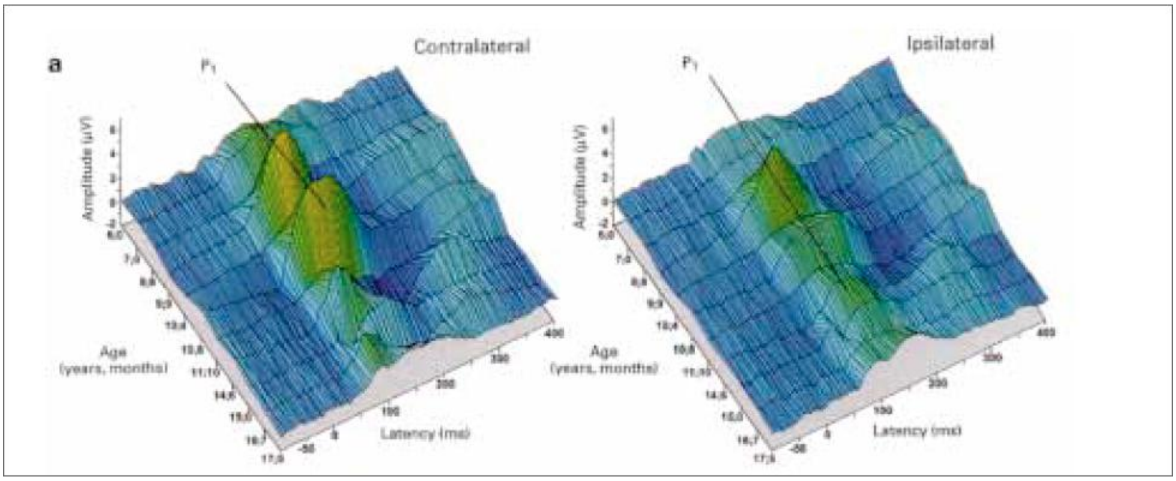

Figure 5 . Surface plots of the AEP waveforms for individual CI children and teens.Standard responses from individual implanted subjects are shown for electrode sites located over the hemisphere contralateral and ipsilateral to the stimulated side.. Figure from Ponton et al. (2000).

As for categorization of tones, Kileny et al. (1997) were able to systematically identify the N1 response. The latency of the N1 peak appeared to fall within the expected latency range, whereas the amplitude of the N1 peak was often reduced than expected. Beynon et al. (2002) managed to identify the N1 response only in those children with better word recognition performance, but not in those with poor word recognition performance. Nevertheless, the N1 latency was relatively long and the N1 amplitude was significantly attenuated in CI as compared to NH children.

With respect to discrimination of non-linguistic sounds, Kileny et al. (1997) detected the MMN and the P3a responses in nearly all the CI children. The latency of the MMN and P3a responses resulted to fall within the expected latency range, whereas their amplitude was often attenuated than expected. Beynon et al. (2002) were able to identify the MMN and the P3b responses only in those children with better word recognition performance, although not systematically. When MMN and P3a were present, their latencies were delayed and their amplitudes were reduced in CI as compared to NH children. Dinces et al. (2009) found that only one out of the three subjects presented the MMN and the P3a responses already from the first day of CI use. However, some differences emerge among the three contrasts. In the case of the duration contrast, the MMN response was present from the first day of CI use, but its latency shortened with the time; the P3a response, on the other hand, emerged starting from the first month of CI use. In the frequency contrast, both MMN and P3 were clearly visible starting from the first month of CI use. In the intensity contrast, only MMN was identified after three months of CI use (cf. Figure 12).

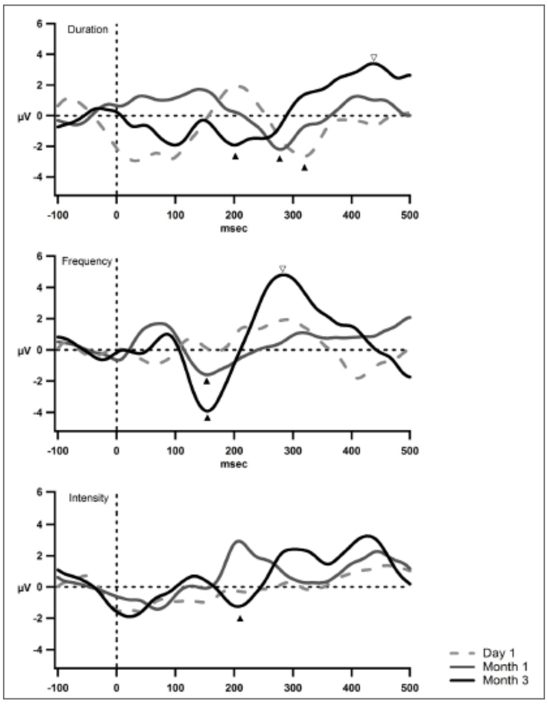

Figure 12. Three graphs at F4 electrode, each with its condition labeled. The three time points are plotted together for each condition as indicated in the legend [Day 1, (dashed gray line) Month 1, (solid gray line) and Month 3 (solid black line]. The duration condition is represented on the top. The frequency condition is in the middle and the intensity condition is on the bottom. The MMN is labeled with the dark up-pointing arrowheads. The P3a is labeled with open down-pointing arrowheads. Figure from Dinces et al. (2009).

Ponton et al. (2000) and Ponton & Eggermont (2001) were able to identify the MMN response in most CI children: its amplitude was larger and its latency was longer in CI as compared to NH children (cf. Figure 13)

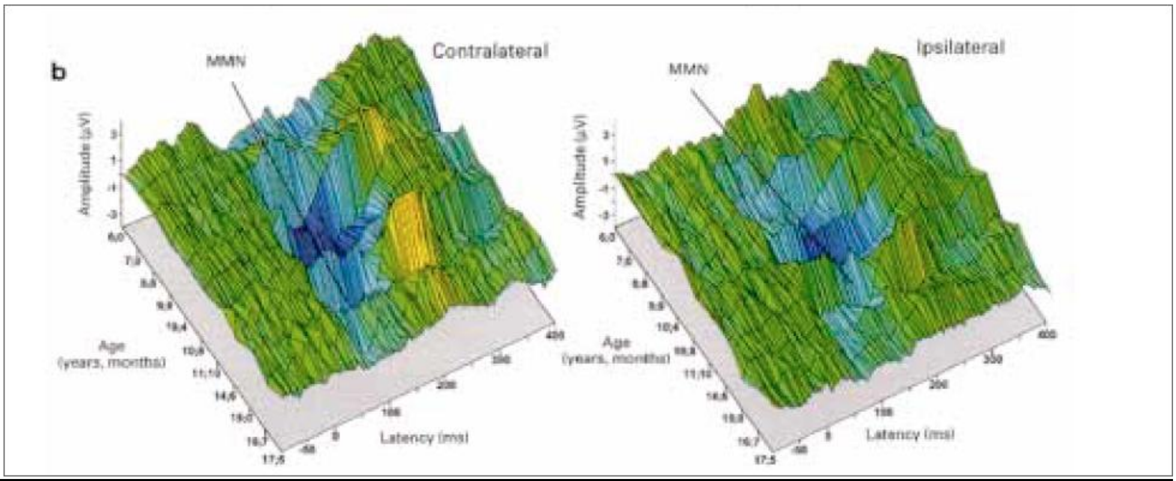

Figure13: Difference waves containing the MMN in CI children. Figure from Ponton et al. (2000).

To resume, the cortical processing of single non-linguistic sounds as well as of pairs of non-linguistic sounds was often delayed and/or less accurate in late-implanted children as compared to NH peers.

3.9 Previous studies exploring auditory processing in Italian pediatric CI users

Few previous studies have investigated auditory processing in Italian CI children. In the following, we will review them. It is worth observing that most studies focusing on auditory processing in CI children exposed to Italian recurred to logopedic measures at the behavioral level (3.9.1), whereas only a few studies relied on neurophysiological measures automatically elicited (3.9.2). Crucially, no studies combined behavioral and neurophysiological measures.

3.9.1 Studies relying on logopedic measures at the behavioral level

To the best of our knowledge, most studies on auditory processing of linguistic and non-linguistic sounds in Italian pediatric CI users recurred to logopedic measures at the behavioral (e.g., conscious) level. Half of them have focused on deaf children implanted later in their lives [cf. Santarelli et al. 2009; Caselli et al. 2012; Scorpecci et al. 2012], whereas the remaining half of them monitored deaf children implanted during the sensitive period of maximal plasticity of the auditory pathways [Colletti et al. 2011; Volpato 2011; Martines et al. 2013].

Scorpecci et al. (2012) investigated music perception (e.g. melody and song identification) in 18 postlingually-deafened children wearing unilateral CI devices, implanted late in their lives (age at surgery range: between 5 and 12 years) and with a CI stimulation experience of at least 12 months, as well as in 23 NH children. Beside music perception, phoneme identification, speech perception, and speech production were monitored as well by recurring to the traditional measures adopted by speech therapists [cf. Zardini et al. 1985; Rustioni 1994; Arslan et al. 1997; Stella et al. 2000]. The main findings of Scorpecci et al. (2012) are the following ones: i) the CI children examined scored below the control children for music (i.e. both melody and song) identification; ii) those CI children benefiting from a longer CI device use were able to identify songs (but not melodies) with a higher accuracy; iii) earlier age at implantation did not facilitate music identification; iv) phoneme identification abilities were significantly correlated with music identification skills in CI children; v) speech perception and production did not correlate with music identification in CI children. The most important finding is that melody and song identification as well as phoneme identification were intercorrelated in CI children, in the sense that if one was defective, the other was defective as well.

Santarelli et al. (2009) explored identification and recognition of disyllabic words as well as identification of vowels in a group of Italian CI children aged 5 to 15 yrs and implanted late in their lives. The particularity of this study is that the children monitored had previously been using the *Sprint/Esprit 3G* speech processors and now are currently using the *Freedom* speech processor. Identification and recognition abilities turned out to be more accurate with the *Freedom* than with the previous generations of speech processors in deaf children.

Caselli et al. (2012) investigated lexical and morphosyntactic skills in comprehension and production in 17 pre-lingually deafened Italian children younger than 6 years and implanted (7 monolateral; 10 bilateral) at a mean age of 54 months (e.g., 4.7 years) as well as in two groups of NH children, the first one matched for chronological age and the second one matched for duration of implant use to CI children. Lexical skills in comprehension and production were evaluated at the behavioral level by recurring to the *Lexical Phonological Test* (cf. Vicari et al. 2007); morphosyntactic skills in comprehension and production were evaluated with the *Grammar Comprehension Test* (cf. Rustioni 2007) and the *Sentence Repetition Task* (cf. Devescovi & Caselli 2007). When comparing CI to NH children, the former were found to score below the latter for lexical and morphosyntactic skills both in production and in comprehension. When comparing children with monolateral vs. bilateral CI devices, the latter showed better lexical and morphosyntactic comprehension, whereas both groups were similar for lexical and morphosyntactic production. Caselli et al. (2012) conclude that even deaf Italian children implanted after the sensitive period for central auditory pathways' maturation are likely to develop good language skills, although some limitations may still remain in comprehension, but not in production. Previous to Caselli et al. (2012), few studies have evaluated the effects of unilateral CI use on language acquisition in deaf Italian children. However, all of them were either case studies (cf. De Iaco et al. 2003) or they included only small groups of late-implanted children with a very wide age range (cf. Bosco et al. 2005; Bortolini et al. 2007).

Martines et al. (2013) threw light on the general auditory abilities as well as the speech intelligibility in a group of pre-lingually deafened children and children deafened before 2 years of age, who underwent CI surgery early in their lives (i.e. before the 3rd year of life) and who had been using their CI for at least 1 year (range: 1 - 4.3 years). The general auditory abilities were investigated with the *Categories of Auditory Performance* [cf. Nikolopoulos et al. 1999] and the *Speech Intelligibility Rating* [cf. Allen et al. 1998]. The logopedic measures were administered during the first 1.6 years in the post-surgery period (i.e., 1, 3, 6, 12, and 18 months). Speech perception and speech intelligibility performance turned out to progressively improve after CI surgery, already after 6 months for 5 children and clearly through the first 12-18 months after surgery for the remaining 11 children.

Colletti et al. (2011) investigated spoken language performance over 10 years in a group of deaf Italian children receiving their unilateral CI between 2 and 11 months. Their performance is compared with two groups of CI children, i.e. a group of deaf children implated between 1 and 2 years and a group of deaf children implanted between 2 and 2.8 years. The auditory abilities have been examined with the *Categories of Auditory Performance* [cf. Nikolopoulos et al. 1999] and the *Infant-Todler Meaningful Auditory Integration Scale* [cf. Kishon-Rabin et al. 2001; Zimmerman et al. 2001]; receptive language has been examined with the *Peabody Picture Vocabulary* [cf. Stella et al. 2000]; understanding of grammatical contrasts in Italian has been evaluated with the *Test of Reception of Grammar* [cf. Bishop 1998]; finally, the speech intelligibility has been measured with the *Speech Intelligibility Rating* [cf. Allen et al. 1998]. Children implanted before the first year of life presented better auditory performance than the other two groups of CI children implanted aferwards. Receptive language of children implanted before the first year of life and the second year of life was comparable to those of NH children matched for age. Receptive language was better in deaf children implanted before the end of the first year of life as compared to the other two groups of deaf children.

Volpato (2011) investigates the production of relative periods by a group of deaf Italian children receiving their unilateral CI early between 1.9 and 3.4 years, and benefiting from a CI stimulation ranging between 4.5 and 8.6 years at testing. A control group matched for age at testing was evaluated as well. The CI children, although being experienced CI users, encountered some difficulties in producing relative periods.

3.9.2 Studies relying on neurophysiological measures at the automatic level

Previous neurophysiological studies on Italian pediatric CI users focused on processing of non-linguistic stimuli, either musical [cf. Vecchiato et al. 2011] or tonal [Burdo et al. 2006] stimuli in deaf children implanted after 3.5 years.

Vecchiato et al. (2011) investigated the pleasantness of music perception in two Italian children affected by acquired SNHL, who underwent CI sugery at ages 8 and 11 years, respectively. The first child received a monolateral CI device, whereas the second child received a bilateral CI device. The pleasantness of music perception was investigated by recurring to variations of particular EEG rhythms correlated with the perceived pleasantness of music. The fruition of music turned out to be statistically higher in the bilaterally implanted child when compared to the monolaterally implanted one.

Burdo et al. (2006) explored the auditory N1 and P2 responses evoked by tones at 500 and 2000 Hz before CI surgery and at the 3rd and 12th months after CI activation in a group of prelingually-deafened Italian children implanted between 3.7 and 8.6 years. The peak latencies of the auditory ERPs decreased in all groups starting from the 3rd through the 12th month after CI activation, thus showing the benefit of hearing restoration.

3.9.3 Gap of previous studies examining auditory processing in Italian CI children

Given the afore-mentioned (cf. 3.9.1 and 3.9.2), we can say that previous studies on the auditory processing in Italian children with unilateral CI devices present the following gaps: i) the general language abilities have been investigated only by recurring to logopedic measures; ii) the auditory processing has been investigated mostly in children implanted late in their lives; iii) the possible role played by age at surgery and/or length of CI use on the general language abilities have not been consistently addressed; iv) behavioral and neurophysiological measures have never been jointly used to monitor detection, categorization, and discrimination of speech sounds in Italian CI children. The present study will try to fill the gap of previous studies on CI children learning Italian.

3.10 Earlier vs. later age at surgery and a sensitive period for the development of the central auditory system

The existence of a sensitive period for the development of the central auditory system in children affected by severe to profound SNHL at the bilateral level has extensively been investigated by Sharma and colleagues [for a review, cf. Sharma & Dorman 2006] by studying the processing of the syllable /ba/.

Sharma et al. (2002a) monitored a group of CI children divided into three subgroups based on their age at surgery: i) children undergoing surgery before 3.5 years were regarded as ‘early-implanted’ children; ii) children undergoing surgery in the age range between 3.5 and 7 years were considered as ‘middle-implanted’ children; and iii) children undergoing surgery after 7 years were labeled as ‘late-implanted’ children. The findings achieved by Sharma et al. (2002a) were the following ones: i) the majority of the early-implanted children had P1 latencies within the normal range appropriate for their age; ii) half of the middle-implanted children presented P1 latencies within the normal age range as compared to their NH peers, whereas the remaining half of them presented delayed P1 latencies of about 100ms when compared with the P1 latencies exhibited by NH children in the same age range; and iii) late-implanted children nearly categorically had delayed P1 latencies of about 100ms than expected (cf. Figure 14 and Figure 15).

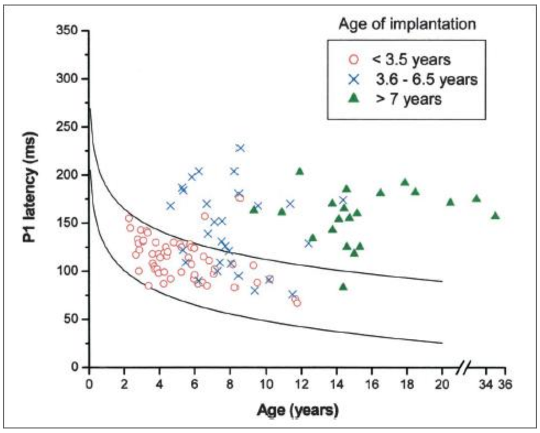

Figure 14. P1 latencies as a function of chronological age for CI children.The solid functions are the 95% confidence limits for NH children. P1 latencies for early-implanted children are shown as circles. P1 latencies for middle-implanted children are shown as crosses. P1 latencies for late-implanted group are shown as triangles. Figure from Sharma et al. (2002a).

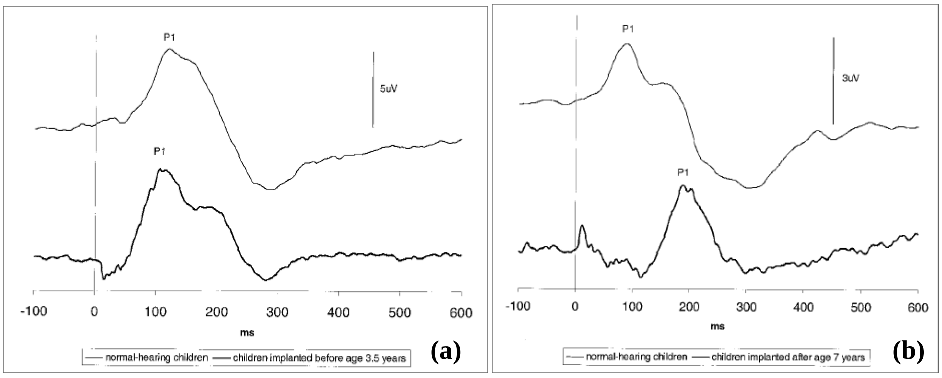

Figure 15. (a) Grand average of the auditory ERPs from a subset of 18 CI children implanted prior to 3.5 years (bottom waveform) and age-matched NH peers (top waveform). (b) Grand average of the ERPs from a subset of 13CI children implanted later than age 7 year (bottom waveform) and age-matched NH peers (to waveform). P1 responses forthe two groups are noted. Figures from Sharma et al. (2002a).

The differences between the early-implanted and the middle-implanted children, as well as the differences between the middle-implanted and the late-implanted children, as compared to NH children demonstrate the existence of a sensitive period up to 3.5 years of age in deaf children affected by SNHL. Middle- and late-implanted children, on the other hand, presented inconsistent outcomes, indicating that there could be additional factors influencing the plasticy of the central auditory system [cf. Sharma et al. 2002a]. Late-implanted children can detect the auditory stimulus (i.e., they hear), but the majority of them are not able to discriminate complex sounds, such as speech sounds, appropriately in everyday situations, even after many years of CI device experience. As a consequence, speech understanding and oral language learning are compromised [cf. Kral & Sharma 2012].

Sharma and colleagues further investigated the influence of the sensitive period on the latency values of P1 in children implanted prior to 3.5 years to cast light on when exactly P1 latency reaches normal limits in CI children. The latency of P1 was found to present normal values in CI children as compared to age-matched NH peers after eight [cf. Sharma et al.

2002b, cf. Figure 16] or even after six [cf. Sharma et al. 2002c, cf. Figure 17] months of CI device stimulation.

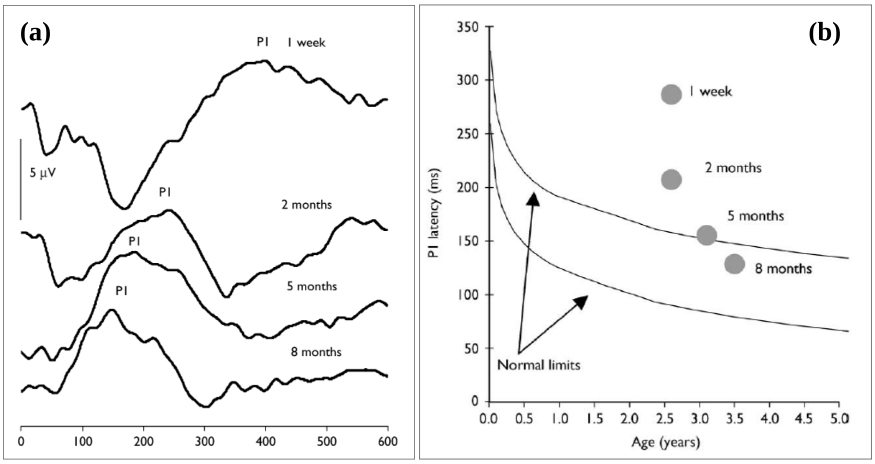

Figure 16. (a) Grand-average ERP waveforms for the four age-matched groups of CI children based on their average duration of CI stimulation (1 week, 2 months, 5 months and 8 months). (b) 95% confidence interval for the normal development of P1 latencie. Superimposed are the mean P1 latencies (circles) from four groups of CI children as a function of their chronological age and based on average duration of CI stimulation (1week, 2 months, 5 months and 8 months). Figures from Sharma et al. (2002b).

The studies by Sharma et al. (2002b, 2002c) provide evidence of minimally degenerated, but still highly plastic central auditory pathways, which are able to overcome a period of auditory deprivation no longer than 3.5 years.

Sharma and colleagues investigated the latency of P1 in children implanted before 3.5 years (the so-called ‘early-implanted’ children) as well as in children implanted after 7 years (the so-called ‘late-implanted’ children) starting from CI activation until the first 18 months of CI use [Sharma et al. 2005a, 2005b]. The ERP waveforms of all congenitally-deaf children were dominated by a large negativity preceding the P1 response (cf. Figure 17). This negativity, whose amplitude decreased as a function of increasing CI stimulation, was similar to the long-latency negative potential seen in pre-term infants before 25 weeks post-conception and it was interpreted as reflecting the lack of stimulation in the auditory system in the pre-implant period. Additionally, the decrease seen in the P1 latency was larger in early-implanted as compared to late-implanted children (cf. Figure 17). In early-implanted children the P1 latency usually reached the normal values observed in age-matched NH peers during the first six months after CI surgery, whereas this did not hold for late-implanted children, whose P1 latency frequently remained atypical until 12 or 18 months of CI stimulation (cf. Figure 17).

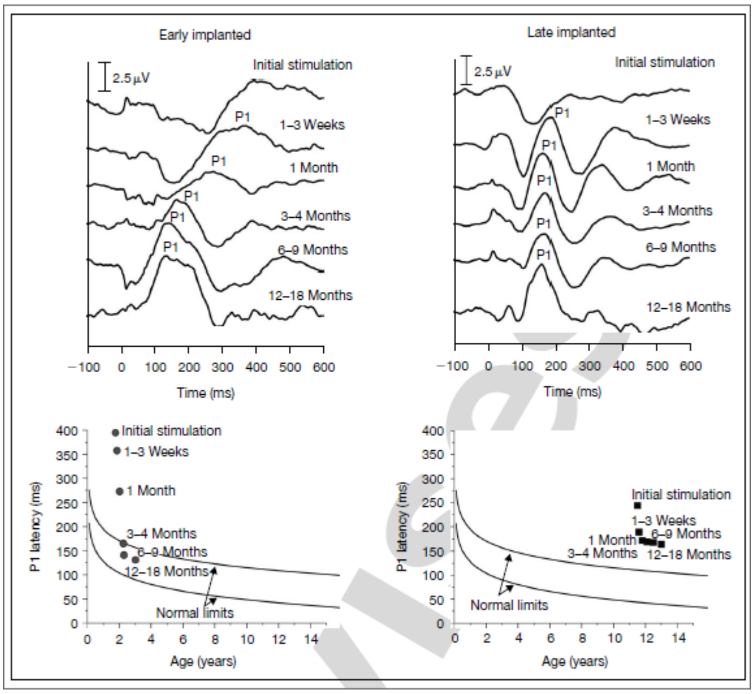

Figure 17. Grand average waveforms and mean developmental trajectories of P1 latency for early- and late-implanted children. The normal limits are 95% confidence intervals. From Sharma et al. (2005b).

In deaf children implanted after 3.5 years, the cortical responses were often abnormal with respect to their prolonged latencies, their reduced amplitudes (cf. Figure 17 above), or because of their polyphasyc morphology (cf. Figure 18). These cortical patterns are usually regarded as the ‘natural’ consequences of a prolonged lack of auditory sensation experienced before CI surgery [cf. Sharma et al. 2009; cf. Sharma & Dorman 2006 for a review].

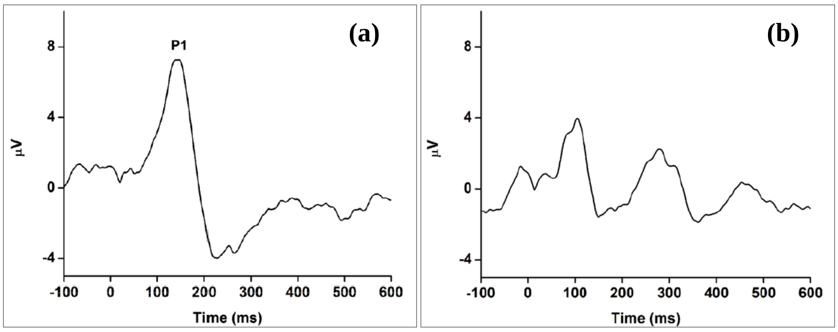

Figure 18: An example of a P1 response in the ERP waveform of an early-implanted child showing age-appropriate morphology and latency (a). An example of an ERP waveform recorded in a late-implanted child whowing evidence from poluphasic morphology (b). Figures from Sharma et al. (2009).

Taken together, the studies by Sharma and colleagues provide evidence in favor of the fact that deaf children implanted before 3.5 years are likely to process speech sounds faster as compared to deaf children implanted after 3.5 years.

3.11 Cortical reorganization in late-implanted children

Development and organization of the sensory pathways in the cortex is crucially dependent on sensory experience. A lack of sensory input, such as deafness, impedes the normal growth and early connectivity needed to form a functional sensory system [cf. Wuesel & Hubel 1965; Knudsen 2004].

Successful rehabilitation of CI users depends not only on the manner in which the acoustic-phonetic cues are delivered by the CI (cf. 3.5), but also on the status of the peripheral and central auditory system, as well as by manner on which acoustic-phonetic cues are encoded in the normal or altered auditory pathways. Indeed, under conditions of deprivation, a circuit is never activated or never activated strongly, depending on the degree of deprivation. Crucially, deprivation usually leads to consolidation of highly abnormal circuit connectivity and the neurons begin to respond to abnormal patterns of input that otherwise would have been too weak to drive the circuit [cf. Knudsen 2004 and references cited therein]. As a consequence, even in case all acoustic cues are preserved by CI stimulation, perception is still dependent on cross-modal reorganization in the auditory cortex as well as by the integrity of the peripheral and central auditory system. For this reason, it is important to understand how impaired peripheral and central auditory mechanisms alter the transduction and the processing of speech sounds [cf. Souza & Tremblay 2006].

Visual stimuli were found to activate the auditory cortices in deaf adults, both in the case of signers [cf. Finney et al. 2001] and in the case of post-lingually deafened CI users [cf. Sandmann et al. 2012]. These studies provided ERP evidence that auditory deprivation induces partial to total reorganization of the auditory cortices. As a consequence, the deafferented auditory areas were more extensively recruited to process sensory inputs other than audition.

In pediatric CI users, deprivation-induced cortical reorganization has been investigated by Gilley et al. (2008) and Sharma et al. (2009), always by recurring to the syllable /ba/. For a review, cf. Sharma et al. (2007).

Gilley et al. (2008) investigated the activation of brain areas in a group of children implanted prior to 3.5 years (e.g., the so-called ‘early-implanted’ children) and in a group of children implanted in the age range between 5 and 9.8 years (e.g., the so-called ‘late-implanted’ children) as compared to a group of NH children matched for biological age to the CI children (mean age at testing was 10.5 years). The patterns of activation found by Gilley et al. (2008) are presented in Figure 19.

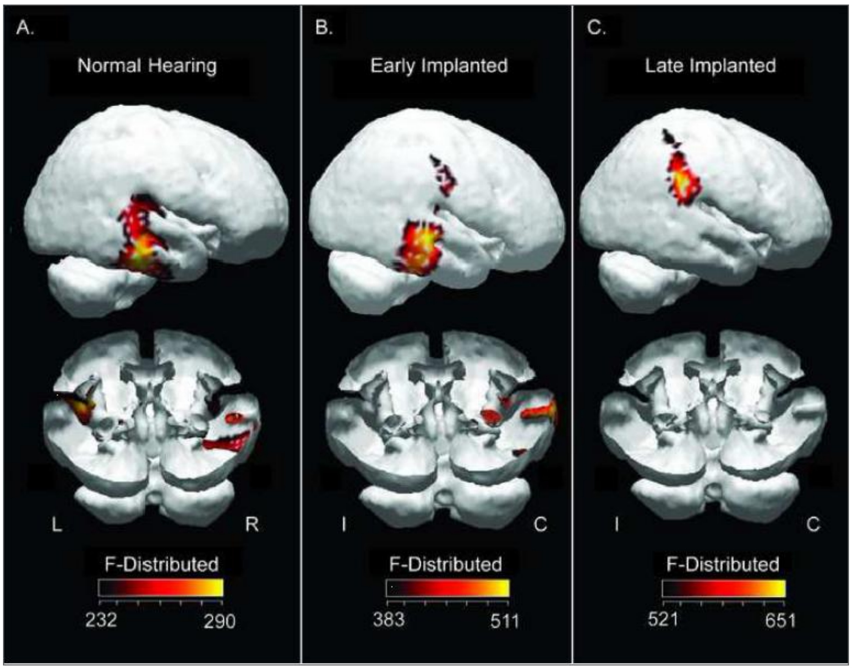

Figure 19. Current density reconstructions of the P1 cortical auditory evoked potential projected to the cortical surface in **A)** normal hearing children, **B)** early implanted children, and **C)** late implanted children. Activity is represented as a normalized probability of cortical activity from the inverse solution; a distributed *F*-value. *F*-distribution values are labeled in the color bar for each group. Deep layer activity at the superior temporal sulcus in normal hearing and early-implanted children is not visible in the surface projections, but can be seen in the cut-plane slices of temporal cortex in the lower panel of each figure section. Electrode positions for children with a right implant were mirrored on the scalp for visualization of contralateral sources. Figure from Gilley et al. (2008).

As expected, the NH children showed bilateral activation of the auditory cortical areas (e.g., superior temporal sulcus and inferior temporal gyrus). Children who received their unilateral CI device prior to 3.5 years showed activation of the auditory cortical areas contralateral to their CI device. Brain area activation in early-implanted children resembled that of normal hearing subjects, for the most part, with additional activation localized to the anterior parietotemporal cortex. Children who received their unilateral CI device after 3.5 years showed activation outside the auditory cortical areas (e.g., visual, insula and parietotemporal areas). Similar patterns were also found in an early-implanted child and in a late-implanted child by Sharma et al. (2009).

Since the generators of early ERP components include input from intracortical and intercortical recurrent activity between primary auditory and association areas, then abnormal presence or the absence of auditory cortical activity in the late-implanted children is assumed to suggest absent or weak connections between primary and association areas, and subsequently, weak feedback activity to thalamic areas [cf. Gilley et al. 2008; Sharma et al. 2009]. These results are consistent with the decoupling hypothesis (cf. Kral et al. 2005) which suggests that a functional disconnection between the primary and higher order cortex underlies the end of the sensitive period in congenitally deaf cats, and presumably, in congenitally deaf, late-implanted children as well.

To sum up, if CI surgery occurs outside the sensitive period, auditory deprivation induces partial to total reorganization of the auditory cortex, and the deafferented auditory areas are more extensively recruited to process sensory inputs other than audition. Reorganized auditory pathways may explain why CI device efficacy is low in many congenitally-deaf or prelingually-deafened children.

3.12 The effect of duration of CI stimulation on the ERP values of CI children

A few among the above-mentioned ERP studies explored whether deaf children who are benefiting from longer periods of CI stimulation manage to process speech sounds faster and more accurately at the cortical level as compared to deaf children benefiting from a shorter duration of CI stimulation.

In the case of children implanted before 3.5 years, the P1 response was found to peak earlier and with enhanced amplitude in CI children who had been using their CI for at least 5 years [cf. Torppa et al. 2013]. Likewise, the MMN response appeared to peak earlier and with enhanced amplitude in CI children who had been using their CI for at least 5 years [cf. Torppa et al. 2013] or 6 years [cf. Ortmann et al. 2013].

In the case of children implanted after 3.5 years, the P1 response was found to peak earlier in those children who had been using their CI for a longer period, but this ‘longer period’ is not better explained [cf. Singh et al. 2004]. The amplitude of P1, on the other hand, appeared insensitive to the duration of CI stimulation [cf. Singh et al. 2004]. Finally, the N1 latency become shorter after 12 months of CI stimulation [cf. Burdo et al. 2006].

3.13 The vowel spaces of CI users

As compared to consonants, vowels are mastered earlier by CI children: vowels are acquired earlier and more accurately than diphthongs and consonants and their production improves relatively soon after CI surgery, thus suggesting the relative ease of production of vowels as compared to other classes of speech sounds [cf. Serry & Blamey 1999; Blamey et al. 2001; Van Lierde et al. 2005; Horga & Liker 2006].

The first two formants are of crucial importance for vowel categorization: F1 values relate to tongue body height, whereas F2 values relate to tongue body place of articulation during vowel production. Building on F1 and F2, a listener is able to identify specific vowels (cf. Lindblom & Sundberg 1971; Kent 1997; Stevens 1999; Ladefoged 2001b). Vowel spaces, both in perception and production, are based on the frequencies of F1 and F2.

Perception and production of speech sounds in CI users, and especially in those prelingually deafened, is characterized by deficits in the perception as well as in the production of speech sounds [cf. Smith 1975]. In the case of CI users, analyzing the vowel spaces in perception and production is of crucial importance to better understand how effective is the stimulation delivered by the unilateral CI device. The size of vowel spaces provides information on how large is the F1-F2 plane covered by the vowel categories, whereas their shape and their internal arrangement provides information on whether or not CI users have mastered the relationship among vowels for place and height within the vowel space [cf. Harnsberger et al. 2001; Löfqvist et al. 2010].

Electrical hearing as provided by a CI device is quite different from normal acoustic hearing (cf. discussion in 3.5). One important difference lies in the listeners’ ability to perceive and discriminate formant frequencies, such as F1 and F2. In CI users, this ability depends on two factors: the frequency-to-electrode map that is programmed into the CI’s speech processor as well as the individual’s ability to discriminate stimulation pulses delivered to different electrodes. For CI users, it is not uncommon that they have formant frequency difference limens that are one order of magnitude larger than those of NH listeners, or even more [cf. Watson 1994; Nelson et al. 1995; Kewley-Port & Zeng 1998]. Having limited frequency discrimination skills, CI users are likely to find it quite difficult to identify vowels accurately during perception [cf. Harnsberger et al. 2001 for adult CI users] and to further produce them accurately [cf. Lane et al. 2001; Schenk et al. 2003; Ménard et al. 2007; Neumayer et al. 2010 for adult CI users; cf. Löfqvist et al. 2010 and Neumayer et al. 2010 for adolescent CI users; cf. Horga & Liker 2006; Liker et al. 2007; Baudonck et al. 2011 for pediatric CI users] , although not regularly [cf. Uchanski & Geers 2003; Campisi et al. 2006]. In the following, we will first deal with vowel spaces in perception (cf. 3.13.1) and then with vowel spaces in production (cf. 3.13.2) in CI users.

3.13.1 Vowel spaces in perception

NH individuals use fine-grained phonetic variation, such as formant frequencies, movements, and duration in order to recognize native vowels. It is widely aknowledged that CI users differ in their ability to perceive, correctly identify and discriminate speech sounds. Harnsberger et al. [2001] investigated the perceptual vowel spaces of postlingually deafened adults exposed to English.

As compared to the perceptual vowel spaces of NH listeners (cf. Figure 20a), the perceptual vowel spaces of CI users were found to differ for the sizes of the perceptual categories, their degree of overlap, and the region of perceptual space that particular categories occupy (cf. Figure 20b and Figure 20c). In CI users, the perceptual vowel spaces hardly ever consisted of vowel categories that overlap very little and that appeared to be in roughly the same (e.g., normal) regions in perceptual space as those obtained from NH listeners (Figure 20b). Most frequently, the perceptual vowel spaces of CI users were reduced (e.g., smaller), compressed (e.g., vowel categories were condensed in a portion of vowel space), and centeralized (e.g., vowel categories were condensed in the central region of the F1/F2 plane), and with a great deal of overlap between front and back vowels (cf. Figure 20c) [cf. Harnsberger et al. 2001].

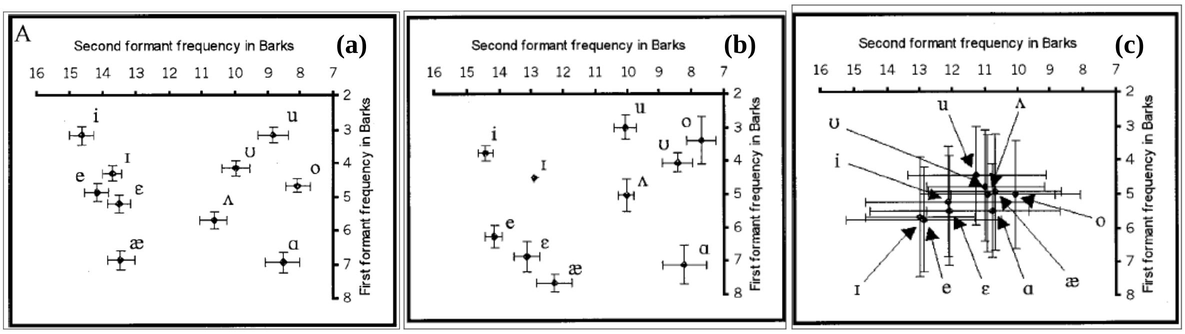

Figure 20: (a) The mean perceptual vowel space of 43 NH listeners, calculated using all the ratings provided. (b) Example of a "nearly normal" perceptual vowel space of a CI user, with vowel categories appearing in roughly the same regions as NH listeners and with little overlap. (c) Example of a compressed, and centered perceptual vowel space of a CI user, with a great deal of overlap among vowel categories. Figures from Harnsberger et al. (2001: 2142).

As far as vowel categorization in adult CI users is concerned, Harnsberger et al. [2001] claim that reduced or impaired vowel categorization in CI users depends on the reduced formant frequency discrimination as well as on the arrangement of the vowel categories in the perceptual space [Figure 20b vs. Figure 20c]. With respect to vowel discrimination in adult CI users, Harnsberger et al. [2001] hypothesized that reduced or impaired vowel discrimination in CI users depend on the size of the vowel categories as well as on their overlap within the acoustic space [Figure 20b vs. Figure 20c].

To the best of our knowledge, there are no studies investigating the perceptual vowel spaces in pediatric CI users. Hence, we can not address this issue in CI children.

3.13.2 Vowel spaces in production

Even though CI devices primarily facilitate speech perception, they play a crucial importance in speech quality and speech production [cf. Tye-Murray et al. 1995; Allen et al. 1998; Serry & Blamey 1999; Van Lierde et al. 2005]. The vowel spaces of CI users in production have been investigated more extensively as compared to the vowel spaces in perception (cf. 3.13.1). The vowel spaces of CI users in production have been investigated for adult [cf. Lane et al. 2001; Schenk et al. 2003; Ménard et al. 2007; Neumayer et al. 2010], adolescent [cf. Löfqvist et al. 2010; Neumayer et al. 2010], and pediatric [cf. Horga & Liker 2006; Liker et al. 2007; Baudonck et al. 2011] CI users.

When compared to NH listeners, CI users typically show a smaller (e.g., with reduced F1/F2 place), compressed (e.g., with vowel phonemes concentrated on a relatively small region of the F1/F2 plane), and fronted (e.g. with higher F2 values as expected) vowel space (cf. Figure 21 and Figure 22). This holds for adult [cf. Schenk et al. 2003; Neumayer et al. 2010], adolescent [cf. Löfqvist et al. 2010; Neumayer et al. 2010], and pediatric [cf. Horga & Liker 2006; Liker et al. 2007; Baudonck et al. 2011] CI users.

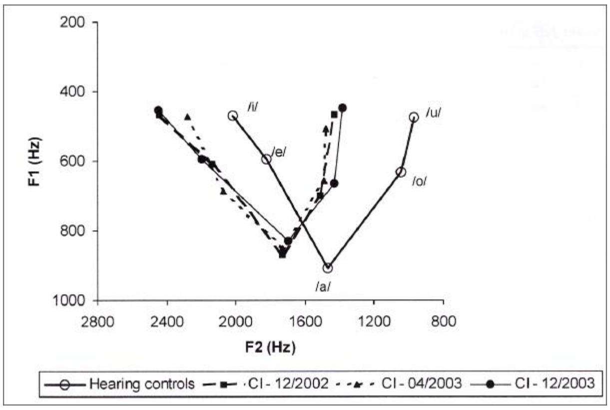

Figure 21: The vowel space of NH children (bold lines) and CI children during 3 testing sessions (dotted lines). Figure adapted by Liker et al. (2007).

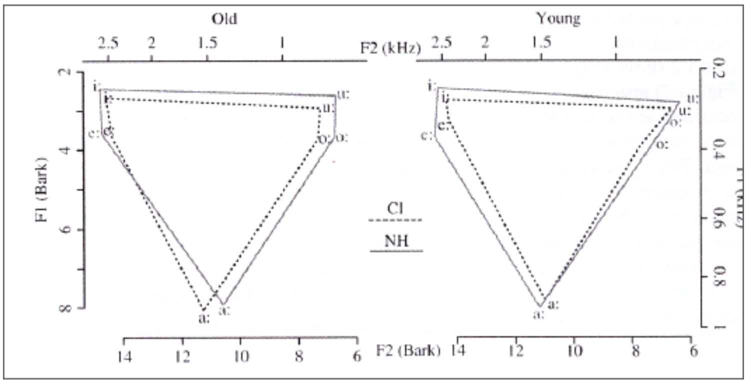

Figure 22: The vowel space of younger and older NH adults (bold lines) and CI adults (dotted lines). Figure adapted by Neumeyer et al. (2010).

All these studies hypothesize that the reduced and degraded auditory feedback provided by CI devices is likely to be the source for the reduced, compressed, and fronted vowel space in production by CI users. Additionally, a smaller vowel space along the F1/F2 plane is likely to indicate a more close artculation [cf. Lane et al. 2001; Schenk et al. 2003; Horga & Liker 2006; Liker et al. 2007; Ménard et al. 2007; Löfqvist et al. 2010; Neumayer et al. 2010].

When comparing the vowels spaces of CI and NH listeners, differences in the F2, but not in the F1, values were systematically found.[5] Neumeyer et al. [2010] found that the distance in F2 values between the Croatian front vowels /i:/ and /e:/ as well as between the back vowels /o:/ and /u:/ was shorter in all CI users as compared to NH listeners. The distance in F1 values among the five Croatian vowels /i:, e:, a:, o:, u:/, on the other hand, was comparable in CI users and NH adults [cf. Neumeyer et al. 2010]. From the study by Liker et al. [2007] emerged that fronting was more pronounced for the Croatian back vowels /u/ and /o/ as well the Croatian central vowel /a/ than for the front vowels /i/ and /e/.

When looking at the individual vowels, different problems emerge. With respect to the vowel /a/, it is found to present a lower F1 value and a higher F2 value in CI as compared to NH listeners, thus suggesting that /a/ is higher and more fronted in CI vs. NH listeners and it results not perfectly intelligibile [cf. Horga & Liker 2006; Liker et al. 2007]. The vowels /e/ and /o/, on the other hand, present a higher F1 value and a higher F2 vales and they henceforth resulted lowered and more fronted in CI as compared to NH children [cf. Liker et al. 2007]. Along the lines of Tobey et al. (1996), Liker et al. (2007) hypothesize that the mid vowels /e/ and /o/ are more difficult for CI children to produce correctly with respect to the high and low ones (e.g., /i, u, a/) which, indeed, act as corner vowels and, henceforth, define the vowel space size .

The above-mentioned studies explain the fact that clear difference were found between CI and NH listeners for F2, but not for F1, values by recurring to the relationship between acoustics and articulation, which is more transparent for F1 than for F2 values (Lindblom & Sundberg 1971). As far as F1 is concerned, F1 changes at the acoustic level are mirrored in jaw and tongue movements at the articulatory level: lowering of the jaw and of the tongue body for height result in an increase in F1 values, whereas raising of the jaw and of the tongue body give raise to a decrease in F1 values. Now, the tongue is largely hidden from the view, whereas the jaw is clearly visible. Except for the tongue body movements concerning height, the lowering of the jaw represents a clearly visible articulatory cue which can be learned by CI users, who can henceforth infer vowel height from the jaw lowering vs. raising. With respect to F2, F2 changes at the acoustic level correspond to tongue body movements for place as well as to lip configurations at the articulatory level: tongue body fronting and lip unrounding give rise to an increase in F2, whereas tongue body backing and lip rounding result in a decrease in F2 values. If the tongue is largely hidden from the view, the lip configuration is clearly visible and CI users can infer vowel place from lip (un)rounding. Previous studies have implicitly considered the jaw movements (opening vs. closing) as a more salient visual cue as compared to the lip configuration (rounded vs. unrounded) and, for this reason, relationship between acoustics and articulation has been said to be more transparent for F1 and less transparent for F2 values [cf. Lindblom & Sundberg 1971]. Additionally, Liker et al. (2007) account for the fronting of the vowel space in CI users by

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[5] An exception is represented by Uchanski & Geers (2003) and by Campisi et al. (2006) which do not acknowledge difference in the F1/F2 values as well as in the configuration of the vowel space between CI and NH listeners.

recurring to the tendency of speech therapists, family, and CI users themselves to move the vowel articulation to where it is more visible, that is to shift it towards the front of the mouth, especially during the first 2 years after the surgery [cf. Välimaa et al. 2002a].

Thanks to CI stimulation, the vowel spaces in production of CI users tend to increase (e.g., to expand the F1/F2 plane with respect to the pre-surgery period) and to become less fronted (e.g., to move backwards by means of reduction of F2 values) in adults [cf. Lane et al. 2001; Ménard et al. 2007], adolescent [cf. Löfqvist et al. 2010; Neumeyer et al. 2010], and pediatric [cf. Horga & Liker 2006; Liker et al. 2007] CI users, starting from one year after regular CI use. This means that, after one year of regular CI use, the F1 and F2 values of CI users tend to shift closer to those of NH listeners. However, this does not happen regularly [cf. Kishon-Rabin et al. 1999].

3.13.3 Final remarks

To sum up, the incomplete perception of the acoustic-phonetic features (e.g., the formant values, especially F1 and F2, which are of crucial importance for vowel categorization, cf. 3.5) of vowels in CI users usually leads them to develop acoustic vowel spaces which are reduced (e.g., compressed (e.g., with vowel phonemes concentrated on a relatively small region of the F1/F2 plane), and fronted (e.g., with higher F2 values) as expected, both in perception and in production.

3.14 Chapter summary

After presenting the different degrees of hearing loss, SNHL, CI devices, electrical hearing, as well as sensitive periods for brain and behavior, this chapter reviews previous studies on CI users. The processing of linguistic and non-linguistic sounds has been investigated both in early-implanted and in late-implanted children. ERP latencies were often shorter and ERP amplitudes were typically attenuated in all CI children as compared to NH children as well as in late-implanted children relative to early-implanted children. The effect of age at surgery on the ERP values was monitored as well. In early-implanted children the ERP latency was found to reach the normal values after 6 to 8 months of CI use, whereas normal ERP values are hardly ever achieved by late-implanted children. The abnormal ERP waveform in late-implanted children is explained by cortical reorganization. The vowel spaces of CI users tend to be reduced, compressed, and more fronted as expected, both in perception and in production.

CHAPTER 4

Subjects, materials, and methods

4.1 Introduction

This chapter widely discusses and justifies the methodology adopted throughout the study. First of all, the methodological innovations adopted in the present study are presented (cf. 4.2), followed by the pediatric subjects (e.g., CI users and controls) selected (cf. 4.3) as well as by the auditory speech stimuli elicited, prepared, selected, and adopted (cf. 4.4). Then, the behavioral (cf. 4.5) and the neurophysiological (cf. 4.6) experiments are discussed in great detail, together with the decision to combine behavioral and neurophysiological measures to investigate auditory processing of speech sounds in pediatric CI users exposed to Italian (cf. 4.7). A summary closes this chapter (cf. 4.8)

4.2 Methodological innovations of the study

As discussed in 3.8, previous ERP studies investigated the processing of single speech sounds as well as of pairs of speech sounds, both consonants and vowels, at the cortical level in CI children learning English, German, Finnish, Hebrew, Croatian, and Finnish. Out of these studies, some focused on early-implanted [cf. Munivrana & Mildner 2013; Ortmann et al. 2013], while others focused on late-implanted [cf. Kileny et al. 1997; Beynon et al. 2002; Singh et al. 2004; Henkin et al. 2008] children, or even on both early- and late-implanted children [cf. Sharma et al. 2002abc, 2005, 2007; 2009; Gilley et al. 2008].

Despite achieving some interesting and crucial findings about cortical processing of speech sounds in CI children, these studies present some methodological limitations. First, they usually rely on (semi)synthetic stimuli [for exceptions, see Kileny et al. 1997; Henkin et al. 2008; Ortmann et al. 2013]. Second, they recurred only to neurophysiological measures, without combining them with behavioral measures [for a notable exception, see Ortmann et al. 2013]. Rather, a few previous studies combined neurophysiological measures of speech sound processing with logopedic measures evaluating the general auditory abilities and the speech intelligibility of CI children [Beynon et al. 2002, Singh et al. 2004, Henkin et al. 2008].

As compared to the above-mentioned ERP studies, the present study introduces two methodological innovations. First, following previous studies [cf. Munro et al. 1996; Guion et al. 2000; Flege et al. 2004; Tsukada et al. 2005; Scharinger et al. 2012], it relies on natural speech stimuli, only minimally normalized. It has to be kept in mind that, although semisynthetic speech stimuli present the advantage of being more homogeneous, more controlled, and easier or faster to prepare as compared to natural stimuli, the former represent only an approximation of natural speech, whereas only the use of the latter may lead to genuine inferences regarding speech sound processing in CI children at the cortical level [cf. Sharma & Dorman 2000; Davids et al. 2011]. Second, along the lines of Sharma & Dorman (2000), the present study combines the use of behavioral measures (e.g., tests of categorization and discrimination of speech sounds, administered attentively) with the use of neurophysiological measures (e.g., the EEG recording for subsequent extraction of the auditory ERPs). By combining behavioral and neurophysiological measures, the present study aims at achieving a more complete picture on vowel processing in Italian CI children.

4.3 Pediatric subjects

Vowel processing was investigated in eight children (6 males) affected by congenital, bilateral, and severe-to-profound SNHL at the level of the cochlea, all wearing unilateral CI devices (7 right). The mean ge at surgery was 2.8 years (range = 2.1 — 4.4 years; s.d. ± 0.9 months); the mean age at testing was 9.1 years (range = 6.7 — 10.7 years; s.d. ± 1.8 years); the mean duration of CI use at testing was 6.3 years (range = 2.4 — 8.1 years; s.d. ± 2.11 years). All the CI children had hearing impairment > 70 dB / SPL at 250Hz and they were using the models *Nucleus 22* or *24,* with linguistic processors *CP810* or *Freedom*, all produced by *Cochlear Italia*.

Seven out of the CI children examined received their unilateral CI during the sensitive period for central auditory pathway maturation, which appears to be of about 3.5years [cf. Sharma A. et al. 2002abc; Sharma A. & Dorman 2006; Gilley et al. 2008; Bishof 2007], and may therefore be regarded as early-implanted children, whereas one child received its unilateral CI later at 4.6 years, and may thus be considered as a late-implanted child. Given that, with one exception, the children participating to the study received their CI devices early in their lives, we will consider the results of the present study as representative for early-implanted Italian children. It is worth mentioning that the CI children selected did not have additional diagnosed developmental, neurological, or linguistic problems. Additionally, all CI children had been consistently using bilateral hearing aids prior to CI surgery as well as six out of the eight CI children examined used to wear an hearing aid in the contralateral, non-implanted ear in everyday life. All the CI children selected were attending a clinical follow-up and oral linguistic rehabilitation at the Ear, Neck, and Throat (ENT) department of the Lecce Hospital.

The control group consisted of nine normal-hearing NH children matched for biological age at testing with the CI children (7 females; mean age at testing = 7.6 years, range= 4.3— 10.9 years, s.d. ± 2.2 years).

Both CI and NH children were right-handed [cf. Oldfield 1971], had normal (n = 14) or corrected-to-normal (n = 3) vision, and they were living in the province of Lecce (Salento, Southern Apulia, Italy). They were exposed to the local dialect and to Italian at home as well as to Italian and English at school. All children were screened for pre- or postnatal difficulties, including prematurity [cf. Lavoie et al. 1998; Bisiacchi et al. 2009; Mento et al. 2010], as well as for iron deficiency [cf. deRegnier et al. 2000], since these factors are thought to be likely to influence the ERP values.

All parents signed the informed consent in accordance with the Declaration of Helsinki. The study, which is in accordance with the latest version of the Good Clinical Practice, was approved by the Ethical Committee of the Lecce Local Sanitary Institution (ASL) in May 2011. Detailed subject information about the children is provided in Table 1 and Table 2.

	Sex	Prior hearing experience	Age at surgery[6]	Age at testing	Duration of CI use	CI type	CI processor	Implanted ear
CI1	F	Bilateral hearing aids	4.5	6.2	1.9	Nucleus 24	Freedom	Right
CI2	M		2.1	6.11	4.10	Nucleus 24	Freedom	Right
CI3	M		2.1	7.5	5.5	Nucleus 22	Freedom	Left
CI4	M		2.10	9.6	6.4	Nucleus 22	Freedom	Right
CI5	M		1.9	9.6	7.8	Nucleus 24	Freedom	Right
CI6	M		3.8	10.8	7	Nucleus 22	Freedom	Right
CI7	M		2.8	10.9	8	Nucleus 22	CP810	Right
CI8	F		2.8	10.9	8	Nucleus 22	CP810	Right
Mean values			2.8 ± 0.9	9.1 ± 1.8	6.3 ± 2.11	-	-	-

Table 1: CI children demographics.

	Sex	Age at testing
NH1	F	4.3
NH2	M	5.2
NH3	M	5.3
NH4	F	7.5
NH5	F	7.11
NH6	F	8.3
NH7	F	8.9
NH8	F	10.8
Mean values		7.6 ± 2.2

Table 2: NH children demographics.

Following Singh et al. (2004), prior to participation to the study, the auditory and speech intelligibility performance of the enrolled CI children were assessed by recurring to the *Category of Auditory Performance* test [cf. Nikolopoulos et al. 1999] and the *Speech Intelligibility Rating* test [cf. Allen et al. 1998], respectively. Altogether, the eight CI children selected appeared to exhibit good general auditory abilities (cf. Table 3) and speech intelligibility performance (cf. Table 4).

Level	Categories of Auditory Performance	CI children involved
0	No awareness of environmental sounds.	0
1	Awareness of environmental sounds.	0
2	Response to speech sounds (e.g., *go*).	0
3	Identification of environmental sounds.	0
4	Discrimination of speech sounds.	0
5	Understand common phrases, no lipreading.	**2**
6	Understand conversation, no lipreading.	**3**
7	Use of telephone with known speakers.	**3**

Table 3. Category of Auditory Performance Criteria.

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[6] Age is expressed in years.months.

Level	Speech Intelligibility Rating	CI children involved
1	Connected speech is unintelligible. Precognizable words in spoken language.	0
2	Connected speech is unintelligible. Intelligible speech is developing in single words when context and lipreading cues are available.	0
3	Connected speech is intelligibile to a listener who concentrates and lipreads.	0
4	Connected speech is intelligibile to a listener who has a little experience of a deaf person’s speech.	**4**
5	Connected speech is intelligibile to all listeners. Child is understood easily in everyday contexts.	**4**

Table 4. Speech Intelligibility Rating Criteria.

To round off this section, we would like to conclude that, from the point of view of the general auditory abilities and the speech intelligibility, the eight CI children selected may be considered as good performers.

4.4 Speech stimuli

With respect to the auditory vowel stimuli administered to CI and NH children, we will discuss their elicitation (cf. 4.4.1), their acoustic (cf. 4.4.2) and articulatory (cf. 4.4.3) characteristics as well as their phonological specification (cf. 4.4.4). Afterwards, we will concentrate on the six vowel pairs selected (cf. 4.4.5). Finally, we will address the normalization of the elicited vowels (cf. 4.4.6) and then the rating of the normalized vowels as genuine exemplars of the intended phonetic categories by Italian NH adults (cf. 4.4.7).

4.4.1 Elicitation of the Salento Italian vowels

Standard Italian has seven vowels: two high vowels (e.g., /i/ and /u/), two mid-high vowels (e.g., /e/ and /o/), two mid-low vowels (e.g., /ɛ/ and /ɔ/), and one low vowel (e.g., /a/). All of them appear in stressed position, whereas just five vowels are to be found in unstressed position, i.e. /a, e, i, o, u/ [cf. Vincent 1998; Bertinetto & Loporcaro 2005]. Contrary to Standard Italian, Italian as spoken in the province of Lecce (e.g., in Central Salento) has just five vowels appearing both in stressed and unstressed position: two high vowels (e.g., /i/ and /u/), two mid-low vowels (e.g., /ɛ/ and /ɔ/), and one low vowel (e.g., /a/). From now on, we will refer to the five Central Salento Italian vowels as the ‘Salento Italian vowels’.

As pointed out in 4.2, previous studies monitoring the auditory processing of speech stimuli in CI users (cf. 3.8), usually recurred to (semi)synthethic [cf. Beynon et al., 2002; Sharma, A. et al., 2002b, 2005b, 2007a; 2009; Gilley et al., 2008; Munivrana & Mildner 2013], rather than to natural speech [cf. Kileny et al. 1997; Henkin et al. 2008; Ortmann et al. 2013] stimuli. Although semisynthetic speech stimuli present the advantage of being more homogeneous, more controlled, and easier or faster to prepare as compared to natural stimuli, the former represent only an approximation of natural speech, whereas only the use of the latter may lead to genuine inferences regarding speech sound processing in individuals at the cortical level [cf. Sharma, A. & Dorman 2000; Davids et al. 2011]. It is for this reason that, along the lines of Sharma, A. & Dorman (2000) and Davids et al. (2011), we decided to confront the children participating to the present study with naturally produced vowel stimuli.

A male speaker of Salento Italian aged 33 years produced 50 isolated vowels (10 repetitions for each vowel phoneme) in the *CRIL* soundproof room. The speech signal was first recorded with *CSL 4500* (sampling rate = 44.1kHz, amplitude resolution = 16 bits) and a *Shure SM58-LCE* microphone and then stored on a laptop for further analysis. The following section deals with the acoustic characteristics of the elicited vowels.

4.4.2 Acoustic characteristics of the Salento Italian vowels

The elicited vowel phonemes were segmented and analyzed acoustically with *Praat 5.3.51* [cf. Boersma & Weenink 2013]. The mean total duration (in ms) and the mean values of the first (F1) and second (F2) formants (in Hz) in the vowel steady tract (0.050s centered at the midpoint) of the elicited vowels are presented in Table 5.

	Mean values (± s.d.) of		
Phonemes	Duration (ms)	F1 (Hz)	F2 (Hz)
/i/	300 (± 44)	268 (± 35)	2333 (± 35)
/u/	299 (± 31)	308 (± 23)	665 (± 22)
/ɛ/	306 (± 39)	539 (± 27)	1890 (± 41)
/ɔ/	304 (± 27)	573 (± 15)	846 (±17)
/a/	296 (± 45)	805 (± 34)	1212 (± 23)

Table 5: Mean acoustic phonetic values (± s.d.) of the vowels elicited.

The first two formants are of crucial importance for vowel categorization [cf. Lindblom & Sundberg 1971; Kent 1997; Stevens 1999]: the F1 values relate to tongue body height, whereas the F2 values relate to tongue body place of articulation during vowel production. High vowels (e.g., /u/ and /i/) are characterized by lower F1 values as compared to mid (e.g., /ɛ/ and /ɔ/) and low (e.g., /a/) vowels, whereas front vowels (e.g., /ɛ/ and /i/) are characterized by higher F2 values as compared to non-front vowels (cf. /a/, /ɔ/, and /u/), as can be seen in Table 5 above. Additionally, front vowels (e.g., /i/ and /ɛ/) exhibit a larger distances between the first two spectral peaks as compared to non-front vowels (e.g., /u/, /ɔ/, and /a/), as can be seen in Table 5 above. It is worth observing that the formant values presented in Table 5 above for vowels as spoken in Salento Italian are in agreement with those found in previous studies investigating the vowel system of some dialectal varieties spoken in Southern Salento [cf. Grimaldi 2009; Grimaldi et al. 2010, 2011] and in Central Salento [cf. Garrapa 2005].

When comparing the formant values of the Salento Italian vowels in Table 5 above with those found by Albano Leoni & Maturi (2001: 106)[7] and by Ferrero et al. (1978)[8] for Italian vowels as well as with those of Grimaldi (2009) and Grimaldi et al. (2010, 2011)[9] for dialectal vowels, it is clear that Central Salento Italian “e” and “o” are realized as mid-low vowels (/e.g., ɛ/ and /ɔ/), rather than as mid-high vowels (e.g., /e/ and /o/), cf. also Figure 1.

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[7] The vowel phonemes analyzed by Albano Leoni & Maturi (2001) are stressed vowels within words.

[8] The vowel phonemes analyzed by Ferrero et al. (1978) are unstressed vowels produced in isolation.

[9] The vowel phonemes analyzed by Grimaldi et al. (2009) and Grimaldi et al. (2010, 2011) are stressed vowels within words.

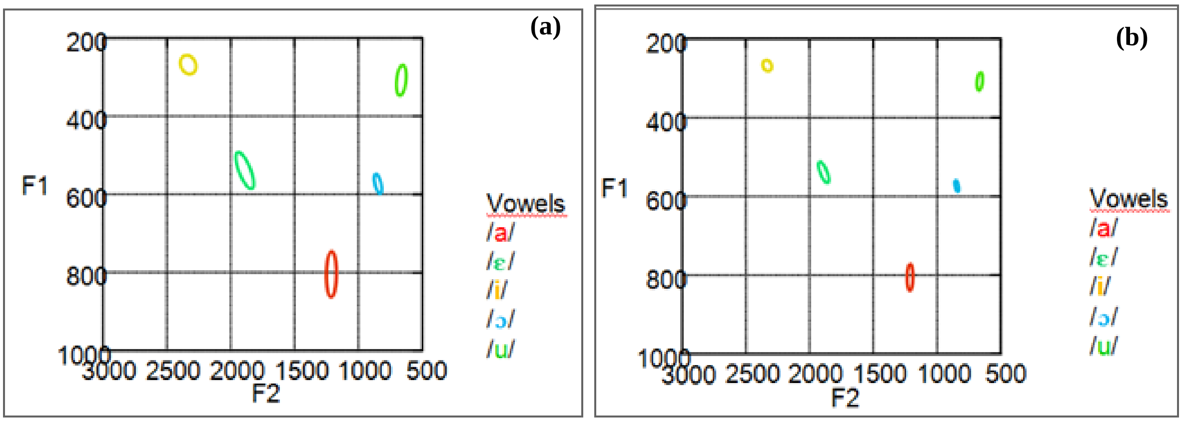

Figure 1: F1 x F2 scatterplots of Central Salento Italian vowels. Ellipses on data (a) with confidence level of 68.8%. Ellipses on centroids (b) with confidence level of 95%.

As a consequence, the children analyzed in the present study will acquire a five-vowel system, which does not have the opposition between mid-high and mid-low vowels. The forthcoming section discuss in great detail the articulatory characteristics and the phonological specification of the vowels elicited as specified in 4.4.1.

4.4.3 Articulatory characteristics of the Salento Italian vowels

As far as the articulation of fivel Salento Italian vowels is concerned, only four articulators are involved in vowel production, i.e. the tongue body, the tongue root, the lips, and the jaw.

The tongue body may assume three positions along the vertical axis for height : i) it is in its rest position for /ɛ/, /ɔ/; ii) it is raised above its rest position for /i/ and /u/; and iii) it is lowered below its rest position for /a/. Additionally, the tongue body may assume two positions along the horizontal axis for place: i) it is retracted towards the velum for /a/, /ɔ/, and /u/; or ii) it is avanced away from the pharynx for /i/ and /ɛ/.

The tongue root may assume two configurations: i) it is advanced with respect to its rest position during production of /i/ and /u/; or ii) it is in its rest position during articulation of /ɛ/, /ɔ/, and /a/.

The lips may assume two positions: i) they are constricted (also referred to as “rounded”) with a consequent narrovwing of the lip orifice in the case of /ɔ/ and /u/; or ii) they are straight (also referred to as “unrounded”) during articulation of /i/ and /ɛ/.

The jaw may assume three configurations: i) it is its rest position for /i/ and /u/; ii) it is slightly lowered for /ɛ/ and /ɔ/; or even iii) it is completely lowered for /a/. After having presented the articulatory characteristics of (Salento) Italian vowels, the following section deals with their phonological specification.

4.4.4 Phonological specification of the Salento Italian vowels

Speech sounds, such as consonants and vowels, are discrete segments that can be decomposed into complexes (e.g., bundles) of distintive features characterized by polar oppositions [cf. Jakobson & Halle 1956; Chomsky & Halle 1968]. There are both phonological studies [e.g., Kenstowicz 1994; Halle 2002; Botma et al. 2010] and acoustic studies [cf. Stevens 1972, 1989, 1998] providing overhelming arguments in favor of this view [for a review, cf. Calabrese 2008: 9-14].

Distinctive features are grounded in the structure, behaviors, movements, and constrictions of the movable components (e.g., the articulators) of the vocal apparatus, i.e. the tongue blade, the tongue body, the tongue root, the soft palate, the larynx, the lips, and the jaw [cf. Halle et al. 2000; Halle 2002]. Building on previous work by Stevens [cf. Stevens 1972, 1989, 1998], Calabrese (2008: 12) points out, given stable acoustic patterns may occur only when the vocal tract is in particular configurations or performs particular manoeuvres, with these configurations or manoeuvred corresponding to distintive features. Distinctive features have a dual function [cf. Halle 2002]: on the one hand, they serve as mnemonic devices to distinguish one phoneme from another in speakers' memories (e.g., mental lexicon); on the other hand, each distintive feature is an instruction for a particular action of one of the movable articulators (cf. 4.4.3).

For the phonological specification of the Salento Italian vowels, we will recur to five distinctive features: [HIGH], [LOW], [BACK], [ROUNDED], and [ATR]. The features [HIGH], [LOW], and [BACK] characterize the movements of the tongue body and, in some respect, of the jaw as well. In [+HIGH] vowels (e.g., /i/ and /u/), the tongue body is raised above its rest position and the jaw is in its rest position, whereas in [-HIGH] vowels (e.g., /ɛ/, /ɔ/, and /a/) there is no raising of the tongue body as well as a deep (e.g., for /a/) or a small (e.g., for /ɛ/ and /ɔ/) jaw lowering. In [+LOW] vowels (e.g., /a/), the tongue body is lowered below its rest position as well as the jaw is completely lowered, whereas in [-LOW] vowels there is no tongue body lowering (e.g., for /i/, /u/, /ɛ/, and /ɔ/) and a small (e.g., for /ɛ/ and /ɔ/) or no (e.g., for /i/ and /u/) jaw opening. In [+BACK] vowels (e.g., /a/[10], /ɔ/, and /u/), the tongue body is retracted towards the velum, whereas the tongue body is avanced away from the pharynx in [-BACK] vowels (e.g., /i/ and /ɛ/). The feature [ROUND] characterizes the behavior of the lips. In [+ROUND] sounds (e.g., /ɔ/ and /u/), the lips are constricted and there is a narrovwing of the lip orifice, whereas [-ROUND] vowels (e.g., /i/, /ɛ/, and /a/) are produced without such constriction. The feature [ADVANCED TONGUE ROOT], or [ATR], characterizes the movements of the tongue root. In [+ATR] vowels (e.g., /i/ and /u/), the tongue root is advanced as compared to its rest position, whereas in [-ATR] vowels (e.g., /ɛ/, /ɔ/, and /a/) the tongue root is in its rest position [cf. Calabrese 2008].

As far as vowel distintive feature specification is concerned, a certain hierarchy appears to exist among vowel features and the features [HIGH], [LOW], and [BACK] are assumed to be ranked higher as compared to the features [ROUND] and [ATR] [cf. Trubetzkoy 1969; Archangeli 1988; Dresher 2003]. We would like to observe that, as far as Salento Italian is concerned, the features [HIGH], [LOW], and [BACK] have wider scope than [ROUND] and [ATR] for the following reasons: i) except for /a/, Salento Italian back vowels are always specified as [+ROUND] (e.g., /ɔ/ and /u/), whereas front vowels are always specified as [-ROUND]; ii) high vowels in Salento Italian are always [+ATR] (e.g., /i/ and /u/), whereas non-high vowels are systematically [-ATR] (e.g., /a/, /ɛ/, and /ɔ/). Even though, this state of affairs is in agreement with Trubetzkoy (1969), Archangeli (1988), and Dresher (2003) statement that the features [HIGH], [LOW], and [BACK] are ranked higher with respect to the features [ROUND] and [ATR], we will assume that Salento Italian vowels are specified for all the above-mentioned distintive features. The motivation behind this decision lies in the

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[10] The low unrounded vowel /a/ is considered as a front vowel in the IPA. In Italian, it has been regarded as a central vowel by Albano Leoni & Maturi (2001: 49) and by Maturi (2006: 73-74) for Standard Italian, but as a back vowel by Calabrese (2000), Ghini (2001), Gaglia (2009), Grimaldi et al. (2010, 2011) for some Italian dialectal varieties. Here, we will consider /a/ as a back vowel (cf. (1)).

fact that the feature [ATR] has been shown to play a crucial role in the vowel system of some Southern Italian dialects: in the dialect of Altamura (Middle Apulia), the feature [ATR] is crucial to account for fronting of back vowels in stressed syllables [cf. Calabrese 2000]; likewise in the Southern Salentino dialects, the feature [ATR] is crucial to explain the application of the harmony processes involving front mid vowels [cf. Grimaldi 2009; Grimaldi et al. 2010, 2011].

Following Calabrese (2000), Grimaldi (2009), and Grimaldi et al. (2010, 2011), we hypothesize that the Salento Italian vowels elicited here (cf. 4.4.1) have the phonological specification detailed in (1).

(1)	/a/	/ɛ/	/i/	/ɔ/	/u/
[HIGH]	−	−	+	−	+
[LOW]	+	−	−	−	−
[BACK]	+	−	−	+	+
[ROUND]	−	−	−	+	+
[ATR]	−	−	+	−	+

After having discussed the phonological specification adopted for the elicited vowels, the vowel pairs selected as well as their Euclidean distance will be the object of the next section.

4.4.5 The vowel pairs selected, their direction of change in the distinctive feature specification, and their Euclidean distance

In the present study, we focus on the processing of the Salento Italian vowels in isolation (e.g., /i, u, ɛ, ɔ, a/) as well as on the processing of three vowel pairs at the behavioral and neurophysiological levels. We selected three vowel pairs differing by two distintive features, i.e. /u/ vs. /i/, /ɛ/ vs. /i/, and /a/ vs. /ɔ/ (cf. 4.4.4).

Articulatorily, /u/ and /i/ are high vowels produced with advanced tongue root and with the jaw in its resting position, differing by place of articulation (/u/ is back, while /i/ is front) and by lip rounding (lips are rounded for /u/ but unrounded for /i/). Phonologically, both /u/ and /i/ are specified as [+HIGH], [-LOW], and [+ATR]; additionally, /u/ is specified as [+BACK] and [+ROUND], while /i/ is specified as [-BACK] and [-ROUND] (cf. 4.4.4). With the pair /u/ vs. /i/, we would like to test the processing of vowels differing by the distintive features [BACK] and [ROUND] in their underlying representation.

Articulatorily, /ɛ/ and /i/ are front vowels realized with unrounded lips, differing by tongue body height (/ɛ/ is mid-low, while /i/ is high), jaw lowering (the jaw is slightly lowered for /ɛ/, while it is in its rest position for /i/), and tongue root advancement (the tongue root is advanced for /i/ but not for /ɛ/). Phonologically, both /ɛ/ and /i/ are specified as [-BACK], [-ROUND], and [-LOW]; additionally, /ɛ/ is specified as [-HIGH] and [-ATR], whereas /i/ is specified as [+HIGH] and [+ATR] (cf. 4.4.4). With the pair /ɛ/ vs. /i/, we would like to explore processing of vowels differing by the distintive features [HIGH] and [ATR] in their underlying representation.

Articulatorily, /a/ and /ɔ/ are non-high, back vowels realized with the tongue root in its neutral position, differing by lip rounding (lips are unrounded for /a/ but rounded for /ɔ/), tongue height (/a/ is low, while /ɔ/ is mid-low), and jaw lowering (the jaw is completely lowered for /a/, while it is slightly lowered for /ɔ/). Phonologically, both /a/ and /ɔ/ are specified as [-HIGH], [+BACK], and [-ATR]; additionally /a/ is specified as [+LOW] and [-ROUND], while /ɔ/ is specified as [-LOW] and [+ROUND].

With respect to direction of change in the distinctive feature specification, it is worth pointing out that, there is a difference between the high and the front vowel pairs on the one hand and the low vowel pair on the other hand. In the case of the high vowel pair, we are testing the processing of /u/, which is is specified as '+' for the features [BACK] and [ROUND], vs. /i/ which is specified as '-' for the same distintive features. Likewise, in the case of the front vowel pair, we are testing the processing of /ɛ/, which is specified as '-' for the features [HIGH] and [ATR], vs. /i/, which is specified as '+' for the same distintive features. In other words, in the case of high vowels, direction of change goes from '+' to '-', whereas it goes from '-' to '+' in front vowels. In the case of /a/ vs. /ɔ/, on the other hand, we are testing the processing of /a/, which is specified as [+LOW] and [-ATR], and of /ɔ/, which is specified as [-LOW] and [+ATR]. That is, direction of change in the distinctive feature specification is not unidirectional, since goes from '+' to '-' for [LOW], but from '-' to '+' for [ATR]. Given the fact that direction of change is different for high and front vowel pairs as compared to the back vowel pair, we expect to see differences in behavioral and neurophysiological processing of the former pairs as compared to the latter pair.

As for the acoustic distance between the vowels of each pair, it was measured as the Euclidean distance in the two-dimensional formant (i.e. F1/F2) space and it is expressed in Mel. The Mel scale is an auditory scale, as opposed to the physical Hz scale, where similar acoustic distances at any frequency range are perceived as being equidistant. The Euclidean distance between the vowels of each pair was calculated by taking into account the values of F1, which is a correlate of tongue body height, and of F2, which is a correlate of tongue body place during vowel production. A small acoustic distance indicates that the vowels are not so different from one another, whereas a broad acoustic distance means that the vowels are (quite) different from one another. The larger the acoustic distance between vowels, the larger is the magnitude of deviance between them and, consequently, the most salient is the contrast. Most salient contrasts usually turned out to be easier-to-process as compared to least salient contrasts at the neurophysiological level by CI children [cf. Henkin et al. 2008], CI adults [cf. Okusa et al. 1999; Kelly et al. 2005], and NH adults [cf. Titinen et al. 1995; Dietsch & Luce 1997; Obleser et al. 2003; Peltola 2003, 2007]. This means that, the higher is the magnitude of deviance between two vowels, the shorter the MMN latency and the larger the MMN amplitude [cf. Titinen et al. 1995; Dietsch & Luce 1997; Sussmann et al. 1998; Okusa et al. 1999; Obleser et al. 2003; Peltola 2003, 2007; Novitski et al. 2004; Kelly et al. 2005; Henkin et al. 2008], although not regularly [cf. Horvàth et al. 2008].In the present experiment, two vowel pairs were acoustically almost equidistant, i.e. /ɛ/ vs. /i/ (Euclidean distance = 322 Mel) and /a/ vs. /ɔ/ (Euclidean distance = 304 Mel). The acoustic distance of the pair /u/ vs. /i/, on the other hand, was larger (847 Mel). This situation follows from the fact that the F1 and F2 values characterizing /ɛ/ and /i/ as well as /a/ and /ɔ/ are not so different from one another, while /u/ and /i/ have similar F1 values, but different F2 values (cf. Table 5 above).

4.4.6 Normalization and of the elicited vowels

It is well known that the stimuli do not have to be acoustically constant for MMN to be elicited. Rather, MMN elicitation tolerates some range of stimulus variation as long as some pattern or rules are shared by the different standard stimuli on the one hand and by the different deviant stimuli on the other hand [cf. Näätänen 2001]. Building on these findings and following the methodology detailed by previous studies in second language acquisition [cf. Munro et al. 1996; Guion et al. 2000; Flege et al. 2004, 2006; Tsukada et al. 2005; Scharinger et al. 2012], the elicited vowels underwent normalization before being used in the present study.

The elicited vowels (n = 50) were normalized for duration by resynthesis (i.e., 100ms), for F0 (i.e., 130Hz for /u/, 140Hz for /ɛ, a, ɔ/, and 145Hz for /i/, cf, Ferrero et al. 1978), for intensity (i.e., 70dB/SPL), for rise/fall times (i.e., 5ms), and for equal volume throughout each token with *Akustyk 1.9.3 for Praat* [cf. Plitcha 2004], to keep our spectrally complex stimuli as homogenous as possible [cf. Näätänen 2001], despite introducing acoustic variation which characterizes everyday speech [cf. Winkler et al. 1999; Phillips 2000, 2001].

The individual formant values, on the other hand, remain unchanged, since especially the F1 and F2 frequencies are crucial for vowel recognition [cf. Lindblom & Sundberg 1971; Kent 1997; Stevens 1999], as pointed out above in 4.4.5.

We would like to make precise the following two points. First, with respect to vowel duration, we are aware of the fact that previous EEG studies typically used isolated speech stimuli with a duration ranging from 97ms to 500ms. The decision to set the vowel duration to 100ms in the present study was driven by the necessity to keep the duration of the experimental session as short as possible in order to prevent distressing the pediatric CI users. Having discussed the normalization of the elicited vowels, the following section addresses rating of the normalized vowel phonemes.

4.4.7 Rating of the elicited vowels and token selection

Along the lines of Munro et al. (1996), Guion et al. (2000), Flege et al. (2004, 2006), Tsukada et al. (2005), and Scharinger et al. (2011, 2012), the normalized vowel stimuli were categorized and rated as good vowel category representatives by five adult Italian native speakers in the soundproof room before presenting them to children. This operation was accomplished to ensure that the tokens selected were actually perceived as genuine representatives of the intended phonetic categories.

In the categorization experiment, each vowel category was represented by multiple (n = 10) tokens realized by the same speaker (cf. 4.4.1 above). In the rating experiment, the adult speakers rated each token for goodness using a five-point scale. The categorization and rating experiments were implemented with *Praat 5.3.51* [cf. Boersma & Weenink 2013]. The tokens selected as stimuli for the subsequent behavioral (cf. 4.5) and neurophysiological (cf. 4.6) experiments administered to children were the five tokens of each vowel category receiving the highest rating.

Following the methodology adopted in a few previous ERP studies [cf. Eulitz & Lahiri 2004; Scharinger et al. 2011, 2012], we decided to confront the children with five different exemplars of each phoneme category. The motivation for this methodological choice is that, in natural speech, a vowel is never uttered in the same way twice, rather the same segment may vary across speakers, contexts, speaking rate, and many other factors. By presenting the children with five different exemplars of the same vowel category, we wanted to introduce some acoustic variation and to guarantee a more natural listening situation.

Having discussed in great detail the preparation of the stimuli used throughout this study, the following section deals with the behavioral study.

4.5 Behavioral study

The behavioral study investigates vowel categorization and vowel discrimination. It was administered before the neurophysiological study. The two forthcoming sections address the recording (cf. 4.5.1) and the (cf. 4.5.2) analysis of the data.

4.5.1 Data recording

Following the study by Sharma, A. & Dorman (2000) in NH children, the one by Davids et al. (2011) in children with SLI, and the one by Ortmann et al. (2013) in CI children, all children participated in two behavioral tasks, a vowel categorization and a vowel discrimination task, both carried out with *Praat 5.3.51* in the soundproof room of the ENT department at Lecce Hospital. This way, we wanted to uncover behavioral (i.e. task-oriented, conscious) vowel categorization and discrimination performance in pediatric CI users.

In the categorization task, we ascertained whether the CI children were able to attentively identify the normalized stimuli (cf. 4.4.6) as exemplars of the intended phonetic categories. Children listened to 50 vowels (10 exemplars for /u/, /i/, /ɛ/, /ɔ/, and /a/) through a loudspeaker placed in front of them at a distance of 1 meter, and they had to identify the stimuli by clicking with a computer mouse on buttons arranged horizontally on the laptop screen and labeled as “U”, “I”, “E”, “O”, and “A” (cf. Figure 2a). The trial’s initial silence was 500ms.

In the subsequent AX (same-different) discrimination task, we assessed whether the CI children could consciously discriminate the sequential presentation of two exemplars of the same phonetic category (i.e. /i/$_1$-/i/$_2$ or /i/$_1$-/i/$_1$) from the presentation of exemplars of two different phonetic categories (i.e. /u/$_1$-/i/$_2$), which is a crucial prerequisite for participation in the ERP session (cf. 4.6). Children discriminated 50 same-vowel pairs (e.g., /i/-/i/, /u/-/u/, /ɛ/-/ɛ/, /ɔ/-/ɔ/, and /a/-/a/) and 60 different-vowel pairs (e.g., /i/-/u/, /u/-/i/, /ɛ/-/i/, /i/-/ɛ/, /ɔ/-/a/, and /a/-/ɔ/), by clicking with a computer mouse on buttons arranged horizontally on the laptop screen, labeled as “SAME” or “DIFFERENT” (cf. Figure 2b). The interstimulus interval (ISI) was 800 ms and the trial’s initial silence was 500ms.

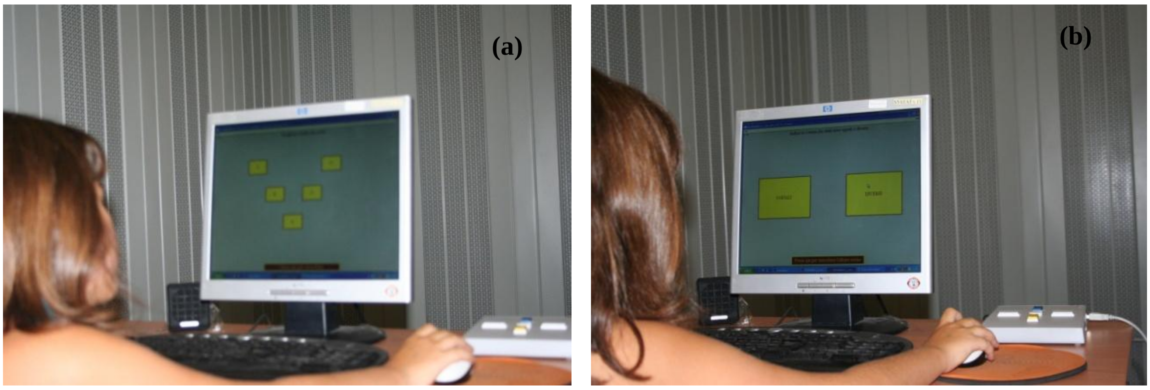

Figure 2: Vowel categorization (a) and discrimination (b) tasks.

Since the discriminability of speech sounds has been shown to depend, in some cases, on the order in which stimuli are presented [cf. Repp et al. 1979; Cowan & Morse 1986; Ladefoged 2001a], the stimulus presentation order was randomized across pediatric subjects. As in everyday exposure to speech, CI children received monaural stimulation through the implanted ear (7 right), while NH children received binaural stimulation. Those deaf children (n = 6) typically wearing an hearing aid in the non-implanted ear, were asked to remove the hearing aid during the behavioral tasks, in order to have all deaf children wearing only unilateral CIs.

4.5.2 Data analysis

Percentages of frequency in correct categorization of isolated vowels and in correct discrimination of vowel pairs to target stimuli were performed at the group level. Statistical analysis of the behavioral data was computed with *IBM SPSS Statistics 20* along the lines of De Boer et al. (2005). For the descriptive statistic analysis, the mean, the standard deviation (henceforth referred to as "s. d."), the lowest value ("Min."), the highest value ("Max."), and the interval between the lowest and the highest value ("Range") were calculated. As for the inferential statistic analysis, the *T-test for independent samples* was computed as follows: i) on the categorization and discrimination percentages to assess whether vowels were categorized and discriminated with comparable frequency by CI as compared to NH children or whether frequency was (slightly) lower in the former as compared to the latter; ii) on the percentages of pairs of high (/u/-/i/ and /i/-/u/), front (/ɛ/-/i/ and /i/-/ɛ/), and back (/a/-/ɔ/ and /ɔ/-/a/) vowels to shed light on whether direction of change in the distinctive feature specification happened to affect the discrimination of high vs. front vs. back vowels in CI children. Repeated-measure-ANOVA was performed as well to uncover whether the vowel quality (e.g., high vs. front vs. back) was likely to constrain the behavioral processing of vowel pairs in CI children, i.e. to cast light on whether pairs of high, of front, or of back vowels were correctly processed with higher frequency by CI children. Additionally, the relationships between age at surgery or duration of CI stimulation on the one hand and behavioral percentages on the other hand were studied by using *Pearson correlation coefficient analysis*.

Since a percentage analysis is not a meaningful measure of discrimination, a *d'*-prime analysis was performed as well [cf. Macmillan & Creelman 2005]. Following Francis & Ciocca [2003], children' accuracy was measured as group *d'* values for each stimulus pair using the method of Kaplan et al. [1978]. According to this method, group *d'* values are based on mean hit- and false-alarm rates of all subjects. In general, Signal Detection Theory (SDT) provides a general model for understanding subjects' sensitivity to difference between stimuli in the context of visual and auditory discrimination [cf. Tanner & Swets 1954, Green & Swets 1966; Pastore & Scheier 1974].

In a typical experiment to which SDT is applied, subjects are presented with stimulus pairs and they must chose one of two responses, "same" and "different". Provided that the stimulus pair consists of two repetitions of the same stimulus and that subjects answer "same", this answer is termed "Hit" (or "H") in the sense of correct discrimination of a same-stimulus pair. When the stimulus pair consists of two different stimuli, on the other hand, and subjects answer "different", this answer is termed "Hit" as well in the sense of correct discrimination of a different-stimulus pair. Crucially, if the subjects' answer is inappropriate, it is a "False alarm" (or "FA"), since subjects incurred in incorrect discrimination of a same-stimulus or a different-stimulus pair. In the case of same-stimulus pair discrimination, H and FA are defined as P ("S" / "S") and as P ("D" / "S"), respectively, where "P" means "probability", "S" means "same", and "D" means "different". In the case of different-stimulus pair discrimination, H and FA are defined as P (“D” / “D”) and as P (“S” / “D”), respectively. The resulting *d’* is a value obtained from the proportion between H and FA rates at the individual and group levels. Using the method of Kaplan et al. [1978], the highest *d’* value at the individual and group levels corresponds to 6.93 [cf. Kaplan et al. 1978: 799-810].

As for the *d’* values, the *T-test for independent samples* was computed on the discrimination *d’* values to clarify whether vowels were discriminated with comparable accuracy by CI as compared to NH children or whether accuracy was (slightly) lower in the former as compared to the latter. Repeated-measure-ANOVA was performed on the *d’* values as well to uncover whether the vowel quality (e.g., high vs. front vs. back) was likely to constrain the accuracy in behavioral processing of vowel pairs in CI children, i.e. to cast light on whether pairs of high, of front, or of back vowels were correctly discriminated with higher accuracy by CI children. Additionally, the relationships between age at surgery or duration of CI stimulation on the one hand and behavioral *d’* values on the other hand were studied by using *Pearson correlation coefficient analysis*.

4.6 Neurophysiologic study

The neurophysiological study investigates vowel detection, categorization, and discrimination. The two forthcoming sections address the recording (cf. 4.6.1) and the analysis (cf. 4.6.2) of the data.

4.6.1 Data recording

Using the counterbalanced design, automatic processing of /u/$_{\text{std}}$-/i/$_{\text{dev}}$, /ɛ/$_{\text{std}}$-/i/$_{\text{dev}}$, and /a/-/ɔ/, as well as of /i/$_{\text{std}}$-/u/$_{\text{dev}}$, /i/$_{\text{std}}$-/ɛ/$_{\text{dev}}$, and /ɔ/-/a/ at the cortical level was investigated by recurring to the P1, N1, and MMN responses (cf. 2.5) of the auditory ERPs.

For each pair, a passive oddball paradigm [cf. Winkler et al. 1999; Phillips et al. 2000] with 680 (p = .85) standard (i.e. frequent) and 120 (p = .15) deviant (i.e. rare) stimuli (ISI = 700, 750, 800, 850, 900ms) was implemented, with at least five standards separating two deviants and with nine standards always preceding the first deviant, as is usual in classical oddball paradigms. The presentation of each block of stimuli took 12 minutes, for a total of 72 minutes of EEG recording.

The EEG signal was recorded from 32 active Ag/AgCl electrodes arranged according to the 10:20 system [cf. Jasper 1958] as stated in the *Guidelines of the American Clinical Neurophysiology Society* (F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, TP9, P7, P3, Pz, P8, TP10, Oz, FP1$_{\text{VEOG}}$, FP2$_{\text{VEOG}}$, FT9$_{\text{HEOG}}$, FT10$_{\text{HEO2}}$, FCz$_{\text{Ref}}$, and AFz$_{\text{Gnd}}$), using the *Acticap System* and *BrainVision Recorder 1.20* (BrainProducts, Gilching, Germany) (cf. Figure 3 and Figure 4).

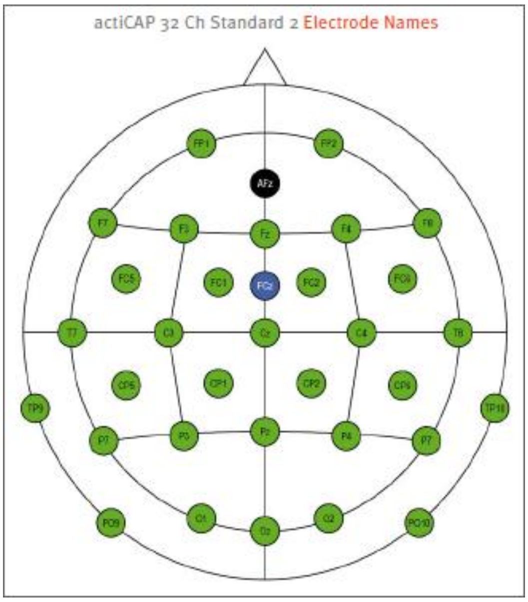

Figure 3. Standard 32 electrode layout of the Acticap System (BrainProducts).

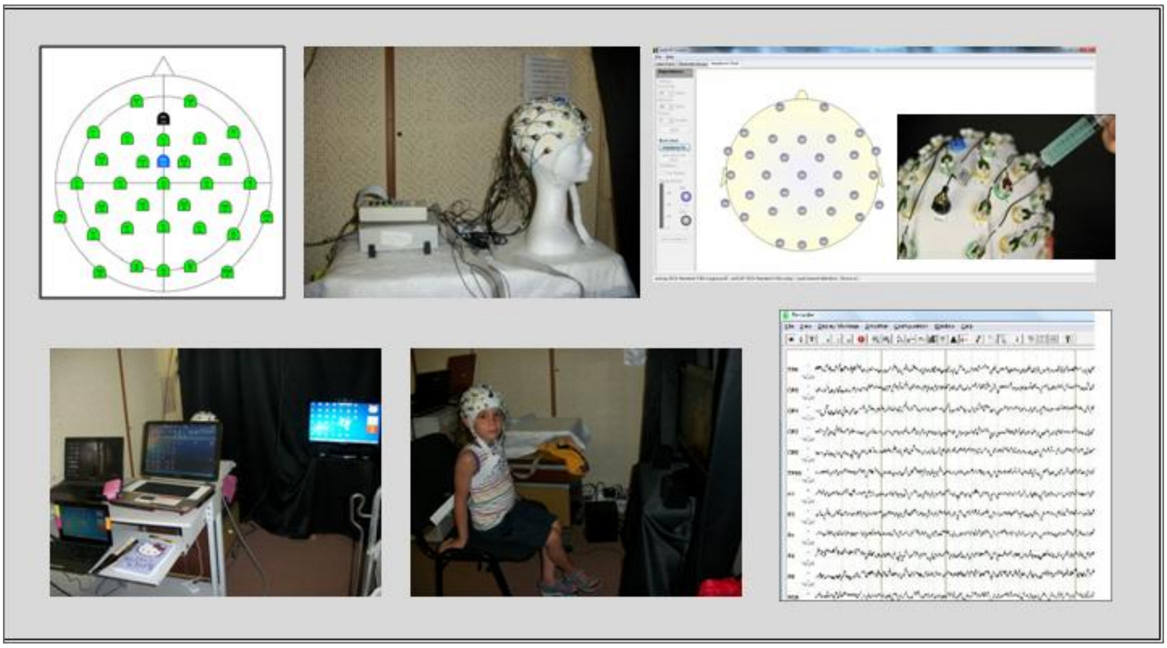

Figure 4. The Setup during the EEG sessions .

When recording EEG signals from CI users, the stimulus onset evokes an electrical artifact that inevitably corrupts the EEG signal. The strength, morphology, shape, and distribution of the CI artifact may be different across CI users, depending on the CI device model, location, and stimulation parameters. The CI artifact is time-locked to the incoming acoustic stimulus and can be much larger than the EEG signal of interest, thus (partially or completely) overlapping and masking the ERP responses recorded at channels in the vicinity of the CI device [cf. Singh et al. 2004; Debener et al. 2008; Henkin et al. 2008]. Building on the aforementioned, we disconnected two electrodes in CI children, i.e. TP9 and P7 for the deaf child implanted on the left side and TP10 and P8 for deaf children implanted on the right side.

The EEG signals were amplified with a *BrainAmp Amplifier*, using a bandpass filter from 0.1 to 200Hz and a sampling rate of 500Hz. Impedances were kept below 10kΩ, which is a standard setting for active electrodes [cf. Usakli 2010; Davids et al. 2011], by injecting the

Lectron-III conductive gel under the active electrodes by means of blunt syringes. During EEG recording sessions, children were watching a silent movie on a TV screen and they had previously been instructed to direct their attention to the silent movie and to ignore (i.e., not to focus on) the acoustic stimuli in the background. This way, it is highly unlikely that children were attending to the auditory stimuli (e.g., the vowels) during the EEG recordings, since the children' attention was distracted by the self-selected silent movie, which was inherently more interesting than the vowels [cf. Allen et al. 2000]. We will now present the motivations behind our methodological decisions.

As far as the stimulus number is concerned, we are aware of the fact, being the MMN a small-amplitude response as compared to the P1 and N1 responses, the presentation of 680 standard and 120 stimuli may not be enough to be obtain a reliable MMN in adults and children [cf. Ponton et al. 1997; Huotilainen et al. 2001; Cacace et al. 2003; Sharma, M. et al. 2004; Garrido et al. 2009; Light et al. 2010; Cong et al. 2011]. Nevertheless, we decided to present no more than 800 stimuli for each vowel pair in order to prevent distressing the pediatric CI users [cf. Johnson et al. 2001; Purdy & Kelly 2001; Purdy et al. 2005; De Boer et al. 2007].[11] In fact, even though increasing the number of stimulus trials may be good for improving the signal-to-noise ration in EEG data, this may result in response habituation and, in the end, in a degraded EEG signal [cf. McGee et al. 2001; Luck, 2005: 148-149].

With respect to the interstimulus interval, we used five types of ISI (i.e. 700, 750, 800, 850, 900ms) pseudorandomly selected to prevent ERP response habituation [McGee et al. 2001] and the brain ability to foresee the onset of the subsequent stimulus presentation [Luck, 2005: 148-149; Eraekannas 2009]. We are aware of the fact that longer ISIs (e.g., ≥ 1s) were typically used in previous MMN studies on adult and pediatric CI users. Nevertheless, we decided to use an ISI between 700ms and 900ms to avoid lengthening the experimental sessions.

As for the stimulus type, we decided to use multiple (n = 5) exemplars of the same vowel category (cf. 4.4.7) in order to introduce some acoustic variation and to ensure that the speech stimuli activated more abstract phonological representations in the ERP study, such that a pure acoustic explaination of the MMN was likely to be excluded [cf. Winkler et al. 1999; Phillips 2000, 2001; Eulitz & Lahiri 2004; Scharinger et al. 2011, 2012]. In fact, as stated by Näätänen (2001), the stimuli do not have to be acoustically constant for MMN to be elicited. Rather, MMN elicitation tolerates some range of stimulus variation (e.g., the F1 and F2 values in the present study, which did not undergo normalization, cf. 4.4.6 above) as long as some patterns (e.g., F0, intensity, volume, and rise/fall times in the present study, which underwent normalization, cf. 4.4.6 above) are shared by the standard stimuli on the one hand and by the deviant stimuli on the other hand.

With respect to the paradigm design, we decided to adopt the passive oddball paradigm with counterbalanced design, which foresees the presentation of a stimulus pair (e.g., /u/-/i/) as well as its reverse (e.g., /i/-/u/) to investigate whether direction of change from standard to deviant affects to some extent cortical processing of speech sounds. This decision is motivated by the findings obtained by Eulitz & Lahiri (2004), Cornel et al. (2011) and Scharinger et al. (2011, 2012) providing neurophysiological evidence for the Featurally Underspecified Lexicon (FUL) model of Lahiri & Reetz (2002, 2010). According to FUL, speech sounds are boundles of feature specifications and their underlying (e.g., phonological) representation in the mental lexicon employs the same bundles of features. However, not

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[11] The data presented in Chapter 7 and in Chapter 8 indicate that we managed in obtaining the MMN response.

every feature is expressed or specified. In the case of vowels, which are of particular interest for us here, both vowel place and vowel height can be unspecified underlyingly, thus resulting in an underspecified phonological entry. As far as vowel place is concerned, coronal (e.g., front) vowels are assumed to be unspecified (e.g., [-]) for place of articulation on the basis of particular assimilatory properties exhibited by them [cf. Avery & Rice 1989]. Being coronal, front vowels (e.g. /i/ and /ɛ/), are assumed to be unspecified for vowel place in FUL, whereas back vowels (e.g., /ɔ/, /u/, and eventually /a/) are specified as [DORSAL]. With respect to vowel height, high vowels (e.g., /i/ and /u/) are specified as [HIGH], low vowels (e.g., /a/ and /ae/) are specified as [LOW], and mid vowels (e.g., /ɛ/ and /ɔ/) are assumed to be unspecified for height in FUL [cf. Eulitz & Lahiri 2004; Cornell et al. 2011; Scharinger et al. 2012].

Direction of change in the vowel distinctive feature specification concerning height and place was found to play a role on the discrimination of vowel pairs. As far as vowel place is concerned, Eulitz & Lahiri (2004) tested the German mid-high vowels /ø/ and /o/, both articulated with rounded lips: /ø/ is unspecified (e.g., [-]) for place, whereas /o/ is specified as [DORSAL]. The MMN response evoked by the pair /o/$_{std}$-/ø/$_{dev}$ appeared to peak significantly earlier and significantly larger amplitude, since the back standard activates its fully specified place feature (e.g., [DORSAL]), whereas the front deviant, being underlyingly unspecified for place, fails to satisfy the prediction that a place feature is specified. The MMN response evoked by the reverse pair /ø/$_{std}$-/o/$_{dev}$, on the other hand, peaked later and with smaller amplitude, because the front standard activates an underspecified phonological representation, for which the dorsal standard does not provide a featural mismatch. With respect to vowel height, Scharinger et al. (2012) tested the front English vowels /ae/ and /ɛ/, both produced with unrounded lips: /ae/ is specified as [LOW] for vowel height, whereas /ɛ/ is unspecified for vowel height (e.g., [-]). The MMN response evoked by the pair /ae/$_{std}$ - /ɛ/$_{dev}$ peakes significantly earlier and with significantly larger amplitude, since the low standard activates a fully specified height feature (e.g., [LOW]) and it generates a strong expectation regarding height specification in the deviant. When the mid deviant is presented, however, it fails to satisfy the prediction of a fully specified height feature. The MMN response evoked by the reverse pair /ɛ/$_{std}$-/ae/$_{dev}$, on the other hand, peaked significantly later and with significantly smaller amplitude, because the mid standard activates an underspecified underlying representation, for which the low standard does not provide a featural violation. More generally, Eulitz & Lahiri (2004), Cornell et al. (2011), and Scharinger et al. (2012) claim that standard vowels, which are underspecified for place or height, make weaker predictions concerning the featural specification of their deviants; as a consequence, the violation of such an expectation from the deviant is less severe and the MMN peaks later and with reduced amplitude.

Even though we do no adopt the FUL model for vowel specification here, but rather a full specified model (cf. 4.4.4 above), along the lines of Eulitz & Lahiri (2004), Cornell et al. (2011), and Scharinger et al. (2012) we aimed at clarifying whether direction of change in the vowel distinctive feature specification actually played a role on the discrimination of vowel pairs or not. More particularly, we would like to understand whether MMN peaks earlier and has larger amplitude, and wider area when the standard is specified as [+] for a given distinctive feature and the deviant is specified as [-] for the same distinctive feature. As an example, let us consider the high vowel pairs /u/$_{std}$-/i/$_{dev}$ and its reverse /i/$_{std}$ -/u/$_{dev}$. In the case of /u/$_{std}$-/i/$_{dev}$, the back standard activates an underlying representation specified as [+] for the features [BACK] and [ROUND] and, henceforth, it generates a strong prediction concerning the specification of the same features in the front deviant. These expectations are not fulfilled by the front deviant, which in its turn, is specified as [-] for the features [BACK] and [ROUND]. In the case of /i/$_{std}$ -/u/$_{dev}$, on the other hand, the front standard activates an underlying representation specified as as [-] for the features [BACK] and [ROUND] and, henceforth, it generates no prediction concerning the specification of the same features in the back deviant. By extending the results of Eulitz & Lahiri (2004) and Scharinger et al. (2012), we hypothesize that the MMN response elicited by the pair /u/$_{std}$-/i/$_{dev}$ peaks earlier and with larger amplitude as compared to that evoked by the pair /i/$_{std}$ -/u/$_{dev}$.

The guidelines and safety instructions for EEG recording [cf. Picton et al. 2000; Luck 2005a: 99-129,131-265; Duncan et al. 2009; Light et al. 2010] and cleaning [cf. Putnan et al. 1992; Pivik et al. 1993; Ferree et al. 2001] in normal and clinical pediatric subjects were respected.

4.6.2 Data analysis

EEG data were analyzed as follows. The *Independent Component Analysis* (ICA, cf. Mennes et al. 2010), runica version, implemented on EEGLAB [cf. Delorme & Makeig 2004] and running in MATLAB (www.mathworks.com) was applied to eliminate, or at least to reduce, the CI artifact in deaf children [cf. Debener et al. 2008] as well as to remove, or at least reduce, ocular and muscle artifacts in CI and NH children [cf. Debener et al. 2010]. The ICA was conducted for each participant on the whole data recording, decomposing it into 16 components and visually inspecting the dynamic of each component, its distribution on the scalp, its distribution across the trials and its power spectrum. Only components clearly showing CI device-related, ocular, and muscle artifacts were removed. EEG data were then imported into *BrainVision Analyzer 2.0*.

At the individual level, the initial standards and the first standard following each deviant were eliminated. The ERP epochs (a 750ms time window including a 100ms pre-stimulus baseline) were re-referenced to Pz and digitally filtered by a 0.1—40Hz bandpass filter. The choice to re-reference offline the EEG data to Pz was based on the fact that Pz is located far away from the CI device and, therefore, it may be regarded as an appropriate reference when analyzing EEG data recorded with low-density systems in CI users [cf. Luck 2005]. Additionally, Pz is also suggested to avoid a reference bias especially when researchers are interested in ERP responses which reach their maximal amplitude over fronto-central scalp electrode sites, as in the case of P1, N1, and MMN [cf. Picton et al. 2000].

Following Kappenmann et al. (2011) and Neuhoff et al. (2012), artifact rejection criteria were set as follows: i) maximum voltage step = 75μV/ms; ii) maximum absolute difference = 120μV in 200ms; iii) amplitude = ±100μV; and iv) lowest activity = 0.5μV in 50ms. Artifact-free segments were separately averaged for each stimulus type at the individual level. Grand Averages were generated over all CI vs. NH children, separately for each stimulus type in order to identify P1, N1, and MMN.

Recall that, in the case of vowel-elicited auditory ERPs, the P1 response indicates that a vowel (i.e., with pronounced formants) has been detected, and its latency is a marker for central auditory pathway maturation (cf. 2.5.1). The N1 response is a neural indicator of extraction of the acoustic-phonetic spectral and temporal features which are relevant for vowel categorization in the auditory cortex (cf. 2.5.1). The MMN response indicates representation of the acoustic-phonetic features which are crucial for vowel categorization in the auditory cortices (cf. 2.5.2). The presence of P1, N1, and MMN in pediatric CI users indicates activation of primary and secondary auditory cortical areas after CI surgery and preservation of the critical auditory pathways for audition despite initial auditory deprivation [cf. Dinces et al. 2009].

The P1 and N1 responses were identified on the waves elicited by the standard and the deviant stimuli in a time window of 40—130ms (for P1) and 130—270ms (for N1). The MMN response was detected on the classical deviant minus standard difference wave and it was measured in a time window of 150—300ms. The peak latencies (in ms) and amplitudes (in μV) of the ERP responses [cf. Martin et al. 2008] were measured on eight frontocentral channels on the left (F3, FC1, FC5, and C3) and right (F4, FC2, FC6, and C4) hemispheres, with a time window surrounding the peak of 30ms (for P1), 40ms (for N1), and 50ms (for MMN). For MMN, the area under the curve was also calculated (in ms*μV) [cf. Beauchemin & De Beaumont, 2005] to get a more reliable measure than a time point estimate of peak amplitude and it is likely to provide us with additional pieces of information beside MMN amplitude [cf. Sharma A. et al. 1993; Sharma A. et al. 1994; McGee et al. 1997; Sussman et al. 2004; Sussman 2007; Petermann et al. 2009; Davids et al. 2011; Neuhoff et al. 2012].

Topographical and distributional evaluation of P1, N1, and MMN responses, as well as their strength were studied as well by means of the voltage maps of the ERP peaks in a time window of 20ms surrounding the peak to infer the brain area activation, the degree of activation, and the patterns of hemisphere involvment, in order to better understand the maturation of the neural mechanisms underlying cortical speech sound processing [Martin et al. 2003].

All data were analyzed statistically with *IBM SPSS Statistics 20* along the lines of De Boer et al. (2005). For the descriptive statistic analysis, the mean, the standard deviation, the lowest value, the highest value, and the interval between the lowest and the highest value were calculated. For the inferential statistic analysis, *Independent t-tests* were computed as follows: (i) on peak latency (ms), amplitude (μV), and area (ms*μV) of the ERP responses to ascertain whether these values were comparable in both groups of children, and (ii) on MMN values to investigate whether MMN was left-lateralized in CI and NH children; and iii) on the MMN values of pairs of high (/u/-/i/ and /i/-/u/), front (/ɛ/-/i/ and /i/-/ɛ/), and back (/a/-/ɔ/ and /ɔ/-/a/) vowels to shed light on whether direction of change in the distinctive feature specification happened to affect the cortical processing of high vs. front vs. back vowels in CI children.. Repeated-measure-ANOVA was performed as well to uncover whether the vowel quality (e.g., high vs. front vs. back) was likely to constrain the MMN values evoked by the vowel pairs in CI children, i.e. to cast light on whether pairs of high, of front, or of back vowels were cortically processed faster, with higher accuracy, and with broader size of neuronal activation by CI children.

The *T-test against 0* was performed on the MMN amplitude and area to ascertain whether they were significantly different from 0. Finally, the relationship between age at surgery or duration of CI stimulation on the one hand and ERP values on the other hand were investigated by studying *bivariate correlations*.

4.7 Combining behavioral and neurophysiological measures of speech sound processing

The benefits of CI stimulation in deaf children are best studied by combining task-oriented linguistic tests at the behavioral level and auditory ERPs at the neurophysiological level. While the former monitor the pediatric subjects' conscious processing of speech sounds, the latter are electrical brain responses evoked automatically (e.g., independently of conscious processing) by discrete stimuli. This is the case of the present study where the processing of single vowels and of vowel pairs was investigated both behaviorally and neurophysiologically. A similar case is represented by the study of Ortmann et al. (2013), where pediatric CI users discriminated vowel and consonant pairs behaviorally and neurophysiologically.

Except for Ortmann et al. (2013), no previous studies adopted both behavioral and neurophysiological measures to achieve a full picture of auditory processing of speech sounds in pediatric CI users. Therefore, not much is known about the relationship between behavioral and neurophysiological speech sound processing. A better understanding of the biological mechanisms underlying normal ad impaired speech perception can be achieved only by combining behavioral and neurophysiological data elicited by the same (speech) sounds and obtained in the same subjects [cf. Kraus et al. 1999; Sharma A. & Dorman 2000; De Haan 2007: 311-312; Conboy et al. 2008; Chang et al. 2012].

More generally, combining behavioral and neurophysiological measures to investigate speech sound processing in CI children is of crucial importance since behavioral measures tend to underestimate the magnitude as well as the persistence of the effects derived by early auditory deprivation on neural circuits, i.e. during the period of mamixal plasticity of the auditory pathways [cf. Knudsen 2004]. The reason for this state of affairs is that behavior results from the information that has previously been processed through hierarchies of neural circuits in the brain operating in parallel. Among these circuits, those operating at higher levels in the hierarchy still remain plastic and, thus, they tend to obscure irreversibile changes in those circuits operating at lower levels [cf. Knudsen 2004].

Previous studies combining logopedic tests and neurophysiological measures found that some CI users may show poor general auditory abilities, but good speech sound processing at the neurophysiological level [for CI children, cf. Beynon et al., 2002; for CI adults, cf. Korzkac et al. 2005), while other CI users may present good general auditory abilities, but absent or poor speech sound processing at the neurophysiological level (for CI children, cf. Henkin et al. 2008; Chang et al. 2012; for CI adults, cf. Kraus & McGee 1994; Souza & Tremblay 2006). The first pattern of results seems likely to suggest that speech sounds are reaching the auditory cortex and that they are being automatically processed. However, in this case, auditory training may be necessary to further enhance the subject general auditory abilities. The fact that neural responses can be obtained even to stimuli that are not consciuosly discriminated by CI subjects suggests that fine-grained auditory processing at the neurophysiological level is likely to occur even in the absence of conscious perception of stimulus differences and that attentive perception does not systematically match the authomatic neural representation of the same stimulus event [cf. Henkin et al. 2008]. These findings may imply that authomatic processing at the neural level may be more precise than conscious processing at the behavioral level and, more generally, that neurophysiological processing tends to be more precise than we think or than we are aware of [cf. Allen et al. 2000; Knudsen 2004]. The possible explaination for the second pattern of results are likely to be at least three: i) the reduced ERP amplites and the prolonged ERP latencies found in CI users with good general auditory abilities signal a subclinical auditory problem, which appears to present itself only in more complicated listening situations; ii) the CI device was not functioning properly at the time of testing or was not optimally fitted to the degree and configuration of the hearing loss; iii) the CI device has altered the signal in a way that it interferes with physiological recordings; iv) differences in the etiology of the hearing loss across subjects [cf. Korzkac et al. 2005; Souza & Tremblay 2006; Martin et al. 2008]. At the other estreme, in cases where ERPs cannot be detected at all, particularly when behavioral responses cannot be observed in response to speech sounds, the ERP technique clearly indicates that something is not optimal [cf. Chang et al. 2012].

Building on the aforementioned premises, we decided to study the benefits of CI stimulation on speech sound processing in deaf children by combining ‘true’ linguistic tests monitoring vowel categorization and discrimination – at the behavioral level – and auditory ERPs monitoring vowel detection, as well as extraction and representation of the acoustic-phonetic features which are relevant in linguistic terms – at the neurophysiological level – [cf. Korczak et al. 2005; Chang et al. 2012. Collectively, behavioral and neurophysiological measures provide insight into how well (e.g., accurately) the brain is perceiving each speech stimulus and how well it is processing one or more speech stimuli, as reflected by the behavioral percentages and *d’* values and the ERP values, in turn [cf. Chang et al. 2012].

Having discussed and justified the methodology adopted in the present study, the forthcoming chapter presents the aims of the study as well as the hypotheses and the expectations behind carryng the whole study.

4.8 Chapter summary

This chapter discusses and justifies the methodology adopted in the study. First, the pediatric subjects selected and the speech stimuli used are accurately presented. Then, the behavioral and the neurophysiological studies are addressed by explaining the reason under the decision to vcombine behavioral and neurophysiological measures.

CHAPTER 5

Aims, hypotheses, and expectations

5.1 Introduction

This chapter presents the aims (cf. 5.2) as well as the hypotheses and expectations (cf. 5.3) of the present study. A summary closes the chapter (cf. 5.4)

5.2 Aims of the study

For the first time, the present study investigates the processing of single vowels and of vowel pairs in a group of Italian pediatric CI users implanted early in their lives (< 3.5 years) as compared to a control group of NH children, by jointly recurring to behavioral measures elicited consciously and to neurophysiological measured evoked automatically. As for the processing of single vowels, the processes investigated are two: i) detection of single vowels, as neutrally encoded by the P1 response at the neurophysiological level (cf. 2.5.1 and 2.6.1); and ii) categorization of single vowels, as indicated by the percentages of frequency in correct vowel categorization at the behavioral level (cf. 4.5) and as suggested by the N1 response at the neurophysiological level (cf. 2.5.1 and 2.6.1). The processing of vowel pairs, on the other hand, has been investigated by recurring to the percentages of frequency and accuracy in correct vowel discrimination at the behavioral level (cf. 4.5) and by relying on the MMN response at the neurophysiological level (cf. 2.5.2 and 2.6.2).

The aims of the present study are the following five. First of all, we want to cast light on whether the performance concerning the processing of single vowels and of vowels pairs exhibited by the CI children examined is statistically comparable to that exhibited by the control group or whether the CI children lag behind their NH peers. Second, we aim at ascertaining whether the earlier vs. later age at surgery is likely to play a role on the processing of vowels in the Italian CI children selected. Third, we want to shed light on whether the longer vs. shorter duration of CI use affects the processing of vowels in the Italian CI children monitored. Fourth, we aim at clarifying whether other external factors are likely to influence vowel processing. The external factors are the following four: i) the quality (e.g., high vs. front vs. back) of the Salento Italian vowels; ii) the articulatory characteristics of the Salento Italian vowels (e.g., /u/, /i/, /ɛ/, /ɔ/, /a/) acoustically codified by the values of F1 and F2; iii) the larger vs. smaller Euclidean distance characterizing the vowel pairs; iv) the direction of change in the distinctive feature specification between the first and the second vowel of each pair. Finally, we want to understand whether the maturational patterns of the behavioral and neurophysiological levels of analysis proceed in parallel or whether the one lags behind the other one.

5.3 Hypotheses and expectations of the study

In the following, we will detail our hypotheses and expectations for detection (cf. 5.3.1) and categorization (cf. 5.3.2) of single vowels as well as for the processing of vowel pairs (cf. 5.3.3) in CI children as compared to NH children as well as for CI children implanted earlier vs. CI children implanted later, but always before 3.5 years.

5.3.1 Detection of single vowels

Detection of single vowels will be investigated only neurophysiologically by recurring to the P1 response.

Building on the results achieved by previous ERP studies [cf. Sharma et al. 2002abc, 2005; Singh et al. 2004; Munivrana & Mildner 2013], we hypothesize that the Italian CI children examined are able to detect the five Salento Italian vowels. Accordingly, we expect to systematically find the P1 response in their ERP waveforms.

We suppose that detection of single vowels is likely to be frequently delayed and less precise in CI as compared to NH children. Accordingly, we expect to find prolonged P1 latencies and attenuated P1 amplitudes in CI relative to NH children. Building on the findings of previous acoustic studies on the vowels produced by pediatric CI users [cf. Liker et al. 2007; Neumeryer et al. 2010; Baudonck et al. 2011], we hypothesize either /ɛ/ and /ɔ/ to be more-difficult to detect with respect to /i/, /a/, and /u/, or /a/, /ɔ/, and /u/ to be more-difficult to detect with respect /i/ and /ɛ/ by the Italian CI as compared to NH children. Should this be the case, we expect to find prolonged P1 latencies and reduced P1 amplitudes in CI as compared to NH children for those vowels which are more-difficult to detect.

We also suspect that the patterns of brain area activation on the scalp and the degree of activation are different in CI as compared to NH children. More particularly, we expect that the patterns of brain activation are (at least partially) different in CI vs. NH children and that the degree of activation is clearly reduced in CI relative to NH children.

As for hemisphere involvement during detection of single vowels, we do not expect to find the left-lateralization of the P1 response in CI children, because the first steps of speech sound processing are known to depend on both hemispheres.

5.3.2 Categorization of single vowels

Categorization of single vowels was investigated at the behavioral and at the neurophysiological levels. At the behavioral level, children' frequency in correct categorization of isolated vowels was measured as group percentages for each vowel phoneme. At the neurophysiological level, categorization of single vowels was studied by monitoring the N1 response which indexes neural extraction of the vowel acoustic-phonetic features which are relevant for linguistic categorization.

Building on the results achieved by previous ERP studies [cf. Kileny et al. 1997; Beynon et al. 2002; Munivrana & Mildner 2013], we hypothesize that the Italian CI children examined are able to categorize the five Salento Italian vowels at the neurophysiological level. We also suppose that the CI children will manage to categorize /a, ɛ, i, ɔ, u/ at the behavioral level. Accordingly, we expect to systematically find the N1 response in their ERP waveforms at the neurophysiological level as well as to find frequency percentages different from zero at the behavioral level.

Because of the frequently degraded auditory input delivered through the CI device with respect to loudness, pitch, and temporal and spectral features (cf. 3.5) as well as because of the consequent reduced formant frequency discrimination (cf. 3.13) in CI users, we expect the correct categorization of single vowels to be (at least partially) compromised in the Italian CI children monitored. More particularly, we suppose that categorization of single vowels is often delayed and less accurate in CI as compared to NH children. Accordingly, we expect to find lower frequency percentages at the behavioral level as well as prolonged N1 latencies and reduced N1 amplitudes in CI relative to NH children. Building on the findings of previous acoustic studies on the vowels produced by pediatric CI users [cf. Liker et al. 2007; Neumeryer et al. 2010; Baudonck et al. 2011], we suppose that either /ɛ/ and /ɔ/ are more-difficult to categorize with respect to /i/, /a/, and /u/, or that /a/, /ɔ/, and /u/ are more-difficult to categorize with respect /i/ and /ɛ/ by the Italian CI as compared to NH children, both behaviorally and neurophysiologically. Should this be true, we expect to find lower frequency percentages together with prolonged N1 latencies and reduced N1 amplitudes in CI as compared to NH children for those vowels which are more-difficult to categorize.

Along the lines of previous studies on the modulation exerted on the N1 values by the vowel spectral properties [cf. Roberts et al. 2000, 2004; Obleser et al. 2003, 2004; Titinen et al. 2005; Pulvermüller & Shyrov 2006; Rinne 2006; Näätänen et al. 2011; Scharinger et al. 2011, 2012; Manca 2014: 75-78], we hypothesize that the articulatory characteristics of the Salento Italian vowels - acoustically codified by the values of F1 and F2 - are likely to modulate the N1 values of latency and amplitude. We expect to see how the spectral properties of the Salento Italian vowels will modulate the latency and the amplitude of N1.

As for the patterns of brain area activation on the scalp, we hypothesize that these are partially different in NH relative to CI children. With respect to the degree of activation of the brain areas, we suppose that it is broader in NH as compared to CI children. As far as hemisphere commitment during categorization of single vowels is concerned, we do not expect to find the left-lateralization of the N1 response in CI children, because the first steps of speech sound processing are known to depend on both hemispheres.

5.3.3 Processing of same-vowel pairs

Discrimination of same-vowel pairs (e.g., /a/-/a/, /ɛ/-/ɛ/, /i/-/i/, /ɔ/-/ɔ/, and /u/-/u/) was investigated only behaviorally by means of an AX same-different discrimination test. Children' frequency in correct discrimination of same-vowel pairs was measured as group percentages for each pair and children's accuracy in correct discrimination of same-vowel pairs was measured as group *d'* values for each pair.

Because of the frequently degraded auditory input delivered through the CI device (cf. 3.5) as well as because of the consequent (at least partially) impaired formant frequency discrimination (cf. 3.13) in CI users, we hypothesize that discrimination of same-vowel pairs is not easy for CI children. Accordingly, we expect to find lower percentages for frequency and lower *d’* values for accuracy concerning discrimination of same-vowel pairs in CI as compared to NH children.

Always relying on the findings of previous acoustic studies on the vowels produced by pediatric CI users [cf. Liker et al. 2007; Neumeryer et al. 2010; Baudonck et al. 2011], we suppose that either /ɛ/-/ɛ/ and /ɔ/-/ɔ/ are likely to be more-difficult to discriminate with respect to /i/-/i/, /a/-/a/, and /u/-/u/, or that /a/-/a/, /ɔ/-/ɔ/, and /u/-/u/ happen to be more-difficult to discriminate with respect /i/-/i/ and /ɛ/-/ɛ/ by the Italian CI as compared to NH children. Should this be true, we expect to find lower percentages for frequency together with lower *d’* values for accuracy in CI as compared to NH children for those same-vowel pairs which turn out to be more-difficult to discriminate.

5.3.4 Processing of different-vowel pairs

The processing of different-vowel pairs (e.g., /u/-/i/, /i/-/u/, /ɛ/-/i/, /i/-/ɛ/, /a/-/ɔ/and /ɔ/-/a/). was investigated both behaviorally and neurophysiologically. At the behavioral level, children’ frequency in correct discrimination of vowel pairs was measured as group percentages for each vowel pair, whereas children’ accuracy in correct discrimination of vowel pairs was measured as *d’* scores. At the neurophysiological level, the processing of different-vowel pairs was explored by monitoring the MMN response in the ERP waveforms. which indexes neural representation of the vowel acoustic-phonetic features which are meaningful in linguistic terms for vowel categorization

Building on the results achieved by previous ERP studies [cf. Kileny et al. 1997; Beynon et al. 2002; Singh et al. 2004; Henkin et al. 2008; Munivrana & Mildner 2013; Ortmann et al. 2013], we hypothesize that the Italian CI children examined are able to process the process the six vowel pairs at the neurophysiological level. We also suppose that the CI children will manage to process the same vowel pairs the behavioral level. Accordingly, we expect to systematically find the MMN response in their ERP waveforms at the neurophysiological level as well as to find percentages for frequency and *d’* values for accuracy in vowel discrimination different from zero at the behavioral level.

Because of the frequently degraded auditory input delivered through the CI device (cf. 3.5) as well as because of the consequent reduced formant frequency discrimination (cf. 3.13) in CI users, we expect the processing of vowel pairs to be partially compromised in the Italian CI children monitored. More particularly, we suppose that the processing of vowel pairs is frequently delayed and less accurate in CI as compared to NH children, as well as that the size of neuronal activation is reduced in CI vs. NH children. Accordingly, we expect to find lower percentages for frequency and *d’* values for accuracy at the behavioral level as well as prolonged MMN latencies, reduced MMN amplitudes, and smaller MMN area at the neurophysiological level in CI relative to NH children. Building on the findings of previous acoustic studies on the vowels produced by pediatric CI users [cf. Liker et al. 2007; Neumeryer et al. 2010; Baudonck et al. 2011], we suppose that either those vowel pairs with at least one mid vowel may be are more-difficult to process with respect to those vowel pairs which do not contain mid vowels, or that those vowel pairs containing at least one back vowel happen to be more-difficult to process as compared to those vowel pairs which do not contain back vowels for CI as compared to NH children, both behaviorally and neurophysiologically. Should this be true, we expect to find lower percentages for frequency and lower *d’* values for accuracy together with prolonged MMN latencies, reduced MMN amplitudes, and smaller

MMN areas in CI as compared to NH children for those vowel pairs which turn out to be more-difficult to process.

As for the patterns of brain area activation on the scalp, we hypothesize that these are partially different in NH relative to CI children. With respect to the degree of activation of the brain areas, we suppose that it is reduced in CI as compared to NH children. As far as hemisphere commitment during categorization of single vowels is concerned, we do not expect to find the left-lateralization of the MMN response in CI children, because of the initial auditory deprivation period experienced by them.

With respect to the quality (e.g., high vs. front vs. back) of the Salento Italian vowels, we investigate whether both pairs of high (e.g., /u/-/i/ and /i/-/u/), front (e.g., /ɛ/-/i/ and /i/-/ɛ/), and back (e.g., /a/-/ɔ/ and /ɔ/-/a/) vowels are easier-to process as compared to one another. Should this be true, we expect to find shorter MMN latencies, larger MMN amplitudes, and wider MMN areas for the pairs of vowels which turn out to be easier-to-process.

As for the Euclidean distance, a small Euclidean distance between vowels means that these vowels are not so different from one another, whereas a broad acoustic distance means that two vowels are (quite) different from one another. The larger the acoustic distance between two vowels, the larger is the magnitude of deviance between them and, consequently, the most salient is the contrast. Most salient contrasts usually turned out to be easier-to-process as compared to least salient contrasts at the neurophysiological level. In the present study, /u/ vs. /i/ are characterized by a larger Euclidean distance (847Mel), as compared to /ɛ/ vs. /i/ and /a/ vs. /ɔ/ which are characterized by a smaller Euclidean distance (322Mel and 304Mel, in turn). Building on the findings achieved by previous studies [cf. Henkin et al. 2008 for CI children; cf. Okusa et al. 1999; Kelly et al. 2005 for CI adults; cf. cf. Titinen et al. 1995; Dietsch & Luce 1997; Obleser et al. 2003; Peltola 2003, 2007 for NH adults] we hypothesize that those vowel pairs characterized by a larger Euclidean distance are easier-to-process for CI children as compared to those vowel pairs presenting a smaller Euclidean distance both at the behavioral and at the neurophysiological levels. Thus, we expect to find shorter MMN latencies, larger MMN amplitudes, and wider MMN areas evoked by the pairs characterized by a larger Euclidean distance (e.g., /u/-/i/ and /i/-/u/) as compared to those evoked by the pairs presenting a smaller Euclidean distance (e.g., /ɛ/-/i/ and /i/-/ɛ/, /a/-/ɔ/ and /ɔ/-/a/).

With respect to direction of change in the distinctive feature specification, we would like to clarify whether, in the case of vowel pairs characterized by the same Euclidean distance (e.g., /u/ vs. /i/), direction of change (e.g., /u/-/i/ vs. /i/-/u/) can shed further light in vowel processing at the behavioral and neurophysiological levels. Let us first take the high vowel pairs /u/$_{\text{std}}$-/i/$_{\text{dev}}$ and /i/$_{\text{std}}$-/u/$_{\text{dev}}$, where the two vowels differ for tongue body place, phonologically coded by [±BACK], and by lip configuration, phonologically coded as [±ROUND]. Building on the findings achieved by Lahiri and colleagues discussed in 4.4.5 and in 4.6.2 [cf. Eulitz & Lahiri 2004; Cornell et al. 2011; Scharinger et al. 2012], we expecte the pair /u/$_{\text{std}}$-/i/$_{\text{dev}}$, where /u/ is specified as [+] for the above-mentioned features, whereas /i/ is specified as [-] for the same features, to be easier-to-process as compared to /i/$_{\text{std}}$ -/u/$_{\text{dev}}$, both behaviorally and neurophysiologically. Let us now take the front vowel pairs /i/$_{\text{std}}$ -/ɛ/$_{\text{dev}}$ and /ɛ/$_{\text{std}}$ -/i/$_{\text{dev}}$, where the two vowels differ for tongue body height, phonologically coded as [±HIGH], and for tongue root advancement, phonologically coded as [[ATR]. We suppose that the pair /i/$_{\text{std}}$ -/ɛ/$_{\text{dev}}$, where /i/ is specified as [+] for the above-mentioned features, whereas /ɛ/ is specified as [-] for the same features, is easier-to-process with respect to /ɛ/$_{\text{std}}$ -/i/$_{\text{dev}}$, both behaviorally and neurophysiologically. More particularly, we expect that /u/$_{\text{std}}$-/i/$_{\text{dev}}$

and /i/$_{\text{std}}$ -/ɛ/$_{\text{dev}}$ are discriminated by recurring to a shorter MMN latency as well as a larger MMN amplitude and a wider MMN area at the neurophysiological level as well as by means of larger discrimination percentages and larger *d'* values at the behavioral level. In other words, by extending the findings of Eulitz & Lahiri (2004), Cornell et al. (2011), and Scharinger et al. (2012), we expect MMN to peak earlier as well as with enhanced amplitude and with wider area when deviant vowels specified as [-] occur after standard vowels specified as [+]. Let us now consider the back vowel pairs /a/-/ɔ/ and /ɔ/-/a/, where the two vowels differ by tongue body height, phonologically coded as [±LOW], and lip configuration, phonologically coded as [±ROUND]. The vowel /a/ is specified as [+LOW, -ROUND], whereas the vowel /ɔ/ is specified as [-LOW, +ROUND]. Being characterized by a 'bydirectional' change, we hypothesize both vowel pairs to be processed during a comparable time window, with a similar accuracy, and with comparable size of neuronal activation. In other words, we expect the MMN evoked by both pairs to present comparable values for latency, amplitude, and accuracy.

5.3.5 The behavioral and neurophysiological levels

As pointed out in 4.7, combining behavioral measures administered consciously and neurophysiological measures evoked automatically to investigate speech sound processing in CI children is of crucial importance, since behavioral measures have been shown to be likely to underestimate the magnitude as well as the persistence of the effects derived by early auditory deprivation on neural circuits [cf. Knudsen 2004]. The reason for this state of affairs is that behavior results from the information that has previously been processed through hierarchies of neural circuits in the brain operating in parallel. Among these circuits, those operating at higher levels in the hierarchy still remain plastic and, thus, they tend to obscure irreversible changes in those circuits operating at lower levels [cf. Knudsen 2004].

Accordingly, we suppose the CI children examined to lag behind their NH peers to a higher degree for vowel processing at the neurophysiological level, and to a lower degree for vowel processing at the behavioral level. Thus, we expect to frequently find delayed ERP latencies and reduced ERP amplitudes in CI as compared to NH children, but to found lower percentages for frequency and lower *d'* values for accuracy in vowel processing only rarely in CI children relative to NH children.

5.3.6 The age at implant surgery

Age at surgery is thought to crucially determine the degree of benefit that deaf children receive from CI stimulation. The sensitive period for central auditory pathway maturation is thought to be of about 3.5 years [cf. Knudsen 2004; Sharma & Dorman 2006; Bishof 2007; Kral & Sharma 2010]. Deaf children implanted before 3.5 years usually receive the greatest benefit from CI stimulation (cf. 3.8.1.1, 3.8.1.2, 3.10, and 3.11), while deaf children implanted afterwards (up to 13 years) typically receive significant benefit from CI stimulation, although much greater variation in auditory performance is acknowledged (cf. 3.8.2.1, 3.8.2.2, 3.10, and 3.11).

With one exception, the CI children examined here underwent CI surgery before 3.5 years, ranging from 2.1 years to 4.4 years (cf. 4.3). We suppose that children implanted early in their lives (e.g., towards 2.1 years) are able to process both single vowels and vowel pairs betters at the behavioral and at the neurophysiological level as compared to deaf children receiving their CI later (e.g., towards 4.4 years). Hence, we expect to find shorter ERP latencies, larger ERP amplitudes, and wider ERP areas at the neurophysiological level together with higher percentages of frequency and higher *d'* values for accuracy at the behavioral level in those children implanted earlier in their lives.

5.3.7 The duration of implant stimulation

Whether duration of CI stimulation affects auditory processing in children implanted early in their lives is still a matter of debate, since previous studies have reported confusing results (cf. 3.12). Shorter ERP latencies and larger ERP amplitudes were found in CI children implanted early in their lives (≤ 3.5 years) provided that they had been using their CI for at least 5 or 6 years, although not systematically.

In the CI children examined, the duration of CI stimulation was longer than 2 years and it ranged from 2.4 to 8.1 years (cf. 4.3). We suppose that children benefiting from a longer duration of CI stimulation (e.g., towards 8.1 years) are able to process both single vowels and vowel pairs betters at the behavioral and at the neurophysiological level as compared to deaf children benefiting from a shorter duration of CI stimulation (e.g., towards 2.4 years). In other words, we expect to find shorter ERP latencies, larger ERP amplitudes, and wider ERP areas at the neurophysiological level together with higher percentages of frequency and higher *d'* values for accuracy at the behavioral level in those children who had been using their CI for a longer period.

5.4 Chapter summary

This chapter presents the aims of the present study as well as the hypotheses and the expectations concerning detection and categorization of single vowels as well as concerning the processing of vowel pairs, by paying special attention to the possible influence played by vowel quality, the Euclidean distance, direction of change in the distinctive feature specification, age at implant surgery, and duration of implant use.

CHAPTER 6

Behavioral vowel processing

6.1 Introduction

The CI and NH children participated in two behavioral tasks, a vowel categorization and a vowel discrimination task: they were directed at the pediatric subjects' conscious attention and they aimed at throwing light on task-oriented vowel processing (cf. 4.5). In the following, we will first present the results of the vowel categorization task (cf. 6.2) and then of the vowel discrimination task (cf. 6.3), both in the case of same- (cf. 6.3.1) and of different-vowel (cf. 6.3.2) pairs. The possible influence played by age at surgery and duration of CI stimulation on behavioral vowel processing will then be addressed (cf. 6.4 and 6.5, in turn). The results of the behavioral study will then be extensively discussed (cf. 6.6). Finally, a summary closes this chapter (cf. 6.7).

6.2 Vowel categorization

The pediatric CI users were asked to categorize five isolated vowels (e.g., /i/, /u/, /ɛ/, /ɔ/, and /a/). Children' frequency in correct categorization of single vowels was measured as group percentages for each vowel category. The percentage analysis revealed that, as expected, NH children showed excellent vowel categorization abilities in 100 percent of the cases (cf. Table 1), while CI children, managed to nearly always correctly categorize single vowels (cf. Table 2 and Figure 1).

% of vowel categorization in NH children					
Vowel	Mean	s. d.	Min.	Max.	Range
/i/	**100**	0	100	100	0
/u/	**100**	0	100	100	0
/e/	**100**	0	100	100	0
/o/	**100**	0	100	100	0
/a/	**100**	0	100	100	0

Table 1. Descriptive statistic analysis of vowel categorization in NH children (in percent).

% of vowel categorization in CI children					
Vowel	Mean	s. d.	Min.	Max.	Range
/i/	**91**	**18**	50	100	50
/u/	**96**	**5**	90	100	10
/ɛ/	**98**	**5**	90	100	10
/ɔ/	**98**	**7**	80	100	20
/a/	**98**	**4**	90	100	10

Table 2. Descriptive statistic analysis of vowel categorization in CI children (in percent).

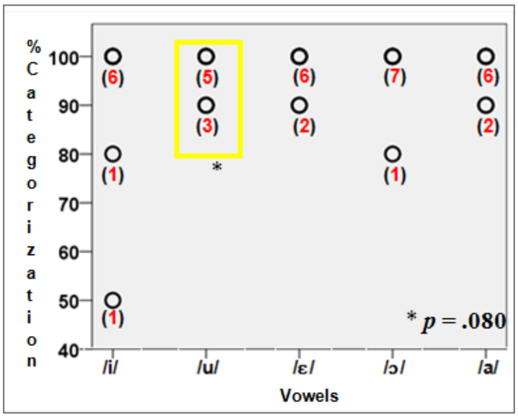


Figure 1. Vowel categorization performance in CI children (mean values are given in percent). The sum of each column in correspondance of each vowel is always eight since eight are the CI children examined. The yellow rectangle refers to the statistical analysis in Table 3.

In spite of the slightly lower percentages exhibited by CI children (cf. Table 2 above) as compared to NH children (cf. Table 1 above), an independent *t*-test confirmed that the percentages exhibited by the former were not significantly different from those of the latter, except for /u/ (cf. Table 3). In the case of /u/, the result returned by the independent *t*-test approached statistical significance.

	Mean % ± s.d.		
Vowel	NH children	CI children	Stat. Sig.
/i/	100	91 ± 18	*t*(7)=1.37, *p*=.213
/u/	**100**	**96 ± 5**	***t*(7)=2.05, *p* = .080**
/ɛ/	100	98 ± 5	*t*(7)=1.528, *p*=.170
/ɔ/	100	98 ± 7	*t*(7)=1.000, *p*=.351
/a/	100	98 ± 4	*t*(7)=1.528, *p*=.170

Table 3. Inferential statistic analysis of the vowel categorization performance in CI vs. NH children (*t-test* for unpaired samples).

After having discussed categorization of isolated vowels in CI children, the forthcoming section focuses on discrimination of vowel pairs.

6.3 Vowel discrimination

In the following, we will first discuss discrimination of same-vowel pairs (6.3.1) and then of different-vowel pairs (6.3.2).

6.3.1 Discrimination of same-vowel pairs

The pediatric CI users had to discriminate five same-vowel pairs: /i/-/i/, /u/-/u/, /a/-/a/, /ɛ/-/ɛ/, and /ɔ/-/ɔ/. Children' frequency (cf. 6.3.1.1) and accuracy (cf. 6.3.1.2) will be presented below.

6.3.1.1 Frequency in correct discrimination

Children' frequency in correct discrimination of same-vowel pairs was measured as group percentages for each vowel pair (cf. Table 4 and Table 5). The percentage analysis revealed that, as expected, the NH children showed an excellent vowel discrimination performance in 100 percent of the cases (cf. Table 4), whereas the CI children, managed to nearly always correctly discriminate same-vowel pairs (cf. Table 5 and Figure 2).

% of same-vowel pair discrimination in NH children					
Vowels	Mean	s. d.	Min.	Max.	Range
/i/-/i/	**100**	0	100	100	0
/u/-/u/	**100**	0	100	100	0
/ɛ/-/ɛ/	**100**	0	100	100	0
/ɔ/-/ɔ/	**100**	0	100	100	0
/a/-/a/	**100**	0	100	100	0

Table 4. Descriptive statistic analysis of same-vowel pair discrimination in NH children (in percent).

% of same-vowel pair discrimination in CI children					
Vowel	Mean	s. d.	Min.	Max.	Range
/i/-/i/	98	5	90	100	10
/u/-/u/	100	0	100	100	100
/ɛ/-/ɛ/	93	10	70	100	30
/ɔ/-/ɔ/	94	14	60	100	40
/a/-/a/	93	10	70	100	30

Table 5. Descriptive statistic analysis of same-vowel pair discrimination in CI children (in percent).

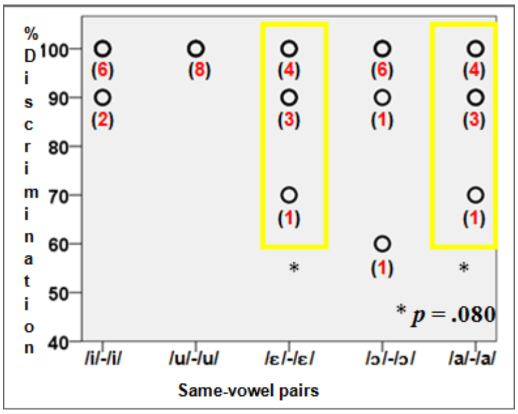


Figure 2. Same-vowel discrimination in CI children (mean values are given in percent). The sum of each column in correspondance of each vowel is always eight since eight are the CI children examined. The yellow rectangles refer to the statistical analysis in Table 6 below.

There pair /u/-/u/ was always correctly discriminated by NH and CI children Despite the slightly lower percentages exhibited by the CI children (cf. Table 5 above) as compared to the NH children (cf. Table 4 above), an independent *t*-test revealed that the percentages exhibited by CI and NH children were statistically comparable for discrimination of the pairs /i/-/i/ and

/ɔ/-/ɔ/. In the case of discrimination of /ɛ/-/ɛ/ and /a/-/a/, on the other hand, the result returned by the independent *t*-test approached statistical significance (cf. Table 6).

	Mean scores ± s. d.		
Vowels	NH children	CI children	Stat. Sig.
/i/-/i/	100	98 ± 5	*t*(7)=1.53, *p*=.170
/u/-/u/	100	100	-
/ɛ/-/ɛ/	**100**	**93 ± 10**	***t*(7)= 2.049, *p* = .080**
/ɔ/-/ɔ/	100	94 ± 14	*t*(7)= 1.256, *p* = .250
/a/-/a/	**100**	**93 ± 10**	***t*(7)= 2.049, *p* = .080**

Table 6. Inferential statistic analysis of same-vowel discrimination in CI vs. NH children (*t*-test for unpaired samples).

6.3.1.2 Accuracy in correct discrimination

Children' accuracy in discrimination of same-vowel pairs was measured as group *d'* values for each pair (cf. Table 7 and Table 8).

D' values of same-vowel pair discrimination in NH children					
Vowels	Mean	s. d.	Min.	Max.	Range
/i/-/i/	**6.93**	0	6.93	6.93	0
/u/-/u/	**6.93**	0	6.93	6.93	0
/ɛ/-/ɛ/	**6.93**	0	6.93	6.93	0
/ɔ/-/ɔ/	**6.93**	0	6.93	6.93	0
/a/-/a/	**6.93**	0	6.93	6.93	0

Table 7. Descriptive statistic analysis of same-vowel pair discrimination in NH children (in *d'* values).

D' values of same-vowel pair discrimination in CI children					
Vowels	Mean	s. d.	Min.	Max.	Range
/i/-/i/	**6.60**	0.61	5.61	6.93	1.32
/u/-/u/	**6.93**	0	6.93	6.93	0
/ɛ/-/ɛ/	**6.08**	1.03	4.12	6.93	2.81
/ɔ/-/ɔ/	**6.35**	1.18	3.66	6.93	1.18
/a/-/a/	**6.08**	1.03	4.12	6.93	2.81

Table 8. Descriptive statistic analysis of same-vowel pair discrimination in CI children (in *d'* values).

The *d'* value analysis indicated that, as expected, the NH children always obtained the highest *d'* value (e.g., 6.93) for same-vowel pair discrimination (cf. Table 7 above). CI children, on the other hand, obtained high *d'* values ranging between 6.08 and 6.93 (cf. Table 8 above). According to Macmillan & Creelman (1991, 2005), the fact that *d'* > 1 both for CI and NH children suggests that there were no a priori psychoacustic differences in the discriminability between the stimulus phonemes in same-vowel pairs.

The statistical analysis of the *d'* values in CI and NH children is presented in Table 9. In the case of discrimination of /u/-/u/, the *d'* value was exactly the same in CI and NH children. Despite the slightly lower *d'* values presented by CI as compared to NH children for the remaining four vowel pairs, an independent *t*-test revealed that *d'* values for discrimination of the pairs /i/-/i/ and /ɔ/-/ɔ/ were statistically comparable in CI and NH children, whereas the results returned by the independent *t*-test for discrimination of the pairs /ɛ/-/ɛ/ and /a/-/a/ approached statistical significance.

	Mean *d'* values		
Vowels	NH children	CI children	Stat. Sig.
/i/-/i/	6.93	6.60	*t*(7) = 1.528, *p* = .170
/u/-/u/	6.93	6.93	-
/ɛ/-/ɛ/	**6.93**	**6.08**	***t*(7) = 2.329, *p* = .053**
/ɔ/-/ɔ/	6.93	6.35	*t*(7) = 1.371, *p* = .213
/a/-/a/	**6.93**	**6.08**	***t*(7) = 2.329, *p* = .053**

Table 9. Mean *d'* values for discrimination of same-vowel pairs in NH and CI children (*t*-test for unpaired samples).

6.3.2 Discrimination of different-vowel pairs

The pediatric CI users had to discriminate six different-vowel pairs: /u/-/i/, /i/-/u/, /ɛ/-/i/, /i/-/ɛ/, /a/-/ɔ/and /ɔ/-/a/. We will investigate both frequency (cf. 6.3.2.1) and accuracy (cf. 6.3.2.2) in correct discrimination of different-vowel pairs. Afterwards, we will focus on other additional factors which are likely to play a role on behavioral vowel processing (cf. 6.3.2.3)..

6.3.2.1 Frequency in correct discrimination

Children' frequency in correct discrimination of different-vowel pairs was measured in group *percentages* for each pair (cf. Table 10 and Table 11). As expected, the NH children correctly discriminated different-vowel pairs in 100 percent of the cases (cf. Table 10), whereas the CI children managed to correctly discriminate different-vowel pairs with high frequencies (cf. Table 11 and Figure 3), although not systematically.

% of different-vowel pair discrimination in NH children					
Vowels	Mean	s. d.	Min.	Max.	Range
/i/-/u/	**100**	0	100	100	0
/u/-/i/	**100**	0	100	100	0
/i/-/ɛ/	**100**	0	100	100	0
/ɛ/-/i/	**100**	0	100	100	0
/ɔ/-/a/	**100**	0	100	100	0
/a/-/ɔ/	**100**	0	100	100	0

Table 10. Descriptive statistic analysis of different-vowel pair discrimination in NH children (in percent).

% of different-vowel pair discrimination in CI children					
Vowels	Mean	s. d.	Min.	Max.	Range
/i/-/u/	94	7	80	100	20
/u/-/i/	99	4	90	100	10
/i/-/ɛ/	91	10	70	100	30
/ɛ/-/i/	90	15	60	100	40
/ɔ/-/a/	88	17	50	100	50
/a/-/ɔ/	94	11	70	100	30

Table 11. Descriptive statistic analysis of different-vowel pair discrimination in CI children (in percent).

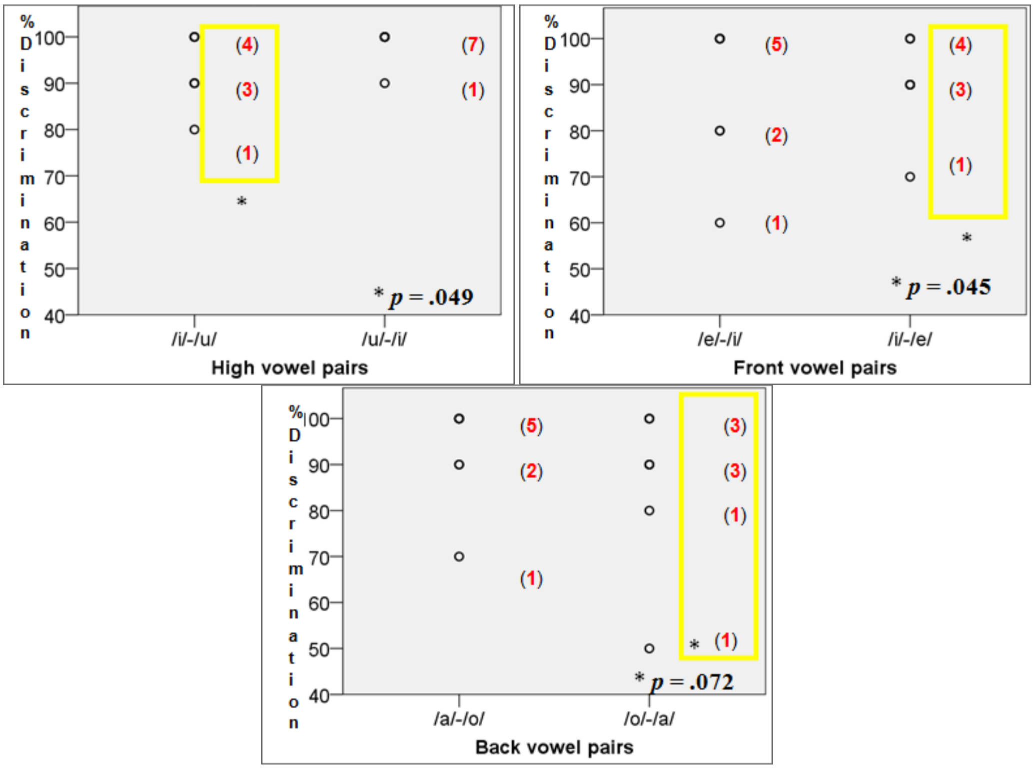


Figure 3. The CI children performance concerning discrimination of high (3a), front (3b), and low (3c) vowels (mean values are given in percent). The sum of each column in correspondance of each vowel is always eight since eight are the CI children examined. The yellow rectanges correspond to the statistical analysis in Table 12.

In spite of the often lower percentages presented by the CI children (cf. Table 11 above) as compared to the NH children (cf. Table 10 above), an independent *t*-test revealed that the percentages were statistically comparable in CI and NH children for discrimination of three (e.g., /u/-/i/, /ɛ/-/i/, and /ɔ/-/a/) out of the six vowel pairs. With respect to discrimination of the remaining three vowel pairs, the percentages were significantly lower in the CI as compared to the NH children for discrimination of the pairs /i/-/u/ and /i/-/ɛ/, whereas the result returned by the independent *t*-test approached statistical significance for discrimination of the pair /ɔ/-/a/ (cf. Table 12).

	Mean ± s. d.		
Vowels	NH children	CI children	Stat. Sig.
/i/-/u/	**100**	**94 ± 7**	**_t_(7)= 2.376, _p_ = .049**
/u/-/i/	100	99 ± 4	_t_(7)= 1.000, _p_ = .351
/i/-/ɛ/	**100**	**91 ± 10**	**_t_(7)= 2.497, _p_ = .045**
/ɛ/-/i/	100	90 ± 15	_t_(7)= 1.871, _p_ = .104
/ɔ/-/a/	**100**	**88 ± 17**	**_t_(7)= 2.118, _p_ = .072**
/a/-/ɔ/	100	94 ± 11	_t_(7)= 1.667, _p_ = .140

Table 12. Inferential statistic analysis of different-vowel pair discrimination in CI vs. NH children (*t*-test for unpaired samples).

We need to draw attention on the fact that, out of the six different-vowel pairs, three were correctly discriminated with comparable frequency by CI and NH children, whereas the remaining three were correctly discriminated with lower frequency by CI as compared to NH children. From these results, we infer that /u/-/i/, /ɛ/-/i/, and /a/-/ɔ/ are easier-to-discriminate for CI as compared to NH children relative to /i/-/u/, /i/-/ɛ/, and /ɔ/-/a/, which, on the other hand, may be regarded as more-difficult-to-discriminate.

6.3.2.2 Accuracy in correct discrimination

Children' accuracy in discrimination of different-vowel pairs was measured in group *d'* values for each pair (cf. Table 13 and Table 14).

D' of different-vowel pair discrimination in NH children					
Vowels	Mean	s. d.	Min.	Max.	Range
/u/-/i/	**6.93**	0	6.93	6.93	0
/ɛ/-/i/	**6.93**	0	6.93	6.93	0
/a/-/ɔ/	**6.93**	0	6.93	6.93	0
/i/-/u/	**6.93**	0	6.93	6.93	0
/i/-/ɛ/	**6.93**	0	6.93	6.93	0
/ɔ/-/a/	**6.93**	0	6.93	6.93	0

Table 13. Descriptive statistic analysis of different-vowel pair discrimination in NH children (in *d'* values).

D' of different-vowel pair discrimination in CI children						
Degree of difficulty	Vowels	Mean	s. d.	Min.	Max.	Range
Easier-to-discriminate	**/u/-/i/**	**6.76**	0.47	5.61	6.93	1.32
	/ɛ/-/i/	**5.97**	1.37	3.66	6.93	3.27
	/a/-/ɔ/	**6.14**	1.31	3.26	6.93	3.67
Difficult-to-discriminate	**/i/-/u/**	**6.16**	0.87	4.72	6.93	2.21
	/i/-/ɛ/	**6.08**	1.03	4.12	6.93	2.81
	/ɔ/-/a/	**5.58**	1.33	3.26	6.93	3.67

Table 14. Descriptive statistic analysis of different-vowel pair discrimination in CI children (in *d'* values).

The *d'* value analysis showed that, as expected, the NH children always obtained the highest *d'* value (e.g., 6.93) for discrimination of different-vowel pairs, whereas the CI children obtained high *d'* values ranging between 5.58 and 6.76. Along the lines of Macmillan & Creelman [1991, 2005], the fact that *d'* > 1 both for CI and NH children suggests that there were no a priori psychoacustic differences in discriminability between the stimulus phonemes in different-vowel pairs. The statistical analysis of the *d'* values is presented in Table 15 and it revealed some interesting results. First of all, the *d'* values concerning accuracy in discrimination of /u/-/i/ and /a/-/ɔ/ were statistically comparable in CI and NH chldren. Second, the *d'* values relative to accuracy in discrimination of /i/-/ɛ/ and /ɛ/-/i/ approached statistical significante. Third, the *d'* values conceening accuracy in discrimination of /i/-/u/ and /ɔ/-/a/ were significantly lower in CI as compared to NH children.

Mean *d'* values			
Vowels	NH children	CI children	Stat. Sig.
/i/-/u/	**6.93**	**6.16**	***t*(7)= 2.04 , *p* = .041**
/u/-/i/	6.93	6.76	*t*(7)= 1.00, *p* = .351
/i/-/ɛ/	**6.93**	**6.08**	***t*(7)= 2.32, *p* = .053**
/ɛ/-/i/	**6.93**	**5.97**	***t*(7)= 1.990, *p* = .051**
/ɔ/-/a/	**6.93**	**5.58**	***t*(7)= 2.85, *p* = .024**
/a/-/ɔ/	6.93	6.14	*t*(7)= 1.07, *p* = .132

Table 15. Mean *d'* values for discrimination of different-vowel pairs in NH and CI children (*t*-test for unpaired samples).

6.3.2.3 Vowel quality, the Euclidean distance, and direction of change in the direction of change in the distinctive feature specification

With respect to vowel quality, the CI children discriminated pairs of high (e.g., /u/-/i/ and /i/-/u/), front (e.g., /ɛ/-/i/ and /i/-/ɛ/), and back (e.g., /a/-/ɔ/ and /ɔ/-/a/) vowels. An independent *t*-test was run to investigate whether vowel quality played an influence on the frequency and accuracy of correct discrimination of different-vowel pairs (cf. Table 16).

	in CI children			
	High vowels (/i/$_{std}$ - /u/$_{dev}$, /u/$_{std}$ - /i/$_{dev}$) (E.d. = **847 Mel**)	Front vowels (/i/$_{std}$ - /ɛ/$_{dev}$, /ɛ/$_{std}$ - /i/$_{dev}$) (E.d. = **322 Mel**)	Back vowels (/a/$_{std}$ - /ɔ/$_{dev}$, /ɔ/$_{std}$ - /a/$_{dev}$) (E.d. = **304 Mel**)	Stat. Sig.
percentages	96 ± 6	91 ± 6	89 ± 16	$F(2, 28) = 1.422$, $p = .257$
d' values	7 ± .7	6 ± 1.2	6 ± 1.3	$F(4, 33) = 1.841$, $p = .179$

Table 16. Vowel quality and vowel discrimination at the behavioral level.

Independently of vowel quality, high, front, and back vowels were processed with comparable frequency and accuracy by CI children.

As for the Euclidean distance between the vowels of a pair, it was smaller for /ɛ/ vs. /i/ (322Mel) and for /a/ vs. /ɔ/ (304 Mel), but larger for /u/ vs. /i/ (834Mel). As Table 16 above clearly shows, despite the larger Euclidean distance characterizing the high vowel pairs, they were discriminated neither with higher frequency nor with higher accuracy by CI children as compared to front and back vowels.

With respect to direction of change in the distinctive feature specification, the pairs /u/-/i/ and /a/-/ɔ/ appeared to be discriminated with higher frequency (cf. Table 12 above) and with higher accuracy (cf. Table 15 above) by the CI children as compared to /i/-/u/ and /ɔ/-/a/. Recall from 4.4.3 that /u/ is specified as [+BACK, +ROUND], while /i/ is specified as [-BACK, -ROUND]. High vowel pairs turn out to be correctly discriminated more frequently and with higher accuracy when the first vowel is specified as [+] for a couple of phonological features and the second vowel is specified as [-] for the same phonological features. Recall from 4.4.3 that /a/ is specified as [+LOW, -ROUND], while /ɔ/ is specified as [-LOW, +ROUND]. Back vowels are correctly discriminated with higher frequency and higher accuracy provided that the first vowel is specified as [+LOW] and the second vowel is discriminated as [-LOW]. Recall from 4.4.3 that /ɛ/ is specified [-HIGH, -ATR], while /i/ is specified as [+HIGH, +ATR], Front vowels appear to be discriminated with higher frequency, but not with higher accuracy, when the first vowel is specified as [-] for a couple of distinctive features and the second vowel is specified as [+] for the same distinctive features.

To conclude, in the case of vowel pairs characterized by a comparable Euclidean distance (e.g., /u/-/i/ and /i/-/u/), direction of change in the distinctive feature specification does not appear to unequivocally constrain discrimination of different-vowel pairs at the behavioral level.

6.4 The age at surgery

One of the aims of the present study consisted in clarifying whether or not, and to what extent, age at CI surgery was likely to influence behavioral vowel processing in a group of deaf Italian children implanted during the sensitive period for maturation of the auditory pathways.

The mean age at surgery of the CI children examined was 2.8 years and it ranged between 2.1 and 4.4 years (cf. 4.3). Our hypothesis (cf. 5.3.5) is that deaf children implanted later in their lives (i.e. towards 4.4 years) were likely to categorize single vowels and to discriminate vowel pairs with a lower frequency and accuracy as compared to deaf children implanted earlier in their lives (i.e. towards 2.1 years). We recurred to a *bivariate correlation analysis* to investigate the possible influence played by age at surgery on behavioral vowel processing (cf. Table 17).

Age at surgery and behavioral vowel processing							
Categorization		V1-V1 discrimination			V1-V2 discrimination		
Vowels	%	Pairs	%	*d'*	Pairs	%	*d'*
/i/	r = .447, p = .227	**/i/-/i/**	r = -.281, p = .501	r = -.336, p = .415	**/i/-/u/**	r = -.257, p = .539	r = -.026, p = .952
/u/	r = -.434, p = .283	**/u/-/u/**	-	-	**/u/-/i/**	r = .404, p = .321	r = .305 , p = .463
/ɛ/	r = .104, p = .806	**/ɛ/-/ɛ/**	r = -.334, p = .419	r = -.536, p = .171	**/i/-/ɛ/**	r = .097, p = .820	r = -.309 , p = .456
/ɔ/	r = -.022, p = 858	**/ɔ/-/ɔ/**	r = -.022, p = .958	r = -.015, p = .971	**/ɛ/-/i/**	r = .049, p = .908	r = -.065, p = .878
/a/	r = -.537, p = .170	**/a/-/a/**	r = .099, p = .815	r = -145, p = .732	**/ɔ/-/a/**	r = .030, p = .944	r = -229, p = .585
-					**/a/-/ɔ/**	r = .050, p = .906	r = -.022, p = .995

Table 17. Correlation between age at surgery and behavioral vowel processing (bivariate correlation).

The results of the statistical analysis presented in Table 17 clearly showed that, in the case of deaf children implanted during the optimal age range, earlier age at surgery did not significantly facilitate either frequency or accuracy in correct categorization of single vowels as well as in correct discrimination of vowel pairs as compared to later age at surgery. Likewise, both the Euclidean distance and direction of change in the vowel phonological specification (cf. 6.3.2.3) turned out to be irrelevant for constraining vowel processing in the case of early-implanted children. Having clarified that age at surgery is irrelevant for the behavioral vowel processing in children implanted early in their lives, the following section investigates whether duration of CI stimulation is likely to contrain behavioral vowel processing.

6.5 The duration of CI stimulation

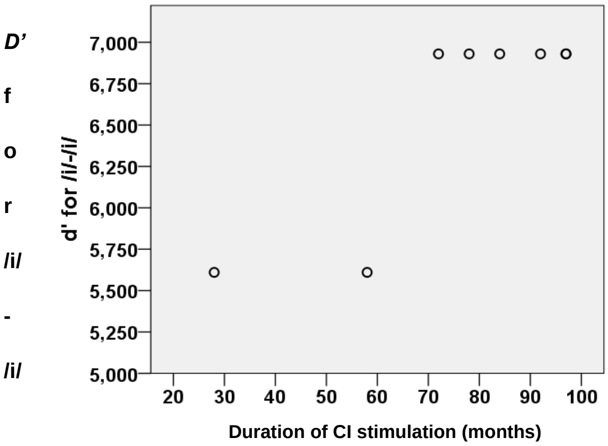
This study wanted to shed light on a crucial issue concerning pediatric CI users, i.e. whether or not duration of CI stimulation crucially constrains behavioral vowel processing in the case of deaf children implanted before 3.5 years.

The mean duration of CI stimulation at testing of the children examined was 6.3 yrs and it ranged between 2.4 and 8.1 years (cf. 4.3). We hypothesize (cf. 5.3.7) that deaf children benefiting from a shorter duration of CI use (i.e. towards 2.4 years) were able to correctly categorize single vowels and to correctly discriminate vowel pairs with a lower frequency and accuracy as compared to deaf children using their CI from a longer period (i.e. towards 8.1 years). Once more, we recurred to a *bivariate correlation analysis* to investigate the possible influence played by duration of CI stimulation on behavioral vowel processing (cf. Table 18).

Duration of CI stimulation and behavioral vowel processing							
Categorization		V1-V1 discrimination			V1-V2 discrimination		
Vowels	%	Pairs	%	*d'*	Pairs	%	*d'*
/i/	$r = .048$, $p = .910$	**/i/-/i/**	$r = .271$, $p = .590$	**$r = .862$,** **$p = .006$**	**/i/-/u/**	$r = .121$, $p = .776$	$r = -.207$, $p = .623$
/u/	$r = .285$, $p = .493$	**/u/-/u/**	-	-	**/u/-/i/**	$r = .306$, $p = .461$	$r = .306$, $p = .461$
/ɛ/	$r = -.309$, $p = .456$	**/ɛ/-/ɛ/**	$r = .068$, $p = .873$	$r = .105$, $p = .804$	**/i/-/ɛ/**	$r = .174$, $p = .681$	$r = .229$, $p = .585$
/ɔ/	$r = 104$, $p = 807$	**/ɔ/-/ɔ/**	$r = .104$, $p = .807$	$r = -.182$, $p = .666$	**/ɛ/-/i/**	$r = - 073$, $p = .864$	$r = -.077$, $p = .856$
/a/	r = .334, $p = .419$	**/a/-/a/**	$r =.052$, $p = .903$	$r = -.231$, $p = .582$	**/ɔ/-/a/**	$r = .007$, $p = .987$	$r = -.349$, $p = .397$
-					**/a/-/ɔ/**	$r = -.016$, $p = .969$	$r = -.300$, $p = .471$

Table 18. Correlation between length of CI use and behavioral vowel processing (bivariate correlation).

The results of the statistical analysis presented in Table 18 indicated that, in the case of deaf children implanted during the optimal age range, longer duration of CI use turned out to be irrelevant either for categorization of single vowels or for discrimination of vowel pairs. A single exception is represented by accuracy in correct discrimination of the pair /i/-/i/ (cf. Figure 4), in the sense that those deaf children benefiting from a duration of CI stimulation of at least 5.8 years turned out to discriminate /i/-/i/ more accurately as compared to deaf children benefiting from a shorter duration of CI stimulation.



Months	= Years.Months
20	= 1.8
30	= 2.6
40	= 3.4
50	= 4.2
60	= 5
70	= 5.8
80	= 6.6
90	= 7.4
100	= 8.2

Figure 4. Correlation between length of CI use (in months) and *d'* values for discrimination of /i/-/i/.

Once more, both the Euclidean distance and direction of change in the vowel phonological specification (cf. 6.3.2.3) appeared to be irrelevant in constraining vowel processing in the case of experienced pediatric CI users. We conclude that, in the case of deaf children implanted before 3.5 years, the longer vs. shorter duration of stimulation hardly ever affects either the frequency or the accuracy of behavioral vowel processing.

6.6 Discussion

For the first time, the present study investigated vowel processing in Italian deaf children wearing unilateral CIs by means of behavioral measures directed at subjects’ conscious categorization and discrimination of vowels. The present study also aimed at ascertaining whether or not younger age at surgery and longer duration of CI stimulation were likely to significantly constrain frequency and accuracy in vowel processing in a group of deaf children who received their unilateral CIs before 3.5 years.
First of all, the findings of the present study clearly show that, despite the initial auditory deprivation (from 2.1 to 4.4 years) experienced by Italian CI children, the behavioral performance of vowel categorization and discrimination of the CI children examined was largely comparable to that of the NH children examined. In the following, we will first discuss vowel categorization (cf. 6.6.1) and then discrimination of same- and different-vowel pairs (cf. 6.6.2). Finally, the role played by age at surgery (cf. 6.6.3), duration of CI stimulation (cf. 6.6.4), and additional minor factors (cf. 6.6.5) will also be addressed.

6.6.1 Vowel categorization

The Italian CI children had to behaviorally categorize the five Salento Italian vowels, i.e. /i/, /u/, /a/, /ɛ/, and /ɔ/. The five vowels were correctly categorized with comparable frequency by CI and NH children,.Thus, in contrast to previous acoustic studies (cf. 3.13.2), our data indicate that vowel quality hardly ever contrain vowel categorization in CI children. Rather, in spite of the often reduced and degraded auditory feedback provided by CI devices, pediatric CI users manage to correctly categorized the Salento Italian vowels in the absence of background noise and provided that they underwent CI surgery during the optimal age range.

6.6.2 Vowel discrimination

The pediatric CI users were asked to behaviorally discriminate five same-vowel pairs (e.g., /i/-/i/, /u/-/u/, /a/-/a/, /ɛ/-/ɛ/, and /ɔ/-/ɔ/) and six different-vowel pairs (e.g., /u/-/i/, /i/-/u/, /ɛ/-/i/, /i/-/ɛ/, /a/-/ɔ/and /ɔ/-/a/) (cf. 5.3).

As far as discrimination of same-vowel pairs is concerned, different patters were categorized. First, the pair /u/-/u/ was always correctly discriminated with the highest frequency and accuracy by all children. Second, the pairs /i/-/i/ and /ɔ/-/ɔ/ were discriminated with comparable frequency and accuracy by CI and NH children. Finally, the pairs /ɛ/-/ɛ/ and /a/-/a/ were correctly discriminated by CI children with a slight lower frequency and accuracy as compared to NH children. Hence, when comparing Italian CI and NH children, /u/-/u/, /i/-/i/, and /ɔ/-/ɔ/ appeared easier-to-discriminate as compared to /ɛ/-/ɛ/ and /a/-/a/ for CI children.

With respect to discrimination of different-vowel pairs, the results relative to frequency in correct discrimination did not always match with the findings concerning accuracy in correct discrimination. As for frequency in correct discrimination, Italian CI children were able to correctly discriminate the pairs /u/-/i/, /ɛ/-/i/, and /a/-/ɔ/ with comparable frequency with respect to NH children. The pairs /i/-/u/, /i/-/ɛ/, and /ɔ/-/a/, on the other hand, were correcty discriminated with significantly lower frequencies by CI as compared to NH children.

If we now move to accuracy in vowel discrimination, a more fine-grained picture will emerge. First, the pairs /u/-/i/ and /a/-/ɔ/ were discriminated with comparable accuracy by CI and NH chldren. Second, the pairs /i/-/ɛ/ and /ɛ/-/i/ were discriminated with a slightly lower accuracy by CI relative to NH children. Finally, the pairs /i/-/u/ and /ɔ/-/a/ were clearly discriminated with a lower accuracy by CI as compared to NH children.

Put together, percentages and *d'* values tell us that the pairs /u/-/i/, /ɛ/-/i/, and /a/-/ɔ/ were easier-to-discriminate as compared to /i/-/u/, /i/-/ɛ/, and /ɔ/-/a/ for italian CI as compared to NH children.

6.6.3 The age at surgery

Previous ERP studies have found that deaf children implanted before 3.5 years typically receive the greatest benefit from CI stimulation, while deaf children implanted afterwards (up to 13 years) usually receive significant benefit from CI stimulation, although much greater variation in auditory performance was likely to be acknowledged [Waltzman et al. 2002; Harrison et al. 2005; Sharma et al. 2005, 2009; Sharma & Dorman 2006; Gilley et al. 2008; Holt & Svirsky 2008; Dinces et al. 2009; Munivrana & Mildner 2013]. We wanted to ascertain whther or not age at surgery is likely to constrain speech sound processing at the behavioral level as well.

In the present study, age at surgery (range: 2.1 - 4.4 years) turned out to be irrelevant both for vowel categorization and for vowel discrimination at the behavioral level in CI children: deaf children implanted later in their lives (i.e. towards 4.4 years) did not categorize isolated vowels nor discriminate vowel pairs with a lower frequency or accuracy as compared to deaf children implanted earlier in their lives (i.e. towards 2.1 years).

6.6.4 The duration of CI stimulation

Previous ERP studies monitoring the influence played by duration of CI stimulation on (speech) sound processing at the neurophysiological level in early-implanted CI children have reported confusing results. On the one hand, shorter ERP latencies and larger ERP amplitudes were found in CI children implanted early in their lives (≤ 3.5 years) provided that they had been using their CI for at least 5 years [cf. Torppa et al. 2013] or 6 years [cf. Ortmann et al. 2013]. On the other hand, no differences were found in the ERP values evoked in early-implanted children who had been using their unilateral CI for a period of at least 4 years [cf. Munivrana & Mildner (2013)]. The possible influence played by duration of CI stimulation on vowel processing at the behavioral level had never been investigated before. We want to cast light on this aspect.

In the present study, duration of CI device use (range: 2.4 - 8.1 years) did not appear to affect behavioral vowel categorization and discrimination in CI children: both deaf children using their CI from a longer period (i.e. towards 8.1 years) and deaf children benefiting from a shorter length of CI use (i.e. towards 2.4 years) were able to correctly categorize isolated vowels and to correctly discriminate vowel pairs with comparable frequency.

6.6.5 Vowel quality, the Euclidean distance, and direction of change in the distinctive feature specification

Previous acoustic studies in CI children indicate that mid vowels are likely to be more difficult to produce as compared to low and high vowels or that back vowels are more difficult to realize as compared to front vowels (cf. 3.13.2). We want to cast light on whether mid and/or back vowels are likely to be more difficult to perceive at the behavioral level as well.

Contra previous studies, the results achieved in the present study suggest that mid and back vowels are not more-difficult to categorize as compared to the other vowels. Likewise, those pairs containing at least one mid or one back vowel are not more-difficult to discriminate relative to the other pairs.

With respect to the Euclidean distance, previous ERP studies show that vowel pairs characterized by a larger Euclidean distance are easier-to-discriminate as compared to those vowel pairs characterized by a smaller Euclidean distance (cf. 4.4.5). We aim at clarigying whether this hold at the behavioral level as well.

In contrast to the results of previous researches, the findings of the present study clearly indicate that pairs of high (Euclidean distance: 834Mel), front (Euclidean distance: 322Mel), and back (Euclidean distance: 304Mel) vowels are discriminated with comparable frequency and accuracy by the CI children at the behavioral level.

As for direction of change in the distinctive feature specification, previous ERP studies find out that different-vowel pairs were discriminated faster and more accurately when the first vowel was specified as [+] for a distinctive feature and the second vowel was specified as [-] for the same distinctive feature (cf. 4.6.1). We want to understand whether or not the same findings hold for the behavioral level as well.

The results of the present study demonstrate that direction of change in the distinctive feature specification does not unequivocally constrain the discrimination of vowel pairs at the behavioral level. On the one hand, pairs of high vowels are discriminated with higher frequency and accuracy when the first vowel is specified as [+] for a couple of distinctive features and the second vowel is specified as [-] for the same couple of distinctive features. On the other hand, pairs of front vowels are discriminated with higher frequency and accuracy when the first vowel is specified as [-] for a couple of distinctive features and the second vowel is specified as [+] for the same couple of distinctive features.

6.7 Chapter summary

Categorization of single vowels and discrimination of vowel pairs (both same- and different-vowel pairs) were investigated behaviorally in CI as compared to NH children.

Vowel categorization was compromised neither fro frequency nor for accuracy in CI children. Discrimination of vowel pairs, on the other hand, was likely to be partially impaired for frequency and accuracy in CI as compared to NH children, although not systematically.

CHAPTER 7

Neurophysiological vowel processing I: The vowel-evoked ERP responses, their scalp topography, their response strength, and their scalp distribution

7.1 Introduction

The CI and the NH children participated in a neurophysiological experiment where automatic processing of high (e.g., /i/$_{\text{std}}$ - /u/$_{\text{dev}}$ and /u/$_{\text{std}}$ - /i/$_{\text{dev}}$), mid (e.g., /i/$_{\text{std}}$ - /ɛ/$_{\text{dev}}$ and /ɛ/$_{\text{std}}$ - /i/$_{\text{dev}}$), and back (e.g., /a/$_{\text{std}}$ - /ɔ/$_{\text{dev}}$ and /ɔ/$_{\text{std}}$ - /a/$_{\text{dev}}$) vowels at the cortical level was investigated by recurring to the P1, N1, and MMN responses of the auditory ERPs. The neurophysiological experiment was administered passively, that is at a pre-attentive level, since it aimed at throwing light on the automatic vowel processing in pediatric CI users (cf. 4.6). In the following, we will first present the results concerning the automatic processing of high (cf. 7.2), front (cf. 7.3), and back (cf. 7.4) vowels. The whole neurophysiological results will then be discussed (cf. 7.5). A summary closes this chapter (cf. 7.6).

7.2 The automatic processing of high vowels

The automatic processing of the pairs /i/$_{\text{std}}$ - /u/$_{\text{dev}}$ and /u/$_{\text{std}}$ - /i/$_{\text{dev}}$ will be presented in 6.2.1 and 6.2.2. For the ERP responses, we will present their values of latency, amplitude, and area, their scalp topography (as indicated in the voltage maps), their response strength (as indicated by scalp activation in the voltage maps) as well as their scalp distribution and the consequent hemisphere commitment.

7.2.1 The pair /i/$_{\text{std}}$ - /u/$_{\text{dev}}$

We will first focus on the obligatory (cf. 7.2.1.1) and then on the discriminative (cf. 7.2.1.2) responses of the auditory ERPs evoked by /i/$_{\text{std}}$ and /u/$_{\text{dev}}$ in NH and in CI children.

7.2.1.1 The auditory P1 and N1 responses

The auditory P1 and N1 responses were identified in all children: their values are presented in Table 1 for NH children and in Table 2 for CI children, whereas their grand averages are displayed in Figure 1.

	NH children							
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/i/$_{std}$	Lat. (ms)	**88**	**15**	48	120	72
		Ampl. (μV)	**1.27**	**1.09**	-.27	5.35	5.62
	/u/$_{dev}$	Lat. (ms)	**91**	**17**	48	120	72
		Ampl. (μV)	**0.80**	**1.10**	- 2.53	3.51	6.04
N1	/i/$_{std}$	Lat. (ms)	**185**	**30**	140	256	116
		Ampl. (μV)	**-1.64**	**1.14**	- 4.94	.66	5.60
	/u/$_{dev}$	Lat. (ms)	**189**	**28**	144	260	116
		Ampl. (μV)	**-1.79**	**1.27**	- 4.88	.55	5.42

Table 1: Descriptive statistic analysis of the P1 and N1 values for /i/$_{std}$ and /u/$_{dev}$ in NH children.

	CI children						
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/i/$_{std}$	Lat. (ms)	**86**	**16**	64	128	64
		Ampl. (μV)	**0.85**	**0.88**	-.81	3.54	4.35
	/u/$_{dev}$	Lat. (ms)	**88**	**21**	48	128	80
		Ampl. (μV)	**0.94**	**0.95**	-.52	4.09	4.61
N1	/i/$_{std}$	Lat. (ms)	**181**	**35**	140	260	120
		Ampl. (μV)	**-0.76**	**1.29**	-5.00	2.52	7.53
	/u/$_{dev}$	Lat. (ms)	**185**	**32**	140	260	120
		Ampl. (μV)	**-1.19**	**1.43**	-6.09	1.92	8.01

Table 2: Descriptive statistic analysis of the P1 and N1 values for /i/$_{std}$ and /u/$_{dev}$ in CI children.

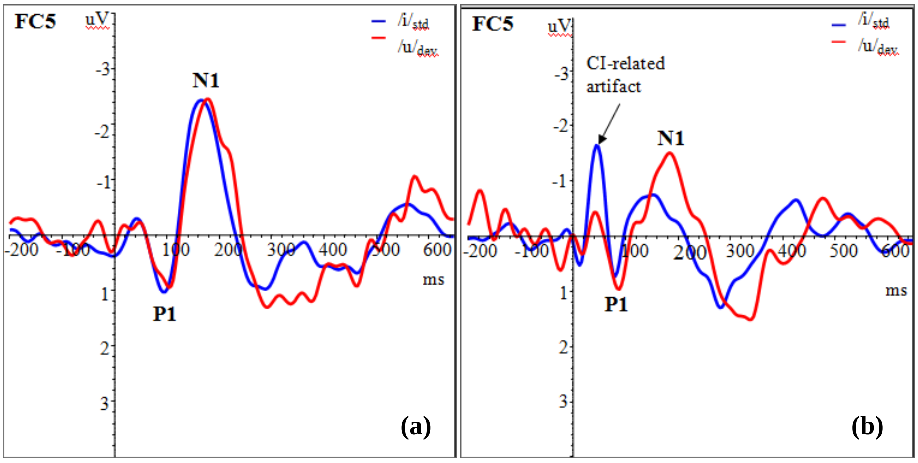


Figure 1: Grand averages to /i/$_{std}$ (blue) and /u/$_{dev}$ (red) at FC5 for NH (a) and CI (b) children.

An independent *t*-test comparing the P1 and N1 values evoked by /i/$_{std}$ and /u/$_{dev}$ in CI and NH children revealed that the latencies of P1 and N1 found in the CI children were not significantly different from those exhibited by the NH children (cf. Table 3). As far as the amplitudes are concerned, the situation is different for P1 relative to N1. The P1 amplitude appeared significantly smaller in the CI as compared to the NH children when P1 had been evoked by /i/$_{std}$, which is clearly reflected in the grand average waves (cf. Figure 1b vs. Figure 1a above), but not when P1 had been evoked by /u/$_{dev}$. The N1 amplitude, on the other hand, was systematically significantly reduced in CI with respect to NH children (cf. Table 3), which is to be clearly seen in the grand average waves of /i/$_{std}$ and /u/$_{dev}$ (cf. Figure 1b vs. Figure 1a above).

	Vowel	Values	NH children	CI children	Stat. Sig.
P1	/i/$_{std}$	Lat. (ms)	88 ±15	86 ± 16	$t(134) = .928$, $p = .355$
		Ampl. (µV)	**1.27 ± 1.09**	**0.85 ± 0.88**	**$t(133) = 2.434$, $p = .016$**
	/u/$_{dev}$	Lat. (ms)	91 ± 17	88 ± 21	$t(134) = 1.607$, $p = .288$
		Ampl. (µV)	0.80 ± 1.10	0.94 ± 0.94	$t(134) = -.793$, $p = .429$
N1	/i/$_{std}$	Lat. (ms)	185 ± 30	181 ± 35	$t(134) = .716$, $p = .475$
		Ampl. (µV)	**-1.64 ± 1.14**	**-0.76 ± 1.29**	**$t(134) = 4.172$, $p < .001$**
	/u/$_{dev}$	Lat. (ms)	189 ± 28	185 ± 32	$t(134) = .817$, $p = .415$
		Ampl. (µV)	**-1.79 ± 1.27**	**-1.19 ± 1.43**	**$t(134) = 2.613$, $p = .010$**

Table 3: Mean (± s.d.) values of P1and N1 evoked by /i/$_{std}$ and /u/$_{dev}$ in NH and CI children.

With respect to the scalp topography and the response strength, the voltage maps illustrating the dynamic of the P1 and N1 peaks are presented in Figure 2 (for P1) and in Figure 3 (for N1).

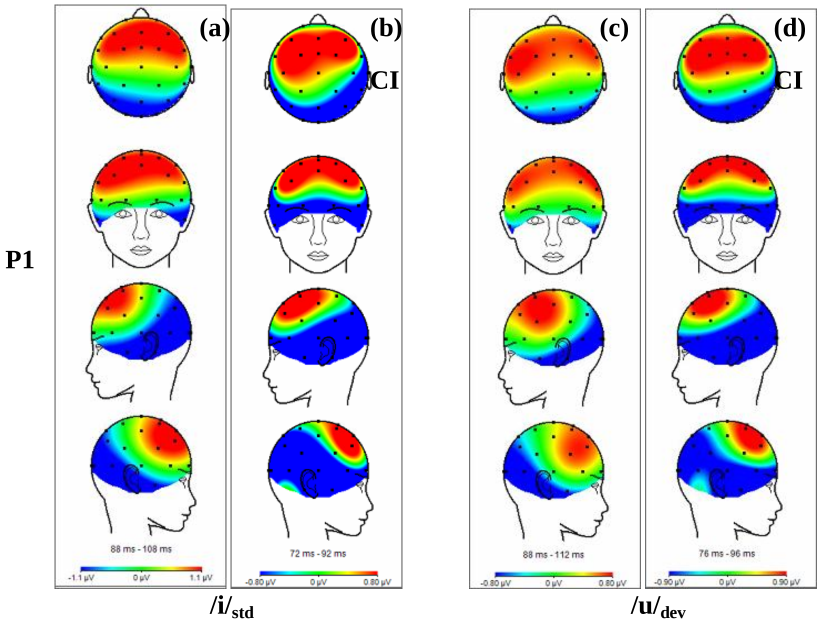


Figure 2: Voltage maps of the P1 peak evoked by **/i/$_{std}$** and **/u/$_{dev}$** in NH (a, c) and CI (b, d) children, illustrating the P1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

Visual inspection of the voltage maps clearly indicates that the P1 response had a similar scalp topography and strength in both groups of children: P1 was a robust positivity with fronto-central displacement both for the NH (cf. Figure 2a and Figure 2c above) and for the CI (cf. Figure 2b and Figure 2b above) children at the bilateral level. Nevertheless, it has to be pointed out that the reduced amplitude of P1 evoked by /i/$_{std}$ in the CI relative to the NH children (cf. Table 3 above) is not reflected in the voltage maps which illustrate a comparable scalp activation (cf. Figure 2b vs. Figure 2a above).

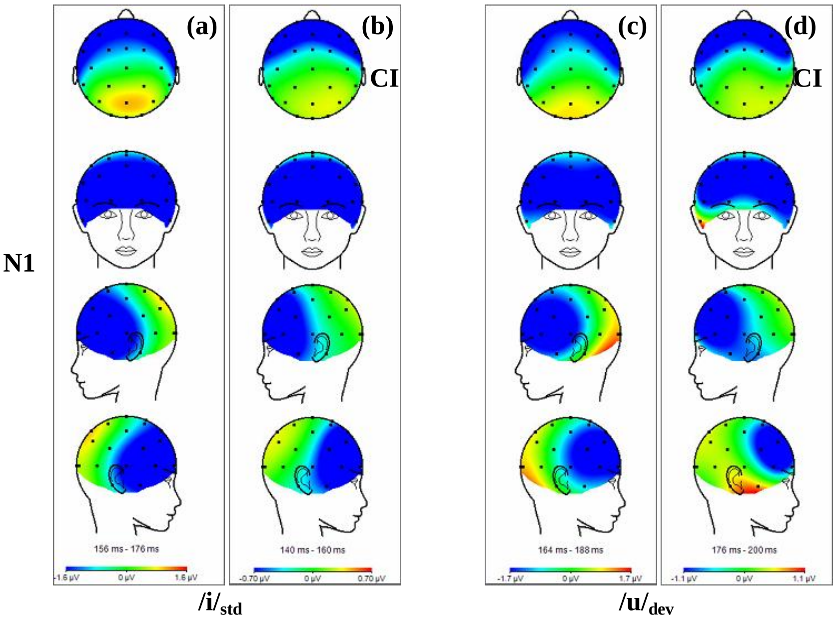


Figure 3: Voltage maps of the N1 peak evoked by **/i/$_{\mathbf{std}}$** and **/u/$_{\mathbf{dev}}$** in NH (a, c) and CI (b, d) children, illustrating the P1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

Visual inspection of the voltage maps suggests that the N1 response presented a similar scalp topography and strength in both groups of children: N1 was a robust negativity with fronto-temporal displacement both in NH (cf. Figure 3a and Figure 3c above) and in CI (cf. Figure 3b and Figure 3b above) children at the bilateral level. The reduced amplitude of N1 evoked by /i/$_{\text{std}}$ in CI relative to NH children (cf. Table 3 above) was clearly reflected in the voltage maps (cf. Figure 3b vs. Figure 3a above), whereas this did not hold for the reduced amplitude of N1 evoked by /u/$_{\text{dev}}$ (cf. Table 3, Figure 3d vs. Figure 3c above).

The scalp distribution of P1 and N1 over both hemispheres and the consequent hemisphere involvement are presented in Table 4 for NH children and in Table 5 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/i/$_{\text{std}}$	Lat. (ms)	**82 ± 16**	**92 ± 13**	**t(70) = 2.263, *p* = .027**
		Ampl. (µV)	1.31 ± 1.11	1.23 ± 1.10	t(70) = .324, *p* = .747
	/u/$_{\text{dev}}$	Lat. (ms)	91 ± 17	91 ± 18	t(70) = .109, *p* = .913
		Ampl. (µV)	.86 ± .94	.74 ± 1.26	t(70) = .476, *p* = .635
N1	/i/$_{\text{std}}$	Lat. (ms)	184 ± 29	186 ± 31	t(70) = -.235, *p* = .815
		Ampl. (µV)	-1.65 ± 1.02	-1.61 ± 1.27	t(70) = -.153, *p* = .879
	/u/$_{\text{dev}}$	Lat. (ms)	188 ± 26	189 ± 30	t(70) = -.100, *p* = .920
		Ampl. (µV)	-1.91 ± 1.27	-1.69 ± 1.28	t(70) = -.718, *p* = .475

Table 4: Scalp distribution of the P1 and N1 values (mean ± s.d.) elicited by /i/$_{\text{std}}$ and /u/$_{\text{dev}}$ in NH children.

In the NH children, the latency and amplitude values of P1 and N1 appeared widely comparable on the left and the right hemispheres (cf. Table 4 above). This situation is also confirmed by the voltage maps showing equal magnitude for P1 (cf. Figure 2a and 2c above) and N1 (cf. Figure 3a and Figure 3c above) over both hemispheres in the NH children. Therefore, it is not surprising that an assessment of the symmetry of the P1 and N1 responses over both hemispheres revealed no statistically significant differences in their values. Even though the P1 and N1 responses evoked by /i/$_{\text{std}}$ and /u/$_{\text{dev}}$ appeared equally distributed over both hemispheres in the NH children, one exception to this situation is nevertheless worth emphasizing: the latency of P1 evoked by /i/$_{std}$ turned out to be significantly shorter over the left as compared to the right hemisphere (t(70) = 2.263, *p* = .027).

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/i/$_{std}$	Lat. (ms)	83 ± 13	89 ± 18	t(57) = 1.425, *p* = .160
		Ampl. (µV)	.86 ± .87	.85 ± .89	t(62) = .009, *p* = .993
	/u/$_{dev}$	Lat. (ms)	89 ± 23	88 ± 19	t(62) = -.047, *p* = .962
		Ampl. (µV)	1.05 ± .95	.83 ± .95	t(62) = .936, *p* = .353
N1	/i/$_{std}$	Lat. (ms)	184 ± 35	178 ± 35	t(62) = .587, *p* = .559
		Ampl. (µV)	-.85 ± 1.09	-.67 ± 1.49	t(62) = -.545, *p* = .588
	/u/$_{dev}$	Lat. (ms)	**193 ± 27**	**177 ± 34**	**t(59) = 2.037, *p* = .046**
		Ampl. (µV)	-1.12 ± 1.29	-1.26 ± 1.57	t(62) = .387, *p* = .700

Table 5: Scalp distribution of the P1 and N1 values (mean ± s.d.) elicited by /i/$_{std}$ and /u/$_{dev}$ in CI children.

As for the CI children, the latencies and amplitudes of P1 and N1 appeared largely comparable on the left and the right electrode sites (cf. Table 4 above). Therefore, it is not surprising that an assessment of the symmetry of P1 and N1 responses over the left and the right electrode sites revealed no statistically significant differences. An exception to this state of affairs is represented by the latency of N1 evoked by /u/$_{dev}$ which resulted significantly shorter (cf. Table 5 above) over the right (ipsilateral) as compared to the left (contralateral) hemisphere. The voltage maps concerning the N1 response (cf. Figure 3b and Figure 3d above) showed an equal commitment of both hemispheres, while those concerning the P1 response (cf. Figure 2b vs. Figure 2d above) displayed a slightly greater commitment of the left hemisphere. With respect to scalp distribution of the P1 and N1 responses in NH and CI children, we may conclude that they tend to be equally distributed over both hemispheres in all children. Nevertheless, the P1 response was likely to be left-lateralized for latency in NH children and the N1 response was likely to be right-lateralized for latency in CI children, although not regularly.

To conclude, we would say that the main differences in the P1 and N1 responses evoked by /i/$_{std}$ and /u/$_{dev}$ between CI and NH children are to be seen to a higher extent in their general amplitude values and in their response strength, but to a lesser extent in their latency values, in their scalp topography, and in their scalp distribution.

7.2.1.2 The MMN response

The auditory MMN was detected in all children: its values are presented in Table 6 for NH children and in Table 7 for CI children, whereas its grand average is displayed in Figure 4.

NH children						
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
/u/$_{dev}$ minus /i/$_{std}$	Lat. (ms)	**226**	**37**	160	288	128
	Ampl. (µV)	**-0.78**	**1.01**	-3.17	1.52	4.69
	Area (µV*ms)	**52**	**34**	10	162	152

Table 6: Descriptive statistic analysis of the MMN values evoked by /u/$_{dev}$ minus /i/$_{std}$ in NH children.

CI children						
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
$/u/_{dev}$ minus $/i/_{std}$	Lat. (ms)	**228**	**34**	160	288	128
	Ampl. (μV)	**-0.98**	**1.50**	-6.98	1.32	8.31
	Area (μV*ms)	**62**	**60**	4	372	368

Table 7: Descriptive statistic analysis of the MMN values evoked by $/u/_{dev}$ minus $/i/_{std}$ in CI children.

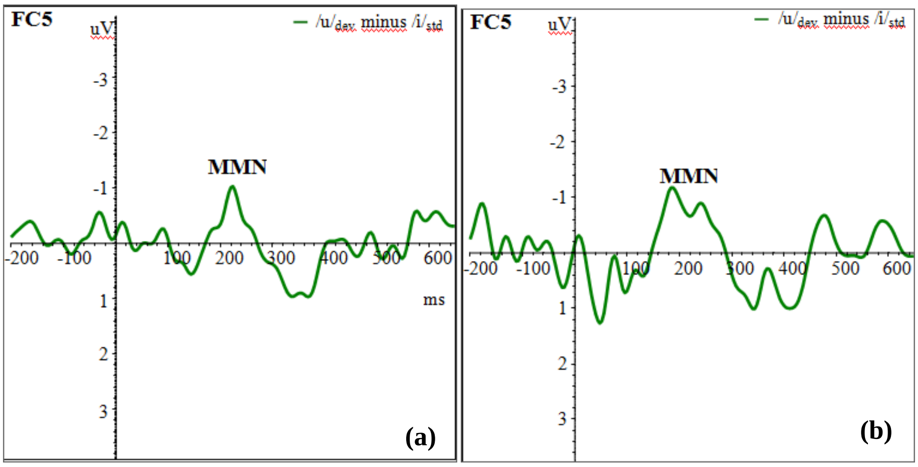


Figure 4: Grand average of the difference wave evoked by $/u/_{dev}$ minus $/i/_{std}$ at FC5 in NH (a) and CI (b) children.

A *T-test against 0* revealed that the MMN amplitudes and areas were significantly different from zero were both in NH (probability: $t(71) = -7.647$, $p < .001$ for amplitude and $t(71) = -12.360$, $p < .001$ for area under the curve) and in the CI (probability: $t(63) = -4.164$, $p < .001$ for amplitude and $t(63) = 9.646$, $p < .001$ for area under the curve) children. An independent *t*-test comparing the MMN values in CI and NH children revealed no statistically significant differences for latency, amplitude, and area (cf. Table 8).

Contrast	MMN values	NH children	CI children	Stat. Sig.
$/u/_{dev}$ minus $/i/_{std}$	Lat. (ms)	226 ± 37	228 ± 34	$t(134) = -.343$, $p = .732$
	Ampl. (μV)	-0.78 ± 1.01	-0.98 ± 1.50	$t(109) = .920$, $p = .359$
	Area (μV*ms)	52 ± 34	62 ± 60	$t(134) = 1.351$, $p = .179$

Table 8: Mean (± S.d.) values of the MMN evoked by $/u/_{dev}$ minus $/i/_{std}$ in NH and CI children.

With respect to the scalp topography and response strength, the voltage maps illustrating the dynamic of the MMN peak are presented in Figure 5.

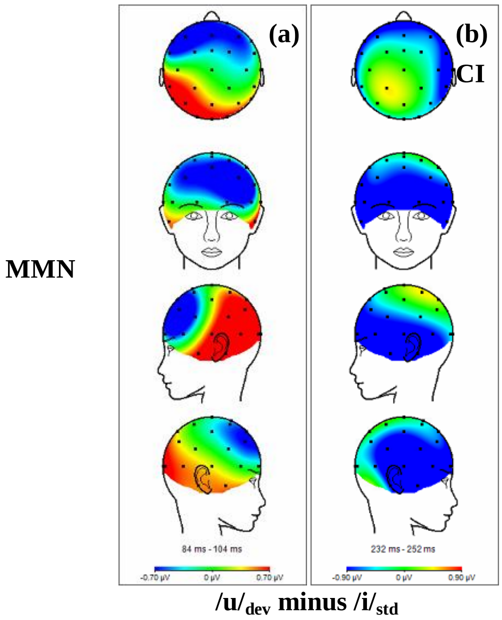


Figure 5: Voltage maps of the MMN peak in the difference wave in NH (a) and CI (b) children, illustrating its dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

In spite of the fact that no statistically significant differences were found between the MMN values presented by CI as compared to NH children (cf. Table 8 above), visual observation of the voltage maps clearly suggest that the MMN response had a different scalp topography in CI relative to NH children. The MMN was a robust negativity with fronto-central displacement in the NH children (cf. Figure 5a above), but with fronto-temporal displacement in the CI children (cf. Figure 5b above), always bilaterally. The brain area activation appeared broader in the CI as compared to the NH children.

The scalp distribution of MMN over both hemispheres and the consequent hemisphere commitment are presented in Table 9 for NH children and in Table 10 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	$/u/_{dev}$ minus $/i/_{std}$	Lat. (ms)	226 ± 34	226 ± 41	t(68) = -.050, *p* = .960
		Ampl. (µV)	-1.04 ± 1.16	-.52 ± .78	**t(62) = 2.217, *p* = .030**
		Area (µV *ms)	64 ± 41	40 ± 21	**t(22) = 3.118, *p* = .003**

Table 9: Scalp distribution of the MMN values (mean ± s.d.) elicited in the difference wave of $/u/_{dev}$ minus $/i/_{std}$ in NH children.

In the NH children, the latency of MMN appeared comparable over both hemispheres, whereas its amplitude appeared larger and its area was wider over the left hemisphere (cf. Table 9 above). This situation was also statistically confirmed by the inferential analysis (cf. Table 9 above) as well as by the voltage maps in the NH children (cf. Figure 5a above).

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	$/u/_{dev}$ minus $/i/_{std}$	Lat. (ms)	225 ± 35	231 ± 33	t(62) = -.766, *p* = .466
		Ampl. (µV)	-0.93 ± 1.69	-1.04 ± 1.31	t(62) = .305, *p* = .762
		Area (µV *ms)	62 ± 71	65 ± 48	t(62) = .201, *p* = .780

Table 10: Scalp distribution of the MMN values (mean ± s.d.) elicited in the difference wave of $/u/_{dev}$ minus $/i/_{std}$ in CI children.

As for the CI children, the values of MMN latency, amplitude, and area appeared very similar over both hemispheres (cf. Table 10 above). Therefore, it is not surprising that an assessment for the symmetry of the MMN response over both hemispheres revealed no significant differences in the MMN values (cf. Table 10 above). This situation was visually confirmed in the voltage maps as well (cf. Figure 4b above).

To sum up, we can say that MMN was left-lateralized for amplitude and area in NH children, whereas it was equally distributed over both hemispheres in CI children. To conclude, we would say that the main differences in the MMN response evoked by /i/$_{std}$-/u/$_{dev}$ between CI and NH are to be seen to a higher extent in the scalp topography, in the response strength, and in the scalp distribution of the MMN, but not in the general MMN values.

7.2.2 The pair /u/$_{std}$ - /i/$_{dev}$

We will first concentrate on the obligatory (cf. 7.2.2.1) and then on the discriminative(cf. 7.2.2.2) responses of the auditory ERPs evoked by /u/$_{std}$ and /i/$_{dev}$ in NH and in CI children.

7.2.2.1 The P1 and N1 responses

The auditory P1 and N1 responses were identified in all children: their values are presented in Table 11 for NH children and in Table 12 for CI children, whereas their grand averages are displayed in Figure 6.

	NH children						
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/u/$_{std}$	Lat. (ms)	**86**	**16**	48	128	80
		Ampl. (µV)	**1.03**	**0.81**	0.06	3.36	3.36
	/i/$_{dev}$	Lat. (ms)	**89**	**17**	48	120	72
		Ampl. (µV)	**1.67**	**1.26**	-.24	5.52	5.76
N1	/u/$_{std}$	Lat. (ms)	**184**	**29**	140	260	120
		Ampl. (µV)	**-1.41**	**0.95**	-4.17	.58	4.75
	/i/$_{dev}$	Lat. (ms)	**185**	**30**	140	260	120
		Ampl. (µV)	**-2.01**	**1.54**	-5.79	-.04	5.75

Table 11: Descriptive statistic analysis of the P1 and N1 values for /u/$_{std}$ and /i/$_{dev}$ in NH children.

	CI children						
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/u/$_{std}$	Lat. (ms)	**84**	**15**	56	112	56
		Ampl. (µV)	**0.63**	**0.61**	-1.41	1.95	3.36
	/i/$_{dev}$	Lat. (ms)	**83**	**17**	52	120	68
		Ampl. (µV)	**0.56**	**1.09**	-2.34	3.73	6.07
N1	/u/$_{std}$	Lat. (ms)	**191**	**28**	144	256	112
		Ampl. (µV)	**-0.90**	**0.72**	-2.79	.32	3.12
	/i/$_{dev}$	Lat. (ms)	**188**	**31**	132	260	128
		Ampl. (µV)	**-1.70**	**1.91**	-6.64	2.53	9.17

Table 12: Descriptive statistic analysis of the P1 and N1 values for /u/$_{std}$ and /i/$_{dev}$ in CI children.

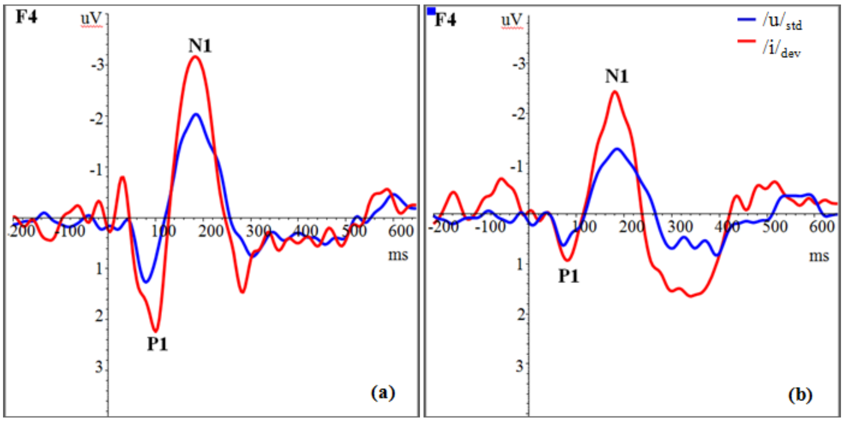


Figure 6: Grand averages to /u/$_{std}$ and /i/$_{dev}$ at F4 for NH (a) and CI (b) children.

An independent t-test comparing the P1 and N1 values evoked by /u/$_{std}$ and /i/$_{dev}$ in CI and NH children revealed that their latencies found in the CI children were statistically comparable to those exhibited by the NH children (cf. Table 13). As far as the amplitudes are concerned, the situation is not the same for P1 and N1 (cf. Table 13). The P1 amplitude was always significantly smaller in CI as compared to NH children, which is to be clearly seen in the grand average waves (cf. Figure 6b vs. Figure 6a above). The N1 amplitude, on the other hand, was significantly reduced in CI with respect to NH children when N1 had been evoked by /u/$_{std}$, as can also be seen in the grand average waves (cf. Figure 6b vs. Figure 6a above), but not when N1 had been evoked by /i/$_{dev}$.

	Vowel	Values	NH children	CI children	Stat. Sig.
P1	/u/$_{std}$	Lat. (ms)	86 ± 16	84 ± 15	$t(134) = .689$, $p = .492$
		Ampl. (µV)	**1.03 ± 0.81**	**0.63 ± 0.61**	**$t(131) = 3.290$, $p = .001$**
	/i/$_{dev}$	Lat. (ms)	89 ± 17	86 ± 17	$t(134) = 1.100$, $p = .273$
		Ampl. (µV)	**1.67 ± 1.26**	**0.56 ± 1.09**	**$t(134) = 5.476$, $p < .001$**
N1	/u/$_{std}$	Lat. (ms)	184 ± 29	191 ± 28	$t(134) = -1.294$, $p = .198$
		Ampl. (µV)	**-1.41 ± 0.95**	**-0.90 ± 0.72**	**$t(131) = 3.559$, $p = .001$**
	/i/$_{dev}$	Lat. (ms)	185 ± 30	188 ± 31	$t(134) = -.599$, $p = .550$
		Ampl. (µV)	-2.01 ± 1.54	-1.70 ± 1.91	$t(134) = 1.046$, $p = .297$

Table 13: Mean (± s.d.) values of P1 and N1 evoked by /u/$_{std}$ and /i/$_{dev}$ in NH and CI children.

With respect to the scalp topography and the response strength, the voltage maps illustrating the dynamic of the P1 and N1 peaks are presented in Figure 7 (for P1) and in Figure 8 (for N1).

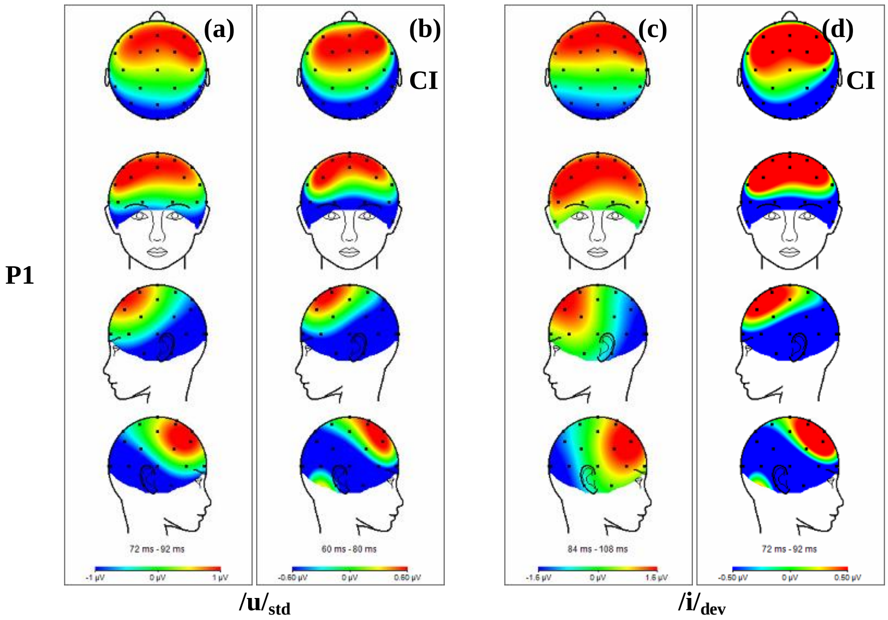


Figure 7: Voltage maps of the P1 peak evoked by **/u/**$_{\textbf{std}}$ and **/i/**$_{\textbf{dev}}$ in NH (a, c) and CI (b, d) children, illustrating the P1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

Visual inspection of the voltage maps clearly indicates that the P1 response had a similar scalp topography in both groups of children: P1 was a robust positivity with fronto-central displacement both for NH (cf. Figure 7a and Figure 7c above) and for CI (cf. Figure 7b and Figure 7b above) children at the bilateral level. The P1 response also had a comparable strength in both groups of children. Nevertheless, it has to be pointed out that the systematic reduced amplitude of P1 in CI relative to NH children (cf. Table 13 above) is not reflected in the voltage maps (cf. Figure 7b vs. Figure 7a above).

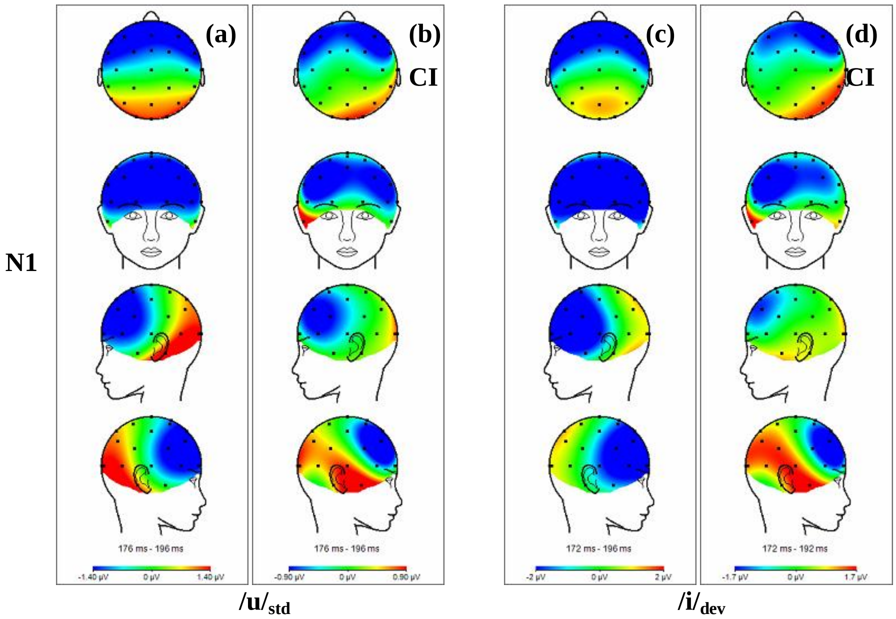


Figure 8: Voltage maps of the N1 peak evoked by **/u/**$_{\textbf{std}}$ (left panels) and **/i/**$_{\textbf{dev}}$ (right panels) in NH (a, c) and CI (b, d) children, illustrating the N1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

Visual inspection of the voltage maps suggests that the N1 response presented a comparable scalp displacement in both groups of children: N1 was a robust negativity with fronto-temporal distribution both in NH (cf. Figure 8a and Figure 8c above) and in CI (cf. Figure 8b and Figure 8b above) children, at the bilateral level. Crucially, N1 appeared to have a broader scalp displacement in NH relative to CI children. The significant reduced amplitude of N1 evoked by /u/$_{std}$ in CI relative to NH children (cf. Table 13 above) was clearly reflected in the voltage maps (cf. Figure 8b vs. 8a above for NH above).

The scalp distribution of P1 and N1 over both hemispheres and the subsequent hemisphere commitment are presented in Table 14 for NH children and in Table 15 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/u/$_{std}$	Lat. (ms)	83 ± 17	89 ± 15	*t*(70) = 1.606, *p* = .113
		Ampl. (μV)	1.04 ± 0.82	1.01 ± 0.80	*t*(70) = .136, *p* = .893
	/i/$_{dev}$	Lat. (ms)	87 ± 17	92 ± 16	*t*(70) = 1.284, *p* = .203
		Ampl. (μV)	1.70 ± 1.37	1.64 ± 1.16	*t*(70) = .188, *p* = .852
N1	/u/$_{std}$	Lat. (ms)	179 ± 28	189 ± 30	*t*(70) = 1.404, *p* = .164
		Ampl. (μV)	-1.49 ± 0.86	-1.33 ± 1.4	*t*(70) = -.693, *p* = .491
	/i/$_{dev}$	Lat. (ms)	181 ± 24	188 ± 33	*t*(70) = -.940, *p* = .350
		Ampl. (μV)	-1.97 ± 1.36	-2.04 ± 1.7	*t*(70) = .183, *p* = .856

Table 14: Scalp distribution of the P1 and N1 values (mean ± s.d.) elicited by /u/$_{std}$ and /i/$_{dev}$ in NH children.

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/u/$_{std}$	Lat. (ms)	82 ± 15	87 ± 15	*t*(62) = 1.318, *p* = .193
		Ampl. (μV)	0.68 ± 0.63	0.57 ± 0.60	*t*(62) = .731, *p* = .467
	/i/$_{dev}$	Lat. (ms)	89 ± 16	83 ± 18	*t*(58) = .800, *p* = .427
		Ampl. (μV)	0.59 ± 0.91	0.54 ± 1.26	*t*(62) = -.533, *p* = .596
N1	/u/$_{std}$	Lat. (ms)	193 ± 32	188 ± 25	*t*(62) = 1.367, *p* = .177
		Ampl. (μV)	-0.95 ± 0.71	-0.85 ± 0.74	*t*(62) =.144, *p* = .886
	/i/$_{dev}$	Lat. (ms)	189 ± 30	187 ± 31	*t*(62) =.341, *p* = .734
		Ampl. (μV)	-1.69 ± 1.72	-1.71 ± 2.12	*t*(62) =.039, *p* = .969

Table 15: Scalp distribution of the P1 and N1 values (mean ± s.d.) elicited by /u/$_{std}$ and /i/$_{dev}$ in CI children.

In the NH children, the latency and amplitude values of P1 and appeared comparable over both hemispheres (cf. Table 14 above). This situation is also confirmed by the voltage maps showing equal magnitude for P1 (cf. Figure 8a and 8c above) and N1 (cf. Figure 9a and Figure 9c above) over both hemispheres in NH children. Therefore, it is not surprising that an assessment of the symmetry of the P1 and N1 responses over both hemispheres revealed no statistically significant differences in the values of latency and amplitude (cf.Table 14 above). In the CI children, the latency and amplitude values of P1 and N1 appeared comparable over both hemispheres as well (cf. Table 15 above). Building on the voltage maps, on the other hand, P1 and N1 appeared in some instances maximal over the right electrode sites (cf. Figure 8b and Figure 8d above), but in other cases equally distributed over both hemispheres (cf. Figure 7b and Figure 7d above). However, in spite of these visual differences, a statistical assessment of the symmetry of P1 and N1 responses over the left and right hemispheres revealed no statistically significant lateralization effect for their values. With respect to scalp distribution of the P1 and N1 responses, we may conclude that are systematically equally distributed over both hemispheres in NH and CI children, even though they show a tendece for exhibiting a wider scalp displacement over the right (ipsilateral) hemisphere in CI children, which is not stastistically confirmed.

To sum up, the main differences concerning P1 and N1 evoked by /u/$_{std}$-/i/$_{dev}$ in CI and NH children were predominantly found in the general P1 and N1 values, and only partially found in the P1 and N1 scalp topography, response strength, or scalp distribution.

7.2.2.2 The MMN response

The auditory MMN response was detected in all children: its values are presented in Table 16 for NH children and in Table 17 for CI children, whereas its grand average is displayed in Figure 9.

NH children						
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
/i/$_{dev}$ minus /u/$_{std}$	Lat. (ms)	**209**	**38**	160	288	128
	Ampl. (μV)	**-0.82**	**0.91**	-3.18	0.54	3.72
	Area (μV*ms)	**51**	**35**	7.73	158.77	151.04

Table 16: Descriptive statistic analysis of the MMN values evoked by /i/$_{dev}$ minus /u/$_{std}$ in NH children.

CI children						
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
/i/$_{dev}$ minus /u/$_{std}$	Lat. (ms)	**203**	**32**	160	288	128
	Ampl. (μV)	**-0.81**	**1.55**	-4.41	3.82	8.23
	Area (μV*ms)	**67**	**56**	8.02	261.94	253.92

Table 17: Descriptive statistic analysis of the MMN values evoked by /i/$_{dev}$ minus /u/$_{std}$ in CI children.

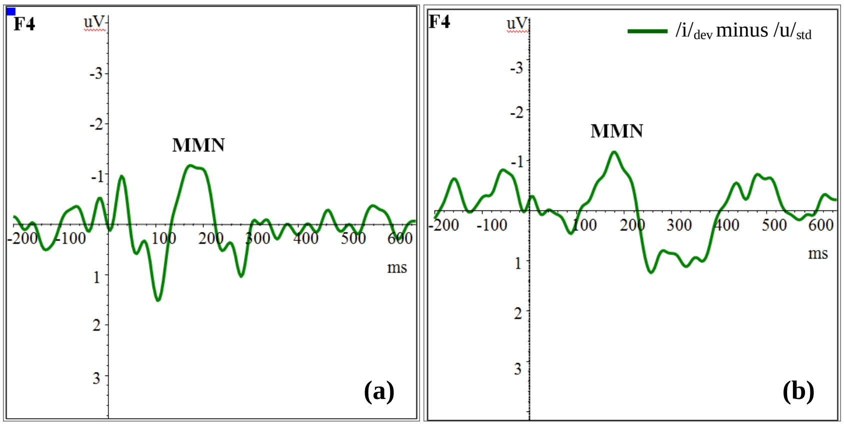


Figure 9: Grand average of the difference wave evoked by /i/$_{dev}$ minus /u/$_{std}$ at FC5 in NH (a) and CI (b) children.

A *T-test against 0* clarified that the MMN amplitude was significantly different from 0 both in the case of NH (*t*(71)= -7.647, *p* < .001) and in CI (*t*(63)= - 4.164, *p* < .001) children. Likewise, the MMN area was significantly different from 0 both in NH (*t*(71)= -12.360, *p* < .001) and in CI (*t*(63)= 9.646, *p* < .001) children. An independent *t*-test comparing the MMN values in CI and NH children revealed no statistically significant differences (cf. Table 18).

Contrast	MMN	NH children	CI children	Stat. Sig.
/i/$_{dev}$ minus /u/$_{std}$	Lat.(ms)	209 ± 38	203 ± 32	*t*(134) = .888, *p* =.376
	Ampl. (μV)	-0.82 ± 0.91	-0.81 ± 1.55	*t*(99) = .063, *p* = .950
	AUC (μV*ms)	**51 ± 35**	**67 ± 56**	***t*(104) = 1.977, *p* = .051**

Table 18: Mean (± SD) MMN values evoked by /u/$_{std}$ -/i/$_{dev}$ in NH and CI children.

With respect to the scalp displacement and the response strength, the voltage maps illustrating the dynamic of the MMN peak are presented in Figure 10.

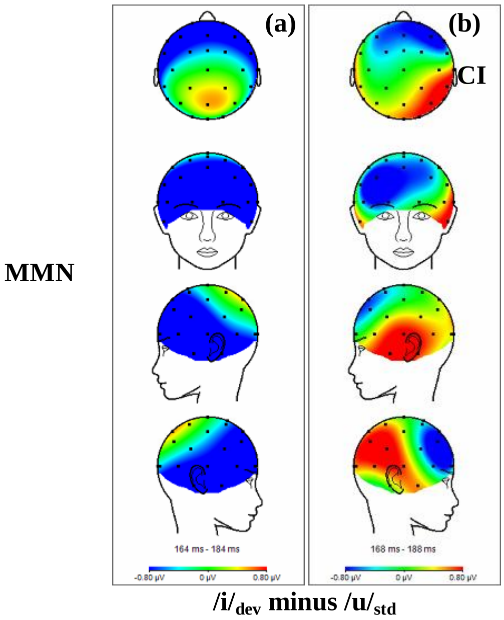


Figure 10: Voltage maps of the MMN peak in the difference wave in NH (a) and CI (b) children, illustrating its dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

In spite of the fact that no statistically significant differences were found between the MMN values presented by CI as compared to NH children (cf. Table 18 above), visual observation of the voltage maps clearly suggests that MMN had a different scalp topography in CI relative to NH children. In NH children, it was a robust negativity with fronto-temporal displacement at the bilateral level (cf. Figure 10a above). In CI children, on the other hand, it appeared as a robust negativity with fronto-central displacement at the bilateral level, but with wider scalp displacement on the right (ipsilateral) hemisphere (cf. Figure 10b above). The degree of scalp activation was higher in NH as compared to CI children.

The scalp distribution of MMN over both hemispheres and the consequent hemisphere commitment are presented in Table 19 for NH children and in Table 20 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	$/i/_{dev}$- minus $/u/_{std}$	Lat. (ms)	204 ± 40	214 ± 37	$t(70) = 1.144$, $p = .257$
		Ampl. (µV)	-0.82 ± 0.88	-0.82 ± 0.95	$t(70) = -.010$, $p = .992$
		Area (µV *ms)	51 ± 31	52 ± 39	$t(70) = .118$, $p = .906$

Table 19: Scalp distribution of the MMN values (mean ± s.d.) elicited in the difference wave of $/i/_{dev}$ minus $/u/_{std}$ in NH children.

In NH children, the MMN values of latency, amplitude, and area were almost the same on the left and the right hemispheres (cf. Table 19 above). This situation is mirrored in the voltage maps as well (cf. Figure 10a above). Therefore, it is not surprising that the independent *t*-test comparing MMN values on the left and the right hemispheres returned statistically comparable values over both hemispheres (cf. Table 19 above).

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	$/i/_{dev}$- minus $/u/_{std}$	Lat. (ms)	210 ± 37	197 ± 27	$t(59) = 1.542$, $p = .129$
		Ampl. (µV)	-0.75 ± 1.40	-0.86 ± 1.71	$t(62) = .289$, $p = .773$
		Area (µV *ms)	64 ± 57	71 ± 55	$t(62) = .535$, $p = .595$

Table 20: Scalp distribution of MMN values (mean ± s.d.) elicited in the difference wave of $/i/_{dev}$ minus $/u/_{std}$ in CI children.

In the case of CI children, on the other hand, the latency appeared slightly shorter, the amplitude appeared larger, and the area under the curve appeared wider on the right (ipsilateral) hemisphere as compared to the left (contralateral) one (cf. Table 20 above). This state of affairs is reflected in the voltage maps as well (cf. Figure 10b above). Despite the above-mentioned situation, the independent *t*-test comparing the MMN values on the left and the right hemispheres returned no statistically significant lateralization effect in CI children as well. Thus, we would like to conclude that the MMN component was equally distributed over both hemispheres in NH and CI children, even though it apparently had a broader scalp distribution on the right (i.e. ipsilateral) hemisphere in CI children.

To conclude, we would like to stress that the main differences between CI and NH children are best reflected in the MMN scalp topography and response strength, rather than in MMN scalp distribution and MMN values.

7.3 The automatic processing of front vowels

The automatic processing of the pairs /i/$_{\text{std}}$-/ɛ/$_{\text{dev}}$ and /ɛ/$_{\text{std}}$-/i/$_{\text{dev}}$ will be presented in 6.3.1 and in 6.3.2. For the ERP components, we will present their values, their scalp topography and their strength as well as their scalp distribution and their consequent hemisphere commitment.

7.3.1 The pair /i/$_{\text{std}}$ - /ɛ/$_{\text{dev}}$

We will first deal with the obligatory (cf. 7.3.1.1) and then with the discriminative (cf. 7.3.1.2) responses of the auditory ERPs evoked by /i/$_{\text{std}}$ and /ɛ/$_{\text{dev}}$ in NH and in CI children.

7.3.1.1 The P1 and N1 responses

The auditory P1 and N1 responses were identified in all children: their values are presented in Table 21 for NH children and in Table 22 for CI children, whereas their grand averages are displayed in Figure 11.

	NH children						
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/i/$_{\text{std}}$	Lat. (ms)	**85**	**14**	48	128	80
		Ampl. (μV)	**1.28**	**0.98**	-0.47	4.69	5.16
	/ɛ/$_{\text{dev}}$	Lat. (ms)	**86**	**19**	48	120	72
		Ampl. (μV)	**1.33**	**1.16**	-1.44	4.36	5.80
N1	/i/$_{\text{std}}$	Lat. (ms)	**177**	**28**	140	248	108
		Ampl. (μV)	**-1.70**	**0.94**	-4.32	0.08	4.25
	/ɛ/$_{\text{dev}}$	Lat. (ms)	**189**	**31**	140	260	120
		Ampl. (μV)	**-2.17**	**1.11**	-4.81	-0.05	4.81

Table 21: Descriptive statistic analysis of the P1 and N1 values for /i/$_{\text{std}}$ and /ɛ/$_{\text{dev}}$ in NH children.

		CI children					
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/i/$_{std}$	Lat. (ms)	**83**	**17**	48	120	72
		Ampl. (µV)	**0.88**	**0.70**	-0.04	4.90	4.94
	/ε/$_{dev}$	Lat. (ms)	**85**	**15**	64	116	52
		Ampl. (µV)	**1.05**	**1.04**	-0.63	4.92	4.29
N1	/i/$_{std}$	Lat. (ms)	**185**	**32**	132	268	136
		Ampl. (µV)	**-1.16**	**0.84**	-3.42	-0.07	3.41
	/ε/$_{dev}$	Lat. (ms)	**188**	**32**	140	252	112
		Ampl. (µV)	**-1.12**	**0.83**	-3.010	-0.01	3.08

Table 22: Descriptive statistic analysis of the P1 and N1 values for /i/$_{std}$ and /ε/$_{dev}$ in CI children.

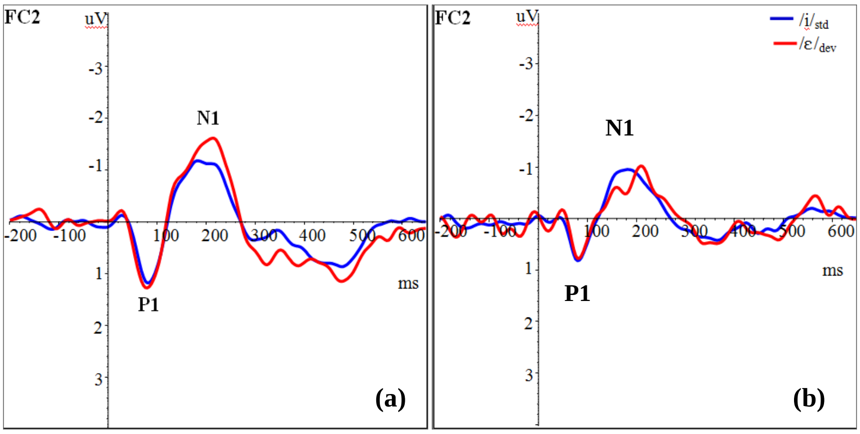


Figure 11: Grand averages to /i/$_{std}$ and /ε/$_{dev}$ at FC2 for NH (a) and CI (b) children.

An independent *t*-test comparing P1 and N1 values evoked by /i/$_{std}$ and /ε/$_{dev}$ in CI and NH children revealed that the latencies of P1 and N1 found in CI children were statistically comparable to those exhibited by NH children (cf. Table 23). As far as the amplitudes are concerned, the situation is not the same for P1 and N1. The P1 amplitude was significantly smaller in CI as compared to NH children when N1 had been evoked by /i/$_{std}$ (cf. Table 23), which is to be clearly seen in the grand average waves (cf. Figure 11b vs. Figure 11a above). The N1 amplitude, on the other hand, was systematically significantly reduced in CI with respect to NH children (cf. Table 23), as can also be seen in the grand average waves (cf. Figure 11b vs. Figure 11a above).

	Vowel	Values	NH children	CI children	Stat. Sig.
P1	/i/$_{std}$	Lat. (ms)	85 ± 14	83 ± 17	*t*(123) = .690, *p* = .492
		Ampl. (µV)	**1.28 ± 0.98**	**0.88 ± 0.70**	***t*(134) = 3.090, *p* = .002**
	/ε/$_{dev}$	Lat. (ms)	86 ± 19	85 ± 15	*t*(132) =.284, *p* = .777
		Ampl. (µV)	1.33 ± 1.16	1.05 ±1.04	*t*(134) = 1.490, *p* = .139
N1	/i/$_{std}$	Lat. (ms)	177 ± 28	185 ± 32	*t*(127) = 1.525, *p* = .130
		Ampl. (µV)	**-1.70 ± 0.94**	**-1.16 ± 0.84**	***t*(134) = 3.529, *p* = .001**
	/ε/$_{dev}$	Lat. (ms)	189 ± 31	188 ± 32	*t*(134) = .202, *p* = .840
		Ampl. (µV)	**-2.17 ± 1.11**	**-1.12 ± 0.83**	***t*(134) = 6.133, *p* < .001**

Table 23: Mean (± SD) values of the P1 and N1 evoked by /i/$_{std}$ and /ε/$_{dev}$ in NH and CI children.

With respect to the scalp topography and the response strength, the voltage maps illustrating the dynamic of the P1 and N1 peaks are presented in Figure 12 (for P1) and in Figure 13 (for N1).

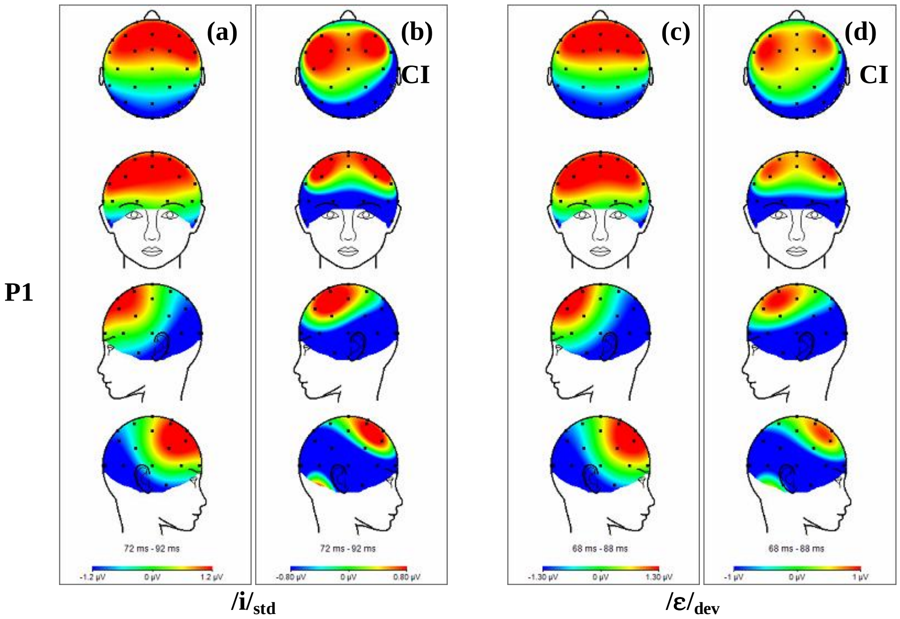


Figure 12: Voltage maps of the P1 peak in NH (a, c) and CI (b, d) children, illustrating the P1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

From the voltage maps in Figure 12, it is clear that the P1 response presented a similar scalp topography in both groups of children: P1 was a robust positivity with fronto-central displacement both for NH (cf. Figure 12a and Figure 12c above) and for CI (cf. Figure 12b and Figure 12b above) children at the bilateral level. Nevertheless, both the scalp topography and the strength of P1 appeared clearly reduced in CI relative to NH children both when P1 had been evoked by /i/$_{\mathrm{std}}$, where we find a significantly reduced amplitude in CI relative to NH children in the grand average waves (cf. Figure 11 above) as well as when it had been evoked by /ɛ/$_{\mathrm{dev}}$.

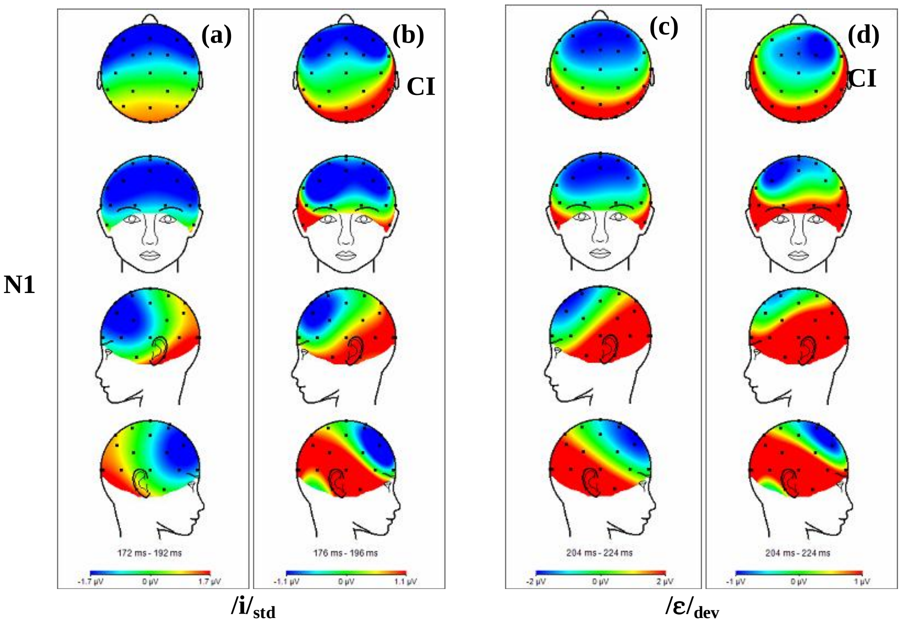


Figure 13: Voltage maps of the N1 peak in NH (a, c) and CI (b, d) children, illustrating the N1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

In the case of NH children, N1 appeared as a robust negativity with fronto-temporal scalp topography when N1 had been evoked by /i/$_{\mathrm{std}}$ (cf. Figure 13a above), but with fronto-central topography when N1 had been evoked by /ɛ/$_{\text{dev}}$ (cf. Figure 13c above). In the case of CI children, on the other hand, N1 had a fronto-central scalp displacement both when it had been evoked by /i/$_{\text{std}}$ (cf. Figure 13b) and when it had been evoked by /ɛ/$_{\text{dev}}$ (cf. Figure 13d above). Crucially, the scalp topography and the strength of the N1 response appeared smaller in CI as compared to NH children (cf. Figure 13b vs. Figure 13d above), thus mirroring the reduced N1 amplitude systematically found in the grand average waves (cf. Figure 11b above).

The scalp distribution of P1 and N1 over both hemispheres and the subsequent hemisphere involvment are presented in Table 24 for NH children and in Table 25 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/i/$_{\text{std}}$	Lat. (ms)	86 ± 15	82 ± 12	t(70) = 1.573, *p* = .120
		Ampl. (μV)	1.31 ± 1.11	1.25 ± .85	t(70) = .275, *p* = .784
	/ɛ/$_{\text{dev}}$	Lat. (ms)	88 ± 19	84 ± 18	t(70) = 1.114, *p* = .269
		Ampl. (μV)	1.41 ± 1.30	1.26 ± 1.03	t(70) = .535, *p* = .594
N1	/i/$_{\text{std}}$	Lat. (ms)	175 ± 28	181 ± 29	t(70) = -.924, *p* = .358
		Ampl. (μV)	-1.70 ± .74	-1.71 ± 1.12	t(61) = -.065, *p* = .949
	/ɛ/$_{\text{dev}}$	Lat. (ms)	185 ± 29	193 ± 33	t(70) = 1.045, *p* = .299
		Ampl. (μV)	-2.233 ±	-2.10 ± 1.23	t(70) = -.498, *p* = .620

Table 24: Scalp distribution of the P1 and N1 values (mean ± s.d.) elicited by /i/$_{\text{std}}$ and /ɛ/$_{\text{dev}}$ in NH children.

In NH children, the latency and the amplitude values of P1 and N1 appeared largely comparable on both hemispheres (cf. Table 24 above). This situation is also confirmed by the voltage maps showing equal magnitude for P1 (cf. Figure 12a and 12c above) and N1 (cf. Figure 13a and Figure 13c above) over both hemispheres in NH children. As a consequence, an assessment of the symmetry of the P1 and N1 responses over both hemispheres revealed no statistically significant differences

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/i/$_{\text{std}}$	Lat. (ms)	**79 ± 15**	**87 ± 18**	**t(62)= 1.677, *p* =. 099**
		Ampl. (μV)	.87 ± .63	.82 ± .96	t(62)= .232, *p* =. 817
	/ɛ/$_{\text{dev}}$	Lat. (ms)	84 ± 15	86 ± 14	t(62)= -.579, *p* =. 565
		Ampl. (μV)	.98 ± .93	1.13 ± 1.15	t(62)= -.578, *p* =. 565
N1	/i/$_{\text{std}}$	Lat. (ms)	190 ± 31	181 ± 32	t(62)= 1.069, *p* =. 289
		Ampl. (μV)	-1.19 ± .72	-1.13 ± .97	t(62)= -.619, *p* =. 538
	/ɛ/$_{\text{dev}}$	Lat. (ms)	185 ± 34	190 ± 30	t(62)= -.620, *p* =. 539
		Ampl. (μV)	-1.25 ± .82	-1.07 ± .83	t(62)= 1.168, *p* =. 247

Table 26: Scalp distribution of the P1 and N1 values (mean ± s.d.) elicited by /i/$_{\text{std}}$ and /ɛ/$_{\text{dev}}$ in CI children.

In CI children, the latency of P1 and N1 evoked by /i/$_{\text{std}}$ and /ɛ/$_{\text{dev}}$ often appeared shorter and the amplitude of P1 and N1 often appeared larger over the left (contralateral) as compared to the right hemisphere (cf. Table 25 above). This situation was also confirmed by the voltage maps illustrating the dynamic of the P1 response, which showed a larger commitment of the left (i.e. contralateral) as compared to the right hemisphere (cf. Figure 12b and Figure 12d above), but not by the voltage maps of the N1 response which, on the other hand, showed an equal commitment of both hemispheres for /i/$_{\text{std}}$ (cf. Figure 13b above), but a larger commitment of the right (i.e. ipsilateral) hemisphere for /ɛ/$_{\text{dev}}$ (cf. Figure 13d above). Nevertheless, an assessment of the symmetry of the P1 and N1 responses over both hemispheres revealed no statistically significant differences in their values (cf. Table 25 above). With respect to scalp distribution of the P1 and N1 responses evoked by /i/$_{\text{std}}$ and

/ε/$_{dev}$, we may conclude that they were systematically equally distributed over both hemispheres in NH and CI children.

To summarize, the main differences in the P1 and N1 values evoked by /i/$_{std}$ and /ε/$_{dev}$ in CI and NH children have to be searched to a higher extent in their general values, in their scalp topography and in their response strength, but to a lower exntent in their scalp distribution.

7.3.1.2 The MMN response

The auditory MMN was identified in all children: its values are presented in Table 26 for NH children and in Table 27 for CI children, whereas its grand average is displayed in Figure 14.

NH children						
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
/ε/$_{dev}$	Lat. (ms)	**232**	**34**	160	288	128
minus	Ampl. (μV)	**-0.99**	**0.78**	-3.43	0.69	4.13
/i/$_{std}$	Area (μV*ms)	**47**	**23**	12	86	74

Table 26: Descriptive statistic analysis of the MMN values evoked by /ε/$_{dev}$ minus /i/$_{std}$ in NH children.

CI children						
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
/ε/$_{dev}$	Lat. (ms)	**225**	**37**	160	288	128
minus	Ampl. (μV)	**-0.77**	**0.75**	-3.99	-0.09	3.98
/i/$_{std}$	Area (μV*ms)	**42**	**17**	24	75	51

Table 27: Descriptive statistic analysis of the MMN values evoked by /ε/$_{dev}$ minus /i/$_{std}$ in CI children.

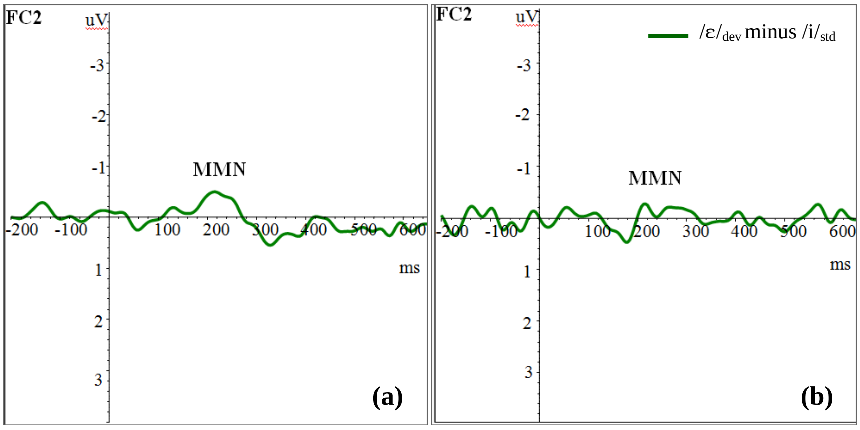


Figure 14: Grand average of the difference wave evoked by /ε/$_{dev}$ minus /i/$_{std}$ at FC2 in NH (a) and CI (b) children.

A *T-test against 0* clarified that the MMN amplitude was significantly different from 0 both in the case of NH ($t(71)= 10.656$, $p < .001$) and of CI ($t(63)= 8.307$, $p < .001$) children. Likewise, the MMN area was significantly different from 0 both in NH ($t(71)= 11.972$, $p < .001$) and in CI ($t(63)= 11.084$, $p < .001$) children. An independent *t*-test (cf. Table 28) showed that the MMN values in CI children were statistically comparable to those exhibited by NH children.

Contrast	MMN values	NH children	CI children	Stat. Sig.
/ε/$_{dev}$	Lat. (ms)	232 ± 34	225 ± 37	$t(134)= 1.249$, $p =.214$
minus	Ampl. (μV)	-0.99 ± 0.78	-0.77 ± 0.75	$t(134)= -1.586$, $p =.115$
/i/$_{std}$	AUC (μV*ms)	46.97 ± 23	42.03 ± 17	$t(134)=.902$, $p =.369$

Table 28: Mean (± S.d.) values of MMN evoked by /ε/$_{dev}$ minus /i/$_{std}$ in NH and CI children.

With respect to the scalp topography and the response strength, the voltage maps illustrating the dynamic of the MMN peak are presented in Figure 15.

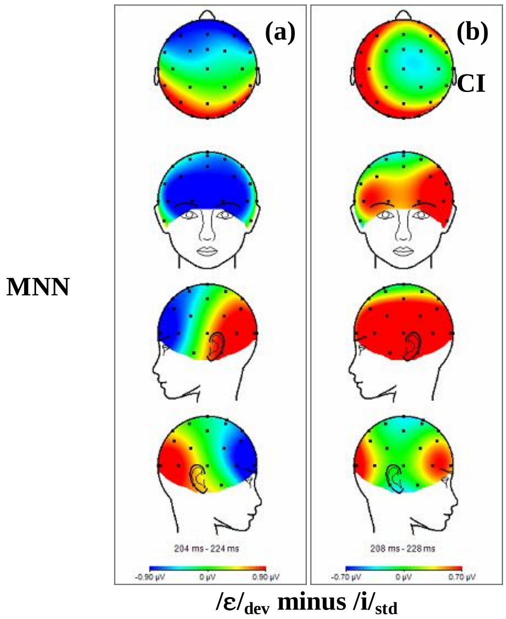


Figure 15: Voltage maps of the MMN peak in the difference wave in NH (a) and CI (b) children, illustrating its dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

In spite of the fact that no statistically significant differences were found between the MMN values presented by CI as compared to NH children (cf. Table 28 above), visual observation of the voltage maps clearly suggested that the MMN was a robust negativity with fronto-central displacement at the bilateral level in NH children (cf. Figure 15a above), but a weak negativity with central displacement over the right electrode sites in CI children(cf. Figure 15b above). As for response strength, MMN involved a broader scalp displacement in NH relative to CI children.

The scalp distribution of MMN over both hemispheres and the consequent hemisphere involvment are presented in Table 29 for NH children and in Table 30 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	/ɛ/$_{dev}$	Lat. (ms)	230 ± 36	235 ± 31	*t*(70) = -.602, *p* = .549
	minus	Ampl. (µV)	**-1.14 ± .740**	**-.83 ± .811**	***t*(70) = 1.686, *p* = .096**
	/i/$_{std}$	Area (µV *ms)	48 ± 34	46 ± 33	*t*(70) = .237, *p* = .813

Table 29: Scalp distribution of MMN values (mean ± s.d.) elicited in the difference wave of /ɛ/$_{dev}$ minus /i/$_{std}$ in NH children.

In NH children, the latency and the area of MMN appeared similar over both hemispheres, whereas the amplitude appeared larger over the left as compared to the right hemisphere (cf. Table 29 above). This situation is statistically confirmed: the MMN latency and area were statistically comparable over both hemispheres, whereas the MMN amplitude were nearly significantly larger over the left hemisphere. This situation is also confirmed in the voltage maps showing a slightly higher commitment of the left hemisphere relative in NH children (cf. Figure 15a above).

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	/ɛ/$_{dev}$	Lat. (ms)	231 ± 39	217 ± 34	$t(62) = 1.534$, $p = .130$
	minus	Ampl. (μV)	-.67 ± .63	-.89 ± .86	$t(62) = 1.137$, $p = .260$
	/i/$_{std}$	Area (μV *ms)	37 ± 26	47 ± 34	$t(62) = 1.403$, $p = .166$

Table 30: Scalp distribution of MMN values (mean ± s.d.) elicited in the difference wave of /ɛ/$_{dev}$ minus /i/$_{std}$ in CI children.

In the CI children, the values of MMN appeared similar over both hemispheres, which is also statistically confirmed (cf. Table 30 above). Nevertheless, the voltage maps (cf. Figure 15b above) shown that the right (i.e. ipsilateral) hemisphere was more committed than the left (i.e. contralateral) hemisphere in CI children. To conclude, we would say that MMN was not far away from being left- lateralized for amplitude in NH children, whereas is was equally distributed over both hemispheres in CI children, even though the right (ipsilateral) hemisphere was apparently more committed.

To round off this section, we would like to highlight that the differences concerning MMN evoked by /ɛ/$_{dev}$ minus /i/$_{std}$ in CI and NH children were found in the MMN scalp topography, strength, and scalp distribution, rather than in the general MMN values.

7.3.2 The pair /ɛ/$_{std}$ - /i/$_{dev}$

We will first deal with the obligatory (cf. 6.3.2.1) and then with the discriminative (cf. 6.3.2.2) responses of the auditory ERPs evoked by /ɛ/$_{std}$ and /i/$_{dev}$ in NH and in CI children.

7.3.2.1 The P1 and N1 responses

The auditory P1 and N1 responses were identified in all children: their values are presented in Table 31 for NH children and in Table 32 for CI children, whereas their grand averages are displayed in Figure 16.

			NH children				
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/ɛ/$_{std}$	Lat. (ms)	**84**	**18**	40	120	80
		Ampl. (μV)	**1.24**	**0.82**	-0.59	3.90	4.49
	/i/$_{dev}$	Lat. (ms)	**87**	**16**	48	120	72
		Ampl. (μV)	**1.22**	**0.90**	0.04	3.53	3.49
N1	/ɛ/$_{std}$	Lat. (ms)	**189**	**34**	140	268	128
		Ampl. (μV)	**-1.73**	**1.03**	-5.52	-0.05	5.20
	/i/$_{dev}$	Lat. (ms)	**182**	**32**	140	268	128
		Ampl. (μV)	**-1.98**	**1.20**	-5.08	-0.03	5.05

Table 31: Descriptive statistic analysis of the P1 and N1 values for /ɛ/$_{std}$ and /i/$_{dev}$ in NH children.

			CI children				
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/ɛ/$_{std}$	Lat. (ms)	**83**	**15**	48	112	64
		Ampl. (μV)	**0.80**	**0.64**	0.01	4.47	4.47
	/i/$_{dev}$	Lat. (ms)	**85**	**19**	48	120	72
		Ampl. (μV)	**1.08**	**0.75**	0.02	3.24	3.22
N1	/ɛ/$_{std}$	Lat. (ms)	**186**	**37**	140	260	120
		Ampl. (μV)	**-1.20**	**0.80**	-2.99	-0.01	2.98
	/i/$_{dev}$	Lat. (ms)	**191**	**30**	140	256	116
		Ampl. (μV)	**-1.68**	**1.33**	-4.74	1.34	6.08

Table 32: Descriptive statistic analysis of the P1 and N1 values for /ɛ/$_{std}$ and /i/$_{dev}$ in CI children.

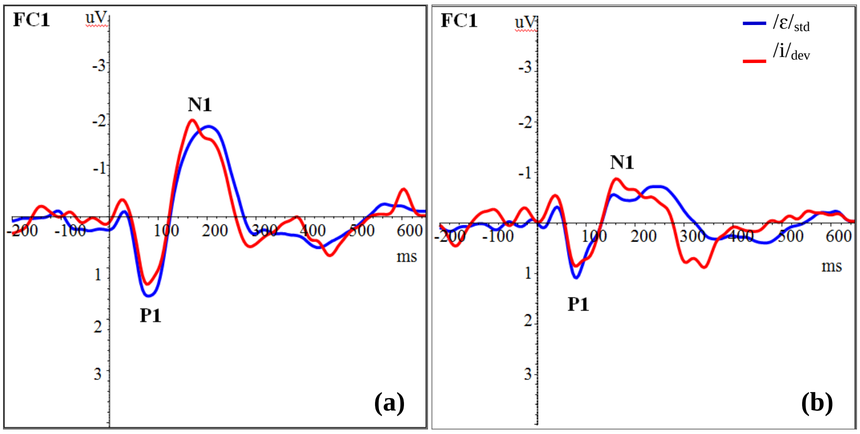


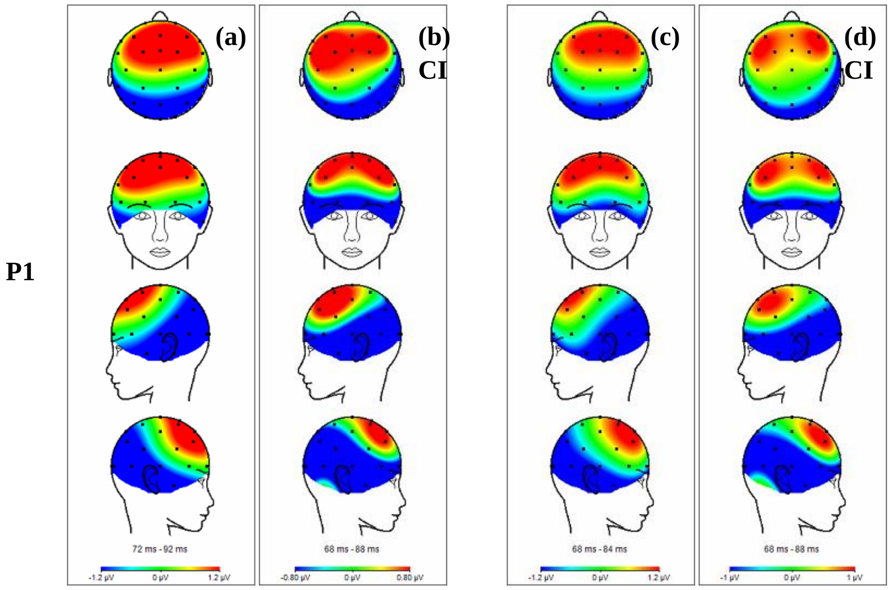
Figure 16: Grand averages to /ε/$_{\text{std}}$ and /i/$_{\text{dev}}$ at FC1 for NH (left) and CI (right) children.

	Vowel	Values	NH children	CI children	Stat. Sig.
P1	/ε/$_{\text{std}}$	Lat. (ms)	84 ± 18	83 ± 15	*t*(134)=.422, *p* =.674
		Ampl. (μV)	**1.24 ± 0.82**	**0.80 ± 0.64**	***t*(132) = 3.488, *p* =.001**
	/i/$_{\text{dev}}$	Lat. (ms)	87 ± 16	85 ± 19	*t* (124)=.567, *p* =.572
		Ampl. (μV)	1.22 ± 0.90	1.08 ± 0.75	*t* (132)=.959, *p* =.339
N1	/ε/$_{\text{std}}$	Lat. (ms)	189 ± 34	186 ± 37	*t* (134)=.411, *p* =.682
		Ampl. (μV)	**-1.73 ± 1.03**	**-1.20 ± 0.80**	***t* (134) = 3.308, *p* =.001**
	/i/$_{\text{dev}}$	Lat. (ms)	**182 ± 32**	**191 ± 30**	***t* (134) = 1.729, *p* =.086**
		Ampl. (μV)	-1.98 ± 1.20	-1.68 ± 1.33	*t* (134)=1.368, *p* =.123

Table 33: Mean (± s.d.) values of P1 and N1 evoked by /ε/$_{\text{std}}$ and /i/$_{\text{dev}}$ in NH and CI children.

An independent *t*-test comparing the P1 and N1 values evoked by /ε/$_{\text{std}}$ and /i/$_{\text{dev}}$ in CI and NH children revealed that their latencies tended to be statistically comparable to those exhibited by NH children (cf. Table 33 above). A single exception is represented by the latency of N1 evoked by /i/$_{\text{dev}}$ which was not far away to be significantly shorter in NH relative to CI children. As far as the amplitudes of P1 and N1 are concerned (cf. Table 33 above), they were likely to be smaller in CI relative to NH children in some instances (e.g., for P1 evoked by /ε/$_{\text{std}}$ and for N1 evoked by /i/$_{\text{dev}}$), but not in the remaining contexts.

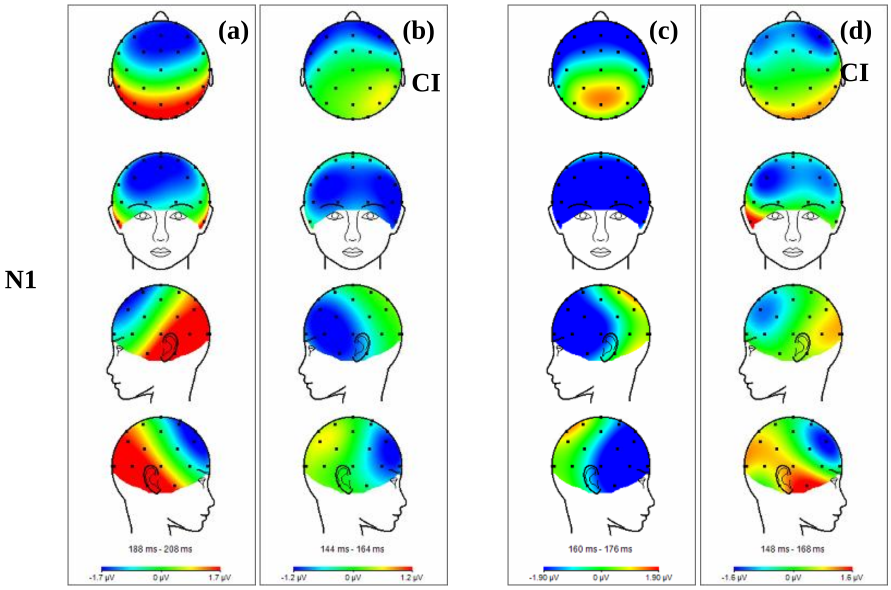
With respect to the scalp topography and the response strength, the voltage maps illustrating the dynamic of the P1 and N1 peaks are presented in Figure 17 (for P1) and in Figure 18 (for N1).



$/\varepsilon/_{\text{std}}$ **$/i/_{\text{dev}}$**

Figure 17: Voltage maps of the P1 peak in NH (a, c) and CI (b, d) children, illustrating the P1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

Visual inspection of the voltage maps clearly indicates that the P1 response had a similar scalp topography in both groups of children: it was a robust positivity with fronto-central displacement both for NH (cf. Figure 17a and Figure 17c above) and for CI (cf. Figure 17b and Figure 17b above) children at the bilateral level. Nevertheless, the strength of the P1 response was broader in NH as compared to CI children when P1 had been evoked by $/i/_{\text{dev}}$; however, this did not hold for P1 evoked by $/\varepsilon/_{\text{std}}$ (cf. Figure 17a vs. Figure 17b above).



$/\varepsilon/_{\text{std}}$ **$/i/_{\text{dev}}$**

Figure 18: Voltage maps of the N1 peak in NH (a, c) and CI (b, d) children, illustrating the P1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

N1 appeared as a robust negativity with different displacement depending on the stimulus type, always at the bilateral level. In the case of NH children, N1 had a fronto-central distribution when it had been evoked by $/\varepsilon/_{\text{std}}$ (cf. Figure 18a above), but a fronto-temporal distribution when it had been evoked by $/i/_{\text{dev}}$ (cf. Figure 18c above). In the case of CI children: N1 had a fronto-temporal dislocation when it had been evoked by /ε/$_{\text{std}}$ (cf. Figure 18b), but a fronto-central displacement when it had been evoked by /i/$_{\text{dev}}$ (cf. Figure 18d above). Once more, N1 appeared to have a broader scalp displacement in NH relative to CI children, especially when it was evoked by /i/$_{\text{dev}}$ (cf. Figure 18c vs. Figure 18d above).

The scalp distribution of P1 and N1 over both hemispheres and the consequent hemisphere commitment are presented in Table 34 for NH children and in Table 35 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/ε/$_{\text{std}}$	Lat. (ms)	85 ± 18	85 ± 18	*t*(70) = .013, *p* = .990
		Ampl. (μV)	1.20 ± 0.84	1.29 ± 0.81	*t*(70) = .393, *p* = .696
	/i/$_{\text{dev}}$	Lat. (ms)	89 ± 15	84 ± 16	*t*(70) = 1.517, *p* = .134
		Ampl. (μV)	1.11 ± 0.96	1.33 ± 0.82	*t*(70) = 1.059, *p* = .293
N1	/ε/$_{\text{std}}$	Lat. (ms)	186 ± 36	192 ± 32	*t*(70) = .644, *p* = .509
		Ampl. (μV)	-1.77 ± 0.95	-1.69 ± 1.12	*t*(70) = .299, *p* = .766
	/i/$_{\text{dev}}$	Lat. (ms)	185 ± 34	179 ± 30	*t*(70) = .886, *p* = .379
		Ampl. (μV)	-1.89 ± 1.14	-2.07 ± 1.26	*t*(70) = .644, *p* = .522

Table 34: Scalp distribution of P1 and N1 values (mean ± s.d.) elicited by /ε/$_{\text{std}}$ and /i/$_{\text{dev}}$ in NH children.

In NH children, the latencies and amplitudes of P1 and N1 appeared comparable on the left and the right hemispheres (cf. Table 34 above). This situation is also confirmed by the voltage maps showing equal magnitude for P1 (cf. Figure 17a and 17c above) and N1 (cf. Figure 18a and Figure 18c above) over both hemispheres in NH children. Therefore, it is not surprising that an assessment of the symmetry of the P1 and N1 responses over both hemispheres revealed no statistically significant differences.

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/ε/$_{\text{std}}$	Lat. (ms)	**80 ± 15**	**87 ± 16**	***t*(62) = 1.738, *p* = .087**
		Ampl. (μV)	0.78 ± 0.45	0.82 ± 0.79	*t*(62) = -.213, *p* = .832
	/i/$_{\text{dev}}$	Lat. (ms)	87 ± 20	83 ± 17	*t*(62) = .808, *p* = .422
		Ampl. (μV)	1.19 ± 0.75	0.98 ± 0.74	*t*(62) = 1.165, *p* = .249
N1	/ε/$_{\text{std}}$	Lat. (ms)	185 ± 43	188 ± 31	*t*(56) = -.376, *p* = .708
		Ampl. (μV)	-1.32 ± 0.82	-1.09 ± 0.77	*t*(62) = 1.180, *p* = .242
	/i/$_{\text{dev}}$	Lat. (ms)	195 ± 29	176 ± 30	*t*(62) = 1.014, *p* = .314
		Ampl. (μV)	-1.88 ± 1.267	-1.49 ± 1.39	*t*(62) = 1.171, *p* = .246

Table 35: Scalp distribution of P1 and N1 values (mean ± s.d.) elicited by /ε/$_{\text{std}}$ and /i/$_{\text{dev}}$ in CI children.

With respect to CI children, on the other hand, building on the voltage maps, P1 and N1 appeared in some instances maximal over the left electrode sites (e.g., P1 evoked by /ε/$_{\text{std}}$; P1 evoked by /i/$_{\text{dev}}$ in the context of /ε/$_{\text{std}}$, cf. Figure 17b and Figure 17d, in turn), in other instances maximal over the right electrode sites (e.g., N1 evoked by /i/$_{\text{dev}}$ in the context of /ε/$_{\text{std}}$, cf. Figure 18d), or equally distributed over both hemispheres (e.g., N1 evoked by /ε/$_{\text{std}}$, cf. Figure 18d). In spite of these visual differences, a statistical assessment of the symmetry of P1 and N1 responses over the left and right hemispheres revealed no statistically significant lateralization effect (cf. Table 35 above). A single exception is represented by the fact that the latency of P1 evoked by /ε/$_{\text{std}}$ was not far away from being significantly shorter over the left hemisphere. As for scalp dislocation of the P1 and N1 responses, we may conclude that they were systematically equally distributed over both hemispheres in NH children, whereas they could present a wider scalp displacement over the right or the left hemisphere in CI children, without being clearly lateralized in both groups of children.

We would like to conclude that the differences concerning P1 and N1 evoked by $/ε/_{std}$ and $/i/_{dev}$ in CI and NH children can be clearly seen in the general values, in theit scalp topography, and in their strength, rather than in their scalp dislocation.

7.3.2.2 The MMN response

The auditory MMN was detected in all children: its values are presented in Table 36 for NH children and in Table 37 for CI children, whereas its grand average is displayed in Figure 19.

NH children						
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
$/i/_{dev}$ minus $/ε/_{std}$	Lat. (ms)	**205**	**37**	160	288	128
	Ampl. (µV)	**- 0.71**	**0.53**	- 2.93	- 0.07	2.92
	Area (µV*ms)	**43**	**14**	27.26	70.61	43.35

Table 36: Descriptive statistic analysis of the MMN values evoked by $/i/_{dev}$ minus $/ε/_{std}$ in NH children.

CI children						
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
$/i/_{dev}$ minus $/ε/_{std}$	Lat. (ms)	**212**	**37**	160	284	124
	Ampl. (µV)	**- 0.84**	**0.70**	- 2.12	- 0.03	2.12
	Area (µV*ms)	**41**	**17**	21.65	68.89	45.24

Table 37: Descriptive statistic analysis of the MMN values evoked by $/i/_{dev}$ minus $/ε/_{std}$ in CI children.

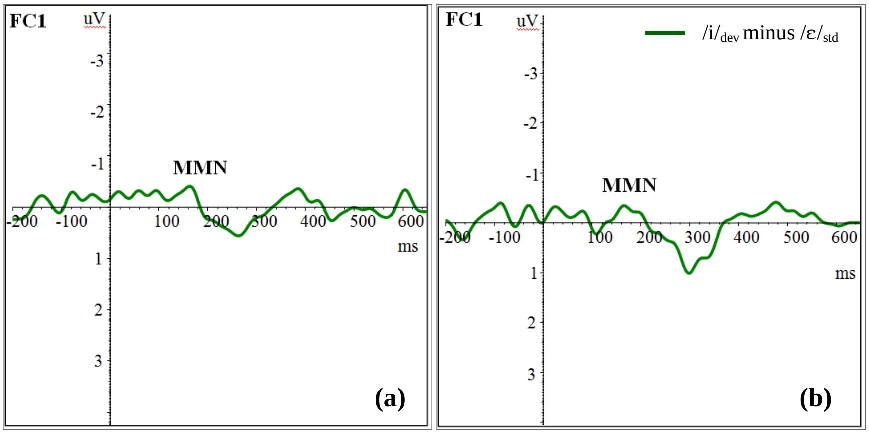


Figure 19: Grand average of the difference wave evoked by $/ε/_{std}$-$/i/_{dev}$ at FC1 in NH (a) and CI (b) children.

A *T-test against 0* indicated that the MMN amplitude was significantly different from 0 for NH children ($t(71)= 11.491$, $p < .001$) and CI ($t(63)= 9.562$, $p < .001$) children; likewise, the MMN area was significantly different from 0 for NH ($t(71)= 13.339$, $p < .001$) and CI ($t(63)= 10.655$, $p < .001$) children. An independent *t*-test showed that statistically comparable MMN values were found in CI and NH children (cf. Table 38).

Contrast	MMN values	NH children	CI children	Stat. Sig.
$/i/_{dev}$ minus $/ε/_{std}$	Lat. (ms)	205 ± 37	212 ± 37	$t(134) = 1.096$, $p = .275$
	Ampl. (µV)	-0.71 ± 0.53	-0.84 ± 0.70	$t(116) = 1.206$, $p = .238$
	AUC (µV*ms)	43 ± 14	41 ± 17	$t(134) = .315$, $p = .754$

Table 38: Mean (±sS.d.) values of MMN evoked by $/ε/_{std}$ -$/i/_{dev}$ in NH and CI children.

With respect to the scalp topography and the response strength, the voltage maps illustrating the dynamic of the MMN peak are presented in Figure 20.

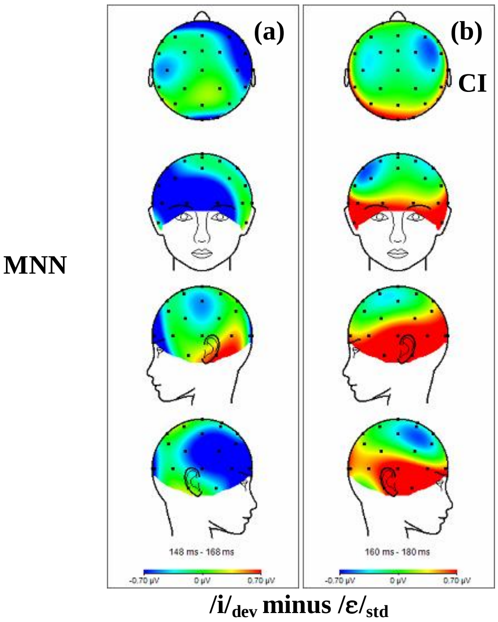


Figure 20: Voltage maps of the MMN peak in the difference wave in NH (a) and CI (b) children, illustrating its dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

Despite the fact that no statistically significant differences were found between the MMN values presented by CI relative to NH children (cf. Table 38 above), visual observation of the voltage maps indicate that MMN had a different topography and strength in CI relative to NH children. In NH children, MMN was a negativity with frontal topography at the bilateral level and with temporal displacement, predominantly on the right side (cf. Figure 20a above). In CI children, on the other hand, MMN was a weak negativity with fronto-central displacement at the bilateral level, predominantly on the right side (cf. Figure 20b above). As for the response strength, the degree of activation was broader in NH relative to CI children.

The scalp distribution of MMN over both hemispheres and the consequent hemisphere involvement are presented in Table 39 for NH children and in Table 40 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	i/$_{dev}$ minus /ɛ/$_{std}$-/	Lat. (ms)	206 ± 37	205 ± 35	*t*(70) = .154, *p* =.878
		Ampl. (µV)	**-0.59 ± 0.43**	**-0.84 ± 0.59**	***t*(70)=2.116, *p* =.038**
		Area (µV *ms)	**36 ± 20**	**51 ± 32**	***t*(59) = 2.405, *p* =.019**

Table 39: Scalp distribution of the MMN values (mean ± s.d.) elicited in the difference wave of /i/$_{dev}$ minus /ɛ/$_{std}$ in NH children.

In the NH children, the MMN latency values appeared similar on the left and the right hemispheres, whereas the MMN amplitude and area values appeared wider over the right hemisphere (Table 39 above). This situation is represented in the voltage maps as well (cf. Figure 20a above). Thus, it is not surprising that the independent *t*-test comparing the MMN values on the left and the right hemispheres returned statistically comparable values for latency, but not for amplitude and area.

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	i/$_{dev}$ minus /ɛ/$_{std}$-/	Lat. (ms)	214 ± 31	211± 43	*t*(57)= .294, *p* = .770
		Ampl. (µV)	-0.86 ± 0.76	-0.82 ± 0.66	*t*(62)=.197, *p* =.845
		Area (µV *ms)	44 ± 32	39 ± 31	*t*(62)=.698, *p* =.488

Table 40: Scalp distribution of the MMN values (mean ± s.d.) elicited in the difference wave of /i/$_{dev}$ minus /ɛ/$_{std}$ in CI children.

In the case of CI children, the MMN values of latency, amplitude, and area were nearly the same over both hemispheres (cf. Table 40 above). Visual inspection of the voltage maps, on the other hand, showed larger amplitudes and wider areas at electrode sites over the right (ipsilateral) hemisphere (cf. Figure 20b above). In spite of the differences emerging from the voltage maps, the independent *t*-test comparing the MMN values on the left vs. right hemispheres in CI children showed no significant lateralization effect for latency, amplitude, and area. To conclude, we can say that MMN is right-lateralized for amplitude and area in NH children, whereas it has wider distribution over the right scalp areas, without being right-lateralized, in CI children.

Once more, the main differences concerning MMN evoked by /i/$_{dev}$ minus /ɛ/$_{std}$ in CI and NH children were to be seen to a higher degree in the scalp topography and response strength and to a lower degree in the general MMN values or in the scalp distribution and in the consequent hemisphere involvment.

7.4 The automatic processing of back vowels

Automatic processing of the pairs /a/$_{std}$-/ɔ/$_{dev}$ and /ɔ/$_{std}$-/a/$_{dev}$ will be presented in 6.4.1 and in 6.4.2. For each ERP response, we will present the values, its scalp displacement (as indicated by the voltage maps) and strength (as conveyed by the scalp activation in the voltage maps) as well as its scalp distribution and hemisphere commitment.

7.4.1 The pair /a/$_{std}$ -/ɔ/$_{dev}$

We will first focus on the obligatory (cf. 7.4.1.1) and then on the discriminative (cf. 7.4.1.2) responses of the auditory ERPs evoked by /a/$_{std}$ and /ɔ/$_{dev}$ in NH and in CI children.

7.4.1.1 The P1 and N1 responses

The auditory P1 and N1 responses were identified in all children: their values are presented in Table 41 for NH children and in Table 42 for CI children, whereas their grand averages are displayed in Figure 21.

	NH children						
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/a/$_{std}$	Lat. (ms)	**94**	**14**	56	120	64
		Ampl. (µV)	**1.02**	**.84**	-.34	3.38	3.72
	/ɔ/$_{dev}$	Lat. (ms)	**92**	**16**	52	128	76
		Ampl. (µV)	**1.18**	**1.12**	-1.72	4.52	6.25
N1	/a/$_{std}$	Lat. (ms)	**190**	**32**	140	248	108
		Ampl. (µV)	**1.23**	**.85**	-2.88	.50	3.38
	/ɔ/$_{dev}$	Lat. (ms)	**192**	**35**	132	256	124
		Ampl. (µV)	**-1.34**	**1.49**	-4.03	3.67	7.71

Table 41: Descriptive statistic analysis of the P1 and N1 values for /a/$_{std}$ and /ɔ/$_{dev}$ in NH children.

	CIchildren						
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/a/$_{std}$	Lat. (ms)	**83**	**15**	48	120	72
		Ampl. (µV)	**.73**	**.60**	-1.83	3.16	4.99
	/ɔ/$_{dev}$	Lat. (ms)	**91**	**17**	56	120	64
		Ampl. (µV)	**.56**	**.96**	-3.18	3.30	6.49
N1	/a/$_{std}$	Lat. (ms)	**196**	**41**	140	268	128
		Ampl. (µV)	**-.94**	**.99**	-3.43	2.38	5.81
	/ɔ/$_{dev}$	Lat. (ms)	**182**	**28**	140	252	112
		Ampl. (µV)	**-1.40**	**1.40**	-6.20	.68	6.88

Table 42: Descriptive statistic analysis of the P1 and N1 values for /a/$_{std}$ and /ɔ/$_{dev}$ in CI children.

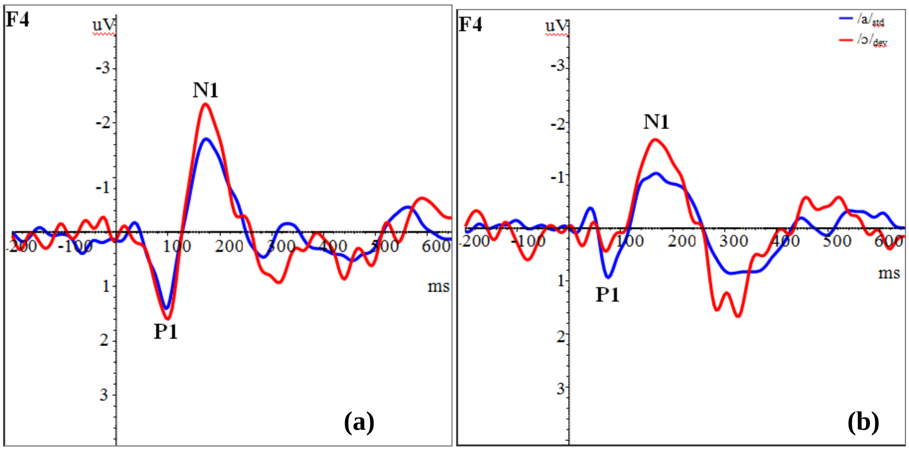


Figure 21: Grand averages to /a/$_{std}$ and /ɔ/$_{dev}$ at F4 for NH (a) and CI (b) children.

An independent *t*-test evaluating P1 and N1 latencies evoked by /a/$_{std}$ and /ɔ/$_{dev}$ in CI and NH children (cf. Table 43) revealed that the latency values found in CI children were statistically comparable to those exhibited by NH children in some instances (i.e., for P1 evoked by /ɔ/$_{dev}$ and for N1 evoked by /a/$_{std}$), but shorter in CI as compared to NH children in the other contexts. As far as the amplitudes are concerned (cf. Table 44 above), the situation is not the same for P1 and N1. The P1 amplitude was systematically significantly smaller in CI as compared to NH children, which is to be clearly seen in the grand average waves (cf. Figure 21b vs. Figure 21a above). The N1 amplitude, on the other hand, was significantly reduced in CI with respect to NH children when N1 had been evoked by /a/$_{std}$, as can also be seen in the grand average waves (cf. Figure 21b vs. Figure 21a above), but not when N1 had been evoked by /ɔ/$_{dev}$.

	Vowel	Values	NH children	CI children	Stat. Sig.
P1	/a/$_{std}$	Lat. (ms)	**94 ± 13**	**83 ± 15**	**t(134) = 4.325, *p* < .001**
		Ampl. (μV)	**1.02 ± 0.84**	**0.72 ± 0.81**	**t(134) = 2.052, *p* = .042**
	/ɔ/$_{dev}$	Lat. (ms)	92 ± 1.12	91 ± 16	t(134) = .461, *p* = .689
		Ampl. (μV)	**1.18 ± 1.12**	**0.56 ± 0.96**	***t*(134) = 3.476, *p* = .001**
N1	/a/$_{std}$	Lat. (ms)	189 ± 33	196 ± 0.41	t(120) = 1.110, *p* = .269
		Ampl. (μV)	**-1.23 ± 0.85**	**-0.94 ± 0.99**	**t(134) = 1.837, *p* = .068**
	/ɔ/$_{dev}$	Lat. (ms)	**191 ± 34**	**182 ± 28**	**t(133) = 1.789, *p* = .076**
		Ampl. (μV)	-1.34 ± 1.48	-1.40 ± 1.39	t(134) = .261, *p* = .794

Table 43: Mean (± SD) values of P1 and N1 evoked by /a/$_{std}$ and /ɔ/$_{dev}$ in NH and CI children.

With respect to the scalp topography and the response strength, the voltage maps illustrating the dynamic of the P1 and N1 peaks are presented in Figure 22 (for P1) and in Figure 23 (for N1).

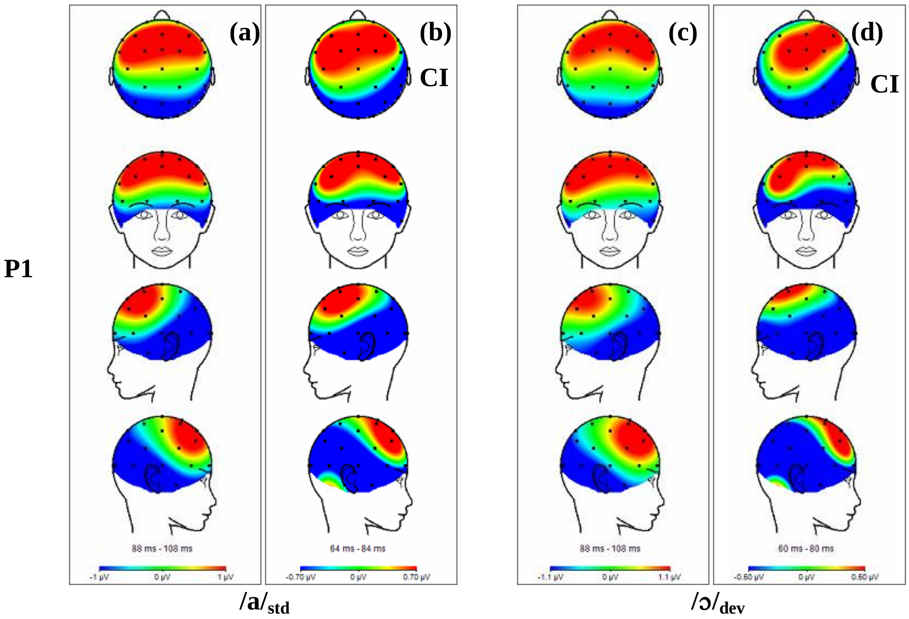


Figure 22: Voltage maps of the P1 peak in NH (a, c) and CI (b, d) children, illustrating the P1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

Visual inspection of the voltage maps clearly indicates that the P1 response evoked by /a/$_{std}$ presented a similar scalp displacement and strength in both groups of children: P1 was a robust positivity with fronto-central displacement both for NH (cf. Figure 22a above) and for CI (cf. Figure 22b above) children, at the bilateral level. Nevertheless, it has to be pointed out that the systematic reduced amplitude of P1 evoked by /a/$_{std}$ in CI relative to NH children was not reflected in the voltage maps (cf. Figure 22b vs. Figure 22a above). As for P1 evoked by /ɔ/$_{dev}$, the situation is not the same for CI and NH children. In both cases, P1 was a robust positivity, but with different scalp displacement: in NH children, P1 had a fronto-central displacement at the bilateral level (cf. Figure 22c above); in CI children, P1 has a fronto-central displacement over the right (ipsilareral) hemisphere, but a frontal displacement over the left (contralateral) hemisphere (cf. Figure 22d above). As for response strength, the degree of scalp activation was more or less the same for both groups of children.

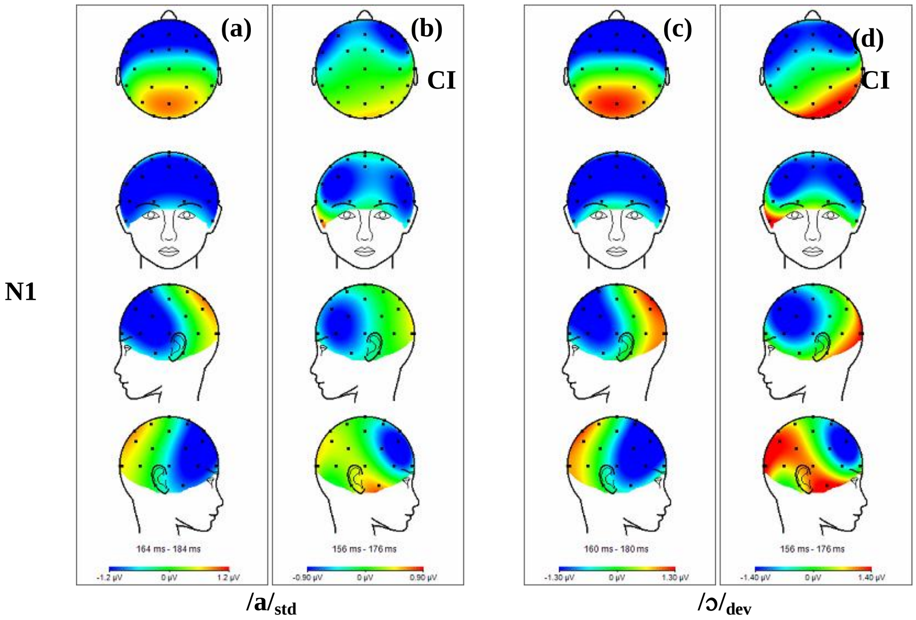


Figure 23: Voltage maps of the N1 peak in NH (a, c) and CI (b, d) children, illustrating the N1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

Visual inspection of the voltage maps indicates that the N1 response was a robust negativity with fronto-temporal scalp displacement at the bilateral level both for NH (cf. Figure 23a and Figure 23c above) and for CI (cf. Figure 23b and Figure 23d above) children. However, once more, the N1 response had a weaker scalp distribution in CI as compared to NH children.

The scalp distribution of P1 and N1 over both hemispheres is presented in Table 44 for NH children and in Table 45 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/a/$_{std}$	Lat. (ms)	**98 ± 12**	**90 ± 15**	**t(70) = 2.520, *p* = .014**
		Ampl. (µV)	1.12 ± .85	.91 ± .84	t(70) = 1.075, *p* = .295
	/ɔ/$_{dev}$	Lat. (ms)	92 ± 18	93 ± 15	t(70) = -.085, *p* = .932
		Ampl. (µV)	1.17 ± 1.22	1.20 ± 1.03	t(70) = -.087, *p* = .931
N1	/a/$_{std}$	Lat. (ms)	191 ± 31	188 ± 34	t(70) = .467, *p* = .642
		Ampl. (µV)	-1.20 ± .85	-1.26 ± .86	t(70) = .322, *p* = .748
	/ɔ/$_{dev}$	Lat. (ms)	197 ± 34	187 ± 34	t(70) = 1.277, *p* = .206
		Ampl. (µV)	-1.30 ± 1.32	-1.38 ± 1.65	t(70) = .220, *p* = .827

Table 44: Scalp distribution of P1 and N1 values (mean ± s.d.) elicited by /a/$_{std}$ and /ɔ/$_{dev}$ in NH children.

In NH children, the latencies and amplitudes values of P1 and N1 appeared comparable over both hemispheres (cf. Table 44 above). This situation is also confirmed by the voltage maps of P1 (cf. Figure 22a and 22c above) and of N1 (cf. Figure 23a and Figure 23c above). Therefore, it is not surprising that an assessment of the symmetry of the P1 and N1 responses over both hemispheres revealed no statistically significant differences. A single exception to this state of affairs was represented by the latency of P1 evoked by /a/$_{std}$ which is significantly shorter on the right hemisphere (cf. Table 44 above).

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/a/$_{std}$	Lat. (ms)	80 ± 16	86 ± 15	t(62) = 1.602, *p* = .114
		Ampl. (µV)	.82 ± .82	.63 ± .80	t(62) = .990, *p* = .326
	/ɔ/$_{dev}$	Lat. (ms)	91 ± 13	91 ± 19	t(54) = -.061, *p* = .951
		Ampl. (µV)	.62 ± .97	.50 ± .96	t(62) = .488, *p* = .627
N1	/a/$_{std}$	Lat. (ms)	190 ± 44	203 ± 36	t(62) = 1.233, *p* = .222
		Ampl. (µV)	-.98 ± .71	-.91 ± 1.22	t(50) = -.276, *p* = .783
	/ɔ/$_{dev}$	Lat. (ms)	177 ± 27	186 ± 30	t(62) = 1.254, *p* = .215
		Ampl. (µV)	-1.68 ± 1.34	-1.13 ± 1.42	t(62) = 1.587, *p* = .118

Table 45: Scalp distribution of P1 and N1 values (mean ± s.d.) elicited by /a/$_{std}$ and /ɔ/$_{dev}$ in CI children.

In CI children, the latencies appeared in some instances shorter (i.e., P1 evoked by /a/$_{std}$ as well as N1 evoked by /a/$_{std}$ and /ɔ/$_{dev}$) as well as the amplitudes appeared always larger on the left (contralateral) hemisphere. However, this situation was not reflected in the voltage maps of P1 (cf. Figure 22b and 22d above) and N1 (cf. Figure 23b and 23d above). A statistical assessment of the symmetry of P1 and N1 responses over the left and right hemispheres revealed no statistically significant lateralization effect. With respect to scalp distribution of the P1 and N1 responses, we may conclude that, although being equally distributed over the scalp areas of both hemispheres in both groups of children, P1 was likely to be clearly left-lateralized for latency in NH children, while both P1 and N1 showm a tendency for presenting a higher magnitude in CI children.

The main differences concerning P1 and N1 evoked by /a/$_{std}$ and /ɔ/$_{dev}$ in CI vs. NH children are to be searched in the general values, in their scalp topography, and in their strength, rather than in their scalp distribution.

7.4.1.2 The MMN response

The auditory MMN component was detectd in all children: its values are presented in Table 46 for NH children and in Table 47 for CI children, whereas its grand average is displayed in Figure 24.

	NH children					
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
/ɔ/$_{dev}$ minus /a/$_{std}$	Lat. (ms)	**219**	**43**	160	288	128
	Ampl. (µV)	**-.56**	**.99**	-3.19	1.90	4.28
	Area (µV*ms)	**46**	**21**	18	82	64

Table 46: Descriptive statistic analysis of the MMN values evoked by /ɔ/$_{dev}$ minus /a/$_{std}$ in NH children.

	CI children					
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
/ɔ/$_{dev}$ minus /a/$_{std}$	Lat. (ms)	**213**	**33**	152	288	136
	Ampl. (µV)	**-.667**	**1.128**	-4.810	1.203	6.013
	Area (µV*ms)	**52**	**21**	32	98	66

Table 47: Descriptive statistic analysis of the MMN values evoked by /ɔ/$_{dev}$ minus /a/$_{std}$ in CI children.

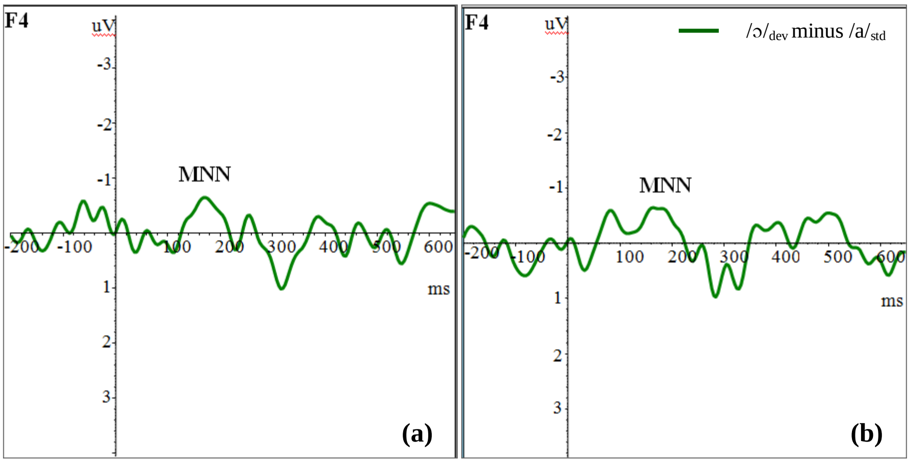


Figure 24: Grand average of the difference wave evoked by /ɔ/$_{dev}$ minus /a/$_{std}$ at F4 in NH (a) and CI (b) children.

A *T-test against 0* revealed that MMN amplitudes and areas were significantly different from zero were both in NH (probability: $t(71) = -4.844$, $p < .001$ for amplitude and $t(71)= 11.174$, $p < .001$ for area under the curve) and in CI (probability: $t(63)= 4.735$, $p < .001$ for amplitude and $t(63)= 9.837$, $p < .001$ for area under the curve) children. An independent *t*-test comparing the MMN values in CI and NH children revealed no statistically significant differences for latency, amplitude, and area (cf. Table 48).

Contrast	MMN values	NH children	CI children	Stat. Sig.
/ɔ/$_{dev}$ minus /a/$_{std}$	Lat. (ms)	219 ± 43	213 ± 33	t(131) = .978, *p* = .330
	Ampl. (µV)	-0.56 ± 0.98	-0.67 ± 1.13	t(134) = .575, *p* = .567
	AUC (µV*ms)	46 ± 21	53 ± 21	t(134) =1 .028, *p* = .306

Table 48: Mean (± s.d.) values of the MMN evoked by /ɔ/$_{dev}$ minus /a/$_{std}$ in NH and CI children.

With respect to the scalp topography and the response strength, the voltage maps illustrating the dynamic of the MMN peak are presented in Figure 25.

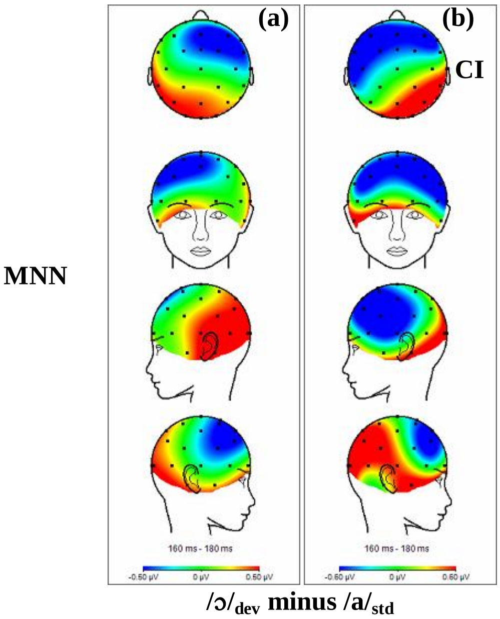


Figure 25: Voltage maps of the MMN peak in the difference wave in NH (a) and CI (b) children, illustrating its dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

In spite of the fact that no statistically significant differences were found between the MMN values presented by the two groups of children (cf. Table 48), visual observation of the voltage maps clearly suggests that the MMN response had a different displacement in the two groups of children. In NH children, MMN was a robust negativity with fronto-central displacement, predominantly over the right scalp areas (cf. Figure 25a above). In CI children, on the other hand, MMN appeared as a robust negativity with fronto-temporal displacement at the bilateral level, but with a deeper involvement of the left (contralateral) scalp areas (cf. Figure 25b above).

The scalp distribution of MMN over both hemispheres is presented in Table 49 for NH children and in Table 50 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	/ɔ/$_{\text{dev}}$	Lat. (ms)	221 ± 42	217 ± 45	t(70) = .381, *p* = .704
	minus	Ampl. (μV)	-.69 ± 1.12	-.44 ± .83	t(64) = 1.059, *p* = .294
	/a/$_{\text{std}}$	Area (μV *ms)	**54 ± 40**	**39 ± 29**	**t(64) = 1.914, *p* = .060**

Table 49: Scalp distribution of MMN values (mean ± s.d.) elicited in the difference wave of /ɔ/$_{\text{dev}}$ minus /a/$_{\text{std}}$ in NH children.

In NH children, the latency of MMN appeared statistically comparable over both hemispheres (cf. Table 49 above). Even though the amplitude of MMN appeared larger over the left hemisphere, this result did not reach statistical significance (cf. Table 49 above). The area of MMN, on the other hand, was not far away from being significantly wider over the left as compared to the right hemisphere (cf. Table 49 above). This situation is not confirmed in the voltage maps which showed a slightly higher commitment of the right hemisphere NH children (cf. Figure 25a above).

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	/ɔ/$_{\text{dev}}$	Lat. (ms)	**202 ± 25**	**223 ± 36**	***t*(56) = 2.682, *p* = .010**
	minus	Ampl. (μV)	**-.99 ± 1.07**	**-.35 ± 1.11**	***t*(62) = 2.353, *p* = .022**
	/a/$_{\text{std}}$	Area (μV *ms)	60 ± 51	47 ± 34	t(62) = 1.213, *p* = .230

Table 50: Scalp distribution of MMN values (mean ± s.d.) elicited in the difference wave of /ɔ/$_{\text{dev}}$ minus /a/$_{\text{std}}$ in CI children.

In CI children, MMN latency was significantly shorter as well as MMN amplitude was significantly larger over the left (contralateral) hemisphere as compared to the right (ipsilateral) hemisphere (cf. Table 50 above). The deeper involvement of the left (ipsilateral) hemisphere in the MMN generation is also evident in the voltage maps (cf. Figure 25b above). It has to be added that MMN area appeared wider over the left hemisphere as well, even though this tendence did not reach statistical significance (cf. Table 50 above). To conclude, we can say that MMN is left-lateralized for area in NH children, whereas it left-lateralized for latency and amplitude in CI children.

Once more, we would like to stress that the main differences concerning MMN evoked by /ɔ/$_{\text{dev}}$ minus /a/$_{\text{std}}$ in CI and NH children are to be seen to a higher extent in the MMN scalp topography, in its response strength, and in its scalp distribution, but to a lesser extent in the general MMN values.

7.4.2 The pair /ɔ/$_{std}$ -/a/$_{dev}$

We will first focus on the obligatory (cf. 6.4.2.1) and then on the discriminative (cf. 6.4.2.2) responses of the auditory ERPs evoked by /ɔ/$_{std}$ and /a/$_{dev}$ in all children.

7.4.2.1 The P1 and N1 responses

The auditory P1 and N1 responses were identified in all children: their values are presented in Table 51 for NH children and in Table 52 for CI children, whereas their grand averages are displayed in Figure 26.

			NH children				
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/ɔ/$_{std}$	Lat. (ms)	**92**	**16**	52	120	68
		Ampl. (μV)	**.81**	**.78**	-1.27	3.32	4.59
	/a/$_{dev}$	Lat. (ms)	**92**	**16**	52	128	76
		Ampl. (μV)	**1.34**	**1.08**	-.86	4.06	4.92
N1	/ɔ/$_{std}$	Lat. (ms)	**181**	**33**	132	256	124
		Ampl. (μV)	**-1.23**	**.82**	-2.89	.85	3.74
	/a/$_{dev}$	Lat. (ms)	**186**	**34**	140	260	120
		Ampl. (μV)	**-1.74**	**1.27**	-4.93	2.51	7.44

Table 51: Descriptive statistic analysis of the P1 and N1 values for /ɔ/$_{std}$ and /a/$_{dev}$ in NH children.

			CI children				
ERPs	Vowel	Values	Mean	S.d.	Min	Max	Range
P1	/ɔ/$_{std}$	Lat. (ms)	**88**	**17**	60	120	60
		Ampl. (μV)	**.70**	**.98**	-1.44	4.36	5.79
	/a/$_{dev}$	Lat. (ms)	**78**	**14**	56	112	56
		Ampl. (μV)	**1.11**	**1.31**	-1.85	7.42	9.27
N1	/ɔ/$_{std}$	Lat. (ms)	**187**	**33**	140	256	116
		Ampl. (μV)	**-1.17**	**.77**	-2.91	.732	3.65
	/a/$_{dev}$	Lat. (ms)	**183**	**33**	140	260	120
		Ampl. (μV)	**-1.03**	**1.22**	-4.32	1.61	5.93

Table 52: Descriptive statistic analysis of the P1 and N1 values for /ɔ/$_{std}$ and /a/$_{dev}$ in CI children.

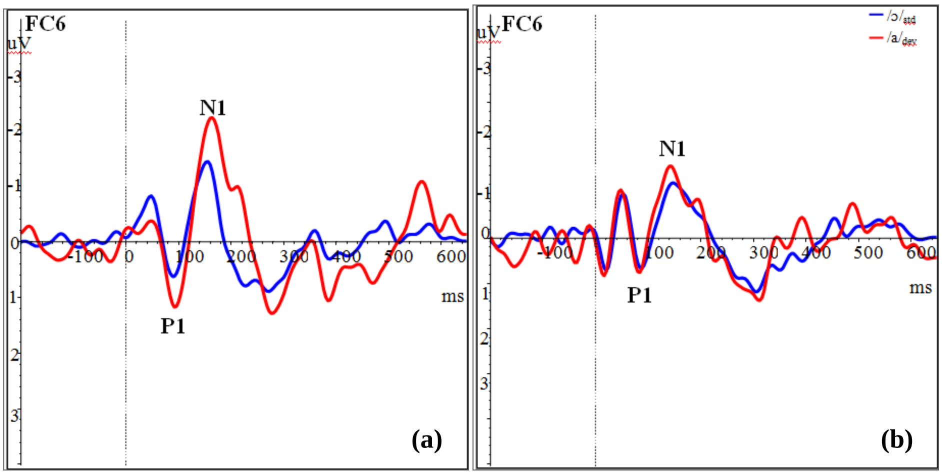


Figure 26: Grand averages to /ɔ/$_{std}$ and /a/$_{dev}$ at FC6 for NH (a) and CI (b) children.

An independent *t*-test comparing P1 and N1 values in CI and NH children revealed that the ERP latencies and the amplitudes found in CI children were statistically comparable to those exhibited by NH children (cf. Table 53). Two exceptions to this situation are represented, on the one hand, by the latency of P1 evoked by /a/$_{dev}$ which appeared significantly shorter in CI relative to NH children and, on the other hand, by the amplitude of N1 evoked by /a/$_{dev}$ which resulted significantly larger in NH relative to CI children. These situations can also be seen in the grand average waves (cf. Figure 26b vs. Figure 26a above).

	Vowel	Values	NH children	CI children	Stat. Sig.
P1	/ɔ/$_{std}$	Lat. (ms)	92 ± 16	88 ± 17	t(134) = 1.470, *p* = .144
		Ampl. (µV)	0.81 ± 0.78	0.70 ± 0.98	t(134) = .723, *p* = .471
	/a/$_{dev}$	Lat. (ms)	**92 ± 16**	**78 ± 14**	**t(134) = 5.689, *p* < .001**
		Ampl. (µV)	1.34 ± 1.08	1.11 ± 1.31	t(134) = 1.115, *p* = .267
N1	/ɔ/$_{std}$	Lat. (ms)	181 ± 33	188 ± 33	t(134) = 1.012, *p* = .313
		Ampl. (µV)	-1.23 ± 0.82	-1.17 ± 0.76	t(134) = -.457, *p* = .649
	/a/$_{dev}$	Lat. (ms)	188 ± 34	183 ± 33	t(134) = .962, *p* = . 338
		Ampl. (µV)	**-1.74 ± 1.26**	**-1.03 ± 1.22**	**t(134) = 3.356, *p* = .001**

Table 53: Mean (± SD) values of P1 and N1 evoked by /ɔ/$_{std}$ and /a/$_{dev}$ in NH and CI children.

With respect to the scalp topography and the response strength, the voltage maps illustrating the dynamic of the P1 and N1 peaks are presented in Figure 27 (for P1) and in Figure 28 (for N1).

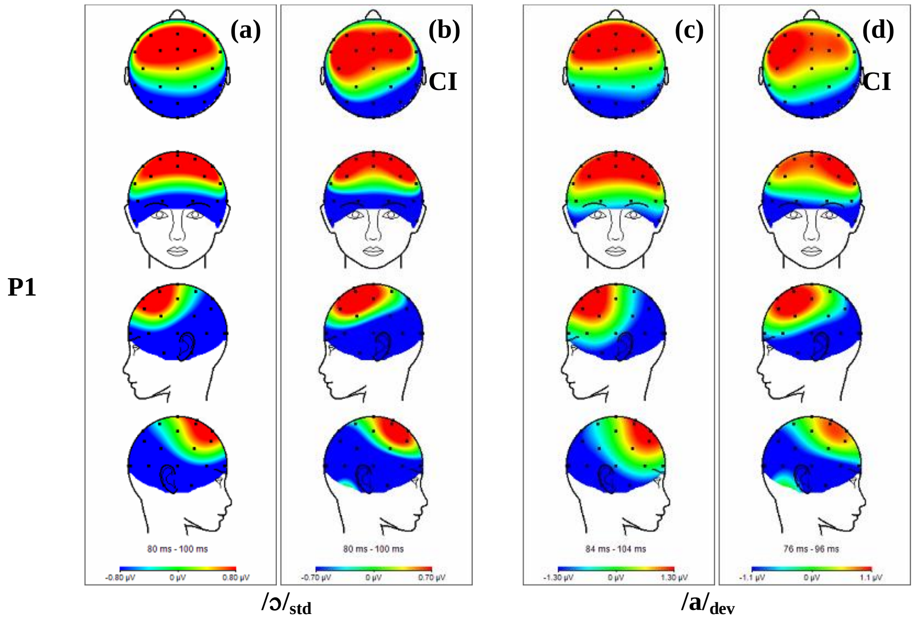
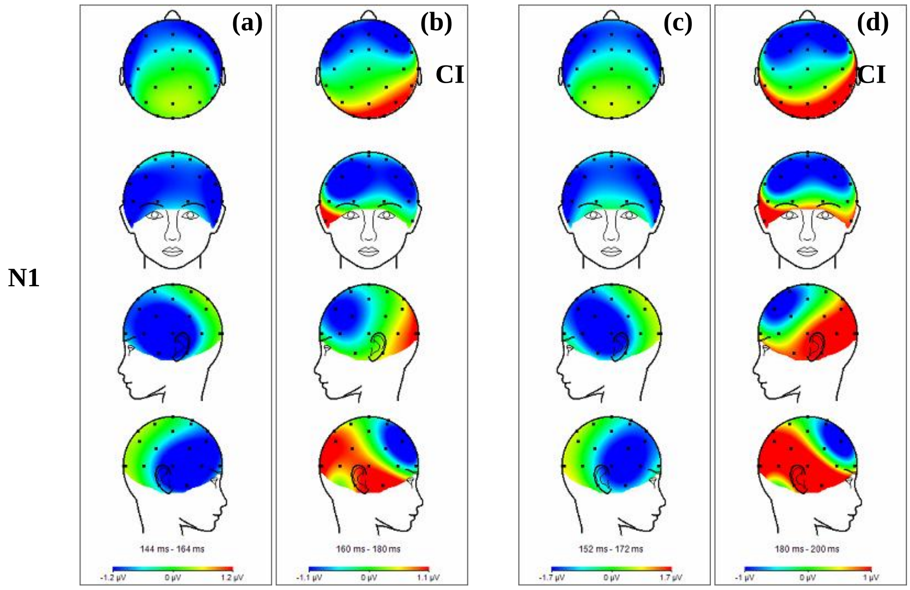


Figure 27: Voltage maps of the P1 peak in NH (a, c) and CI (b, d) children, illustrating the P1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

Visual inspection of the voltage maps clearly indicates that the P1 response had a similar scalp displacement in both groups of children, but a different strength. As for scalp displacement, P1 was a robust positivity with fronto-central displacement both for NH (cf. Figure 27a and Figure 27c above) and for CI (cf. Figure 27b and Figure 27b above) children, at the bilateral level. Nevertheless, in the case of CI children, there was a wider involvement of the left (contralateral) scalp areas. With respect to the response strength, in NH children the P1 strength appeared comparable both when P1 had been evoked by /ɔ/$_{std}$ and /a/$_{dev}$ (cf. Figure 27a and Figure 27c above); in CI children, on the other hand, the P1 strength appeared stronger when it had been evoked by /ɔ/$_{std}$ relative to /a/$_{dev}$ (cf. Figure 27b vs. Figure 27d above).



/ɔ/$_{\text{std}}$ **/a/$_{\text{dev}}$**

Figure 28: Voltage maps of the N1 peak in NH (a, c) and CI (b, d) children, illustrating the N1 dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

From the voltage maps (cf. Figure 28 above), it is clear that N1 had a different scalp topography and response strength in NH and CI children. As for scalp topography, it was fronto-temporal at the bilateral level in NH children (cf. Figure 28a and Figure 28c above), but a fronto-central in CI children (cf. Figure 28b and Figure 28d above). With respect to the response strength, it was reduced in CI relative to NH children.

The scalp distribution of P1 and N1 over both hemispheres is presented in Table 54 for NH children and in Table 55 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/ɔ/$_{\text{std}}$	Lat. (ms)	94 ± 16	90 ± 16	*t*(70) = 1.210, *p* = .344
		Ampl. (µV)	**1.03 ± .82**	**.59 ± .69**	***t*(70) = 2.477, *p* = .016**
	/a/$_{\text{dev}}$	Lat. (ms)	90 ± 14	95 ± 17	*t*(70) = 1.210, *p* = .230
		Ampl. (µV)	1.34 ± 1.18	1.34 ± 1.00	*t*(70) = -.007, *p* = .994
N1	/ɔ/$_{\text{std}}$	Lat. (ms)	186 ± 33	176 ± 32	*t*(70) = 1.215, *p* = .229
		Ampl. (µV)	-1.20 ± .84	-1.27 ± .82	*t*(70) = .350, *p* = .727
	/a/$_{\text{dev}}$	Lat. (ms)	184 ± 32	193 ± 35	*t*(70) = 1. 601, *p* = .292
		Ampl. (µV)	-1.72 ± 1.06	-1.77 ± 1.45	*t*(70) = . 183, *p* = .2855

Table 54: Scalp distribution of the P1 and N1 values (mean ± s.d.) elicited by /ɔ/$_{\text{std}}$ and /a/$_{\text{dev}}$ in NH children.

In NH children, the latencies and amplitudes of P1 and N1 appeared comparable over both hemispheres (cf. Table 54 above). This situation is also confirmed by the voltage maps showing equal magnitude for P1 (cf. Figure 27a and 27c above) and N1 (cf. Figure 28a and Figure 28c above) over both hemispheres in NH children. Therefore, it is not surprising that an assessment of the symmetry of the P1 and N1 responses over both hemispheres revealed no statistically significant differences. A single exception is represented by the amplitude of P1 evoked by /ɔ/$_{\text{std}}$ which turned out to be statistically larger over the left as compared to the right hemisphere (cf. Table 54 above). This situation is, however, not represented in the voltage maps (cf. Figure 27a above).

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
P1	/ɔ/$_{\text{std}}$	Lat. (ms)	86 ± 18	90 ± 15	*t*(62) = -.826, *p* = .412
		Ampl. (μV)	.90 ± .79	.51 ± 1.12	*t*(62) = 1.641, *p* = .106
	/a/$_{\text{dev}}$	Lat. (ms)	75 ± 11	81 ± 16	**_t_(62) = 1.794, _p_ = .078**
		Ampl. (μV)	1.13 ± .99	1.09 ± 1.59	*t*(62) = .116, *p* = .908
N1	/ɔ/$_{\text{std}}$	Lat. (ms)	199 ± 36	176 ± 25	**_t_(62) = 2.840, _p_ = .006**
		Ampl. (μV)	-1.24 ± .73	-1.11 ± .81	*t*(62) = -.681, *p* = .498
	/a/$_{\text{dev}}$	Lat. (ms)	184 ± 36	182 ± 30	*t*(62) = .198, *p* = .844
		Ampl. (μV)	-1.42 ± 1.01	-.63 ± 1.31	**_t_(62) = 2.689, _p_ = .009**

Table 55: Scalp distribution of P1 and N1 values (mean ± s.d.) elicited by /ɔ/$_{\text{std}}$ and /a/$_{\text{dev}}$ in CI children.

In CI children, the latencies and amplitudes of P1 and N1 appeared largerly comparable over both hemispheres (cf. Table 55 above). As for latency, two exceptions are worth emphasizing: the latency of P1 evoked by /a/$_{\text{dev}}$ appeared significantly shorter on the left hemisphere, whereas the latency of N1 evoked by /ɔ/$_{\text{std}}$ resulted significantly shorter over the right hemisphere. As for amplitude, on the other hand, the amplitude of N1 evoked by /a/$_{\text{dev}}$ was significantly larger on the left hemisphere. These results are not to be seen in the voltage maps which, on the other hand, shown that N1 had comparable strength over both hemisphere both when evoked by /ɔ/$_{\text{std}}$ (cf. Figure 28b above) and /a/$_{\text{dev}}$ (cf. Figure 28d above) as well as that P1 had a larger amplitude and scalp distribution on the left (contralateral) hemisphere when evoked by /ɔ/$_{\text{std}}$ (cf. Figure 27b above) and /a/$_{\text{dev}}$ (cf. Figure 27d above). With respect to scalp distribution of the P1 and N1 responses, we may conclude that are usually equally distributed over both hemispheres in NH children, except for being left-lateralized for amplitude (in NH children) and for amplitude and latency (in CI children), in some instances.

To sum up, we would like to stress that the main differences concerning P1 and N1 evoked by /ɔ/$_{\text{std}}$ and /a/$_{\text{dev}}$ in CI and NH children are to be seen in their general values, in their scalp topography, in their response strength, and in their scalp distribution.

7.4.2.2 The MMN response

The auditory MMN was identified in all children: its values are presented in Table 56 for NH children and in Table 57 for CI children, whereas its grand average is displayed in Figure 29.

NH children						
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
/a/$_{\text{dev}}$ minus /ɔ/$_{\text{std}}$	Lat. (ms)	**210**	**33**	164	288	124
	Ampl. (μV)	**-.92**	**.78**	-3.25	.59	3.83
	Area (μV*ms)	**46**	**31**	6	159	153

Table 56: Descriptive statistic analysis of the MMN values evoked by /a/$_{\text{dev}}$ minus /ɔ/$_{\text{std}}$ in NH children.

CI children						
Contrast	MMN Values	Mean	S.d.	Min	Max	Range
/a/$_{\text{dev}}$ minus /ɔ/$_{\text{std}}$	Lat. (ms)	**212**	**42**	160	288	128
	Ampl. (μV)	**-.25**	**1.11**	-3.42	2.36	5.85
	Area (μV*ms)	**48**	**38**	8	211	204

Table 57: Descriptive statistic analysis of the MMN values evoked by /a/$_{\text{dev}}$ minus /ɔ/$_{\text{std}}$ in CI children.

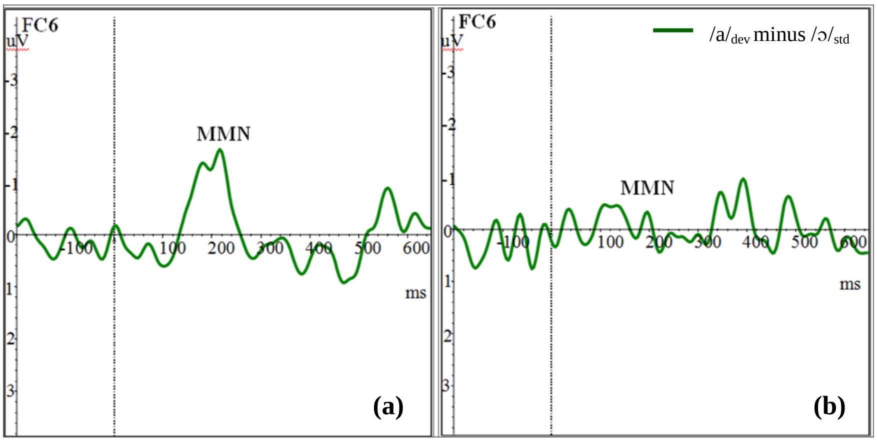


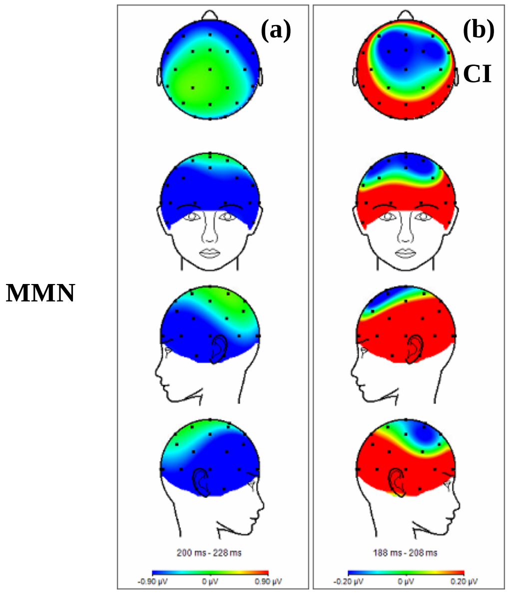
Figure 29: Grand average of the difference wave evoked by /a/$_{dev}$ minus /ɔ/$_{std}$ at FC6 in NH (a) and CI (b) children.

In the case of NH children, a *T-test against 0* revealed that MMN amplitude and area were significantly different from zero (probability: *t*(71) = -10.039, *p* < .001 for amplitude and *t*(71)= 12.794, *p* < .001 for area under the curve). In the case of CI children, on the other hand, the MMN area was significantly different from zero (probability *t*(63)= 10.022, *p* < .001), whereas the MMN amplitude approached statistical significante (probability: *t*(63) = -1.768, *p* = .082). An independent *t*-test comparing the MMN values in CI and NH children revealed no statistically significant differences for latency and area (cf. Table 58). The MMN amplitude, on the other hand, was significantly lager in NH relative to CI children.

Contrast	MMN values	NH children	CI children	Stat. Sig.
/a/$_{dev}$ minus /ɔ/$_{std}$	Lat. (ms)	210 ± 33	213 ± 42	*t*(120) = -.340, *p* = .731
	Ampl. (µV)	-.92 ± .77	-.24 ± 1.11	***t*(111) = 4.045, *p* < .001**
	AUC (µV*ms)	46 ± 31	48 ± 38	*t*(134) = .245, *p* = .807

Table 58: Mean (± S.d.) values of MMN evoked by /ɔ/$_{std}$-/a/$_{dev}$ in NH and CI children.

With respect to the scalp topogtaphy and the response strength, the voltage maps illustrating the dynamic of the MMN peak are presented in Figure 30.



/a/$_{dev}$ minus /ɔ/$_{std}$

Figure 30: Voltage maps of the MMN peak in NH (a) and CI (b) children, illustrating its dynamic in a 20-ms time window surrounding the peak. Four views are presented: top, front, left, and right.

Visual observation of the voltage maps clearly suggest that the MMN response had a different displacement in CI vs. NH children. In NH children, MMN ia a robust negativity with fronto-temporal displacement at the bilateral level (cf. Figure 30a above). In CI children, on the other hand, MMN appeared as a robust negativity with fronto-central displacement at the bilateral level for (cf. Figure 30b above). Additionally, the MMN presented a broader scalp displacement in NH children relative to CI children, as mirrored by the larger amplitude values in the former as compared to the latter (cf. Table 59 above).

The scalp distribution of MMN over both hemispheres is presented in Table 58 for NH children and in Table 59 for CI children.

			NH children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	/a/$_{\text{dev}}$ minus /ɔ/$_{\text{std}}$	Lat. (ms)	213 ± 34	208 ± 33	*t*(70) = .626, *p* = .534
		Ampl. (μV)	-.852 ± .872	-.981 ± .670	*t*(70) = .702, *p* = .485
		Area (μV *ms)	45 ± 32	47 ± 30	*t*(70) = .300, *p* = .765

Table 58: Scalp distribution of MMN values (mean ± s.d.) elicited in the difference wave of /a/$_{\text{dev}}$ minus /ɔ/$_{\text{std}}$ in NH children.

			CI children		
ERPs	Vowels	Values	Left Hem.	Right Hem.	Stat. Sig.
MMN	/a/$_{\text{dev}}$ minus /ɔ/$_{\text{std}}$	Lat. (ms)	**201 ± 39**	**225 ± 42**	***t*(62) = 2.333, *p* = .023**
		Ampl. (μV)	**-.566 ± 1.06**	**-.075 ± 1.08**	***t*(62) = 2.397, *p* = .020**
		Area (μV *ms)	44 ± 30	52 ± 45	*t*(62) = .790, *p* = .433

Table 59: Scalp distribution of MMN values (mean ± s.d.) elicited in the difference wave of /a/$_{\text{dev}}$ minus /ɔ/$_{\text{std}}$ in CI children.

As for NH children, the MMN values appeared statistically comparable over both hemispheres (cf. Table 58 above). As for CI children, the MMN area appeared statistically comparable over both hemispheres. The MMN latency was statistically shorter and the MMN MMN amplitude was statistically larger over the left (contralateral) hemisphere (cf. Table 59 above). To conclude, we can say that MMN was left-lateralized for latency and amplitude in CI children, whereas it was equally distributed over both hemispheres in NH children.

To conclude, MMN presented different general values, a different scalp topography, a different response strength, and a different scalp distribution in CI relative to NH children.

7.5 Discussion

For the first time, the present study investigated vowel processing in Italian deaf children wearing unilateral CIs by means of neurophysiological measures directed at pediatric subjects' automatic discrimination of different kinds of vowel pairs. More particularly, for each vowel pair, we monitored three ERP responses automatically generated at the cortical level: the obligatory P1 and N1 responses as well as the discriminative MMN response.

Recall from 2.5 that, when evoked by speech sounds, P1, N1, and MMN provide information regarding different aspects concerning speech sound processing: i) *timing*, via peak latency (measured in ms); ii) *sensitivity* and *accuracy*, via peak amplitude (measured in μV); iii) *size of neuronal activation* (via area under the curve (measured in ms*μV); iv) *brain area activation* and *response strength*, via scalp topography, as conveyed by the voltage maps; and v) *hemisphere involvement*, via scalp distribution, as conveyed by the voltage maps and by adequate statistical analysis [cf. Beauchemin & De Beaumont, 2005; Martin et al. 2008].

The findings of the present study clearly show that, despite the initial auditory deprivation (from 2.1 to 4.4 yrs) experienced by Italian CI children, vowel processing at the neurophysiological level was largely comparable in the CI and the NH children examined. Nevertheless, some differences emerge between the two groups of children, as expected. In the following, we will discuss first the P1 response (cf. 7.5.1), second, the N1 response (cf. 7.5.2), and, finally, the MMN response (cf. 7.5.3) in CI as compared to NH children.

7.5.1 The P1 response

Recall from 2.5.1, that the P1 response is a correlate of sound detection at the cortical level. It is also a marker for the maturation of the auditory pathways [cf. Sharma, A. et al. 2002abc, 2005b, 2007, 2009; Gilley et al. 2008].

The systematic presence of P1 in all the Italian CI children examined for the six vowel contrasts investigated indicates that all the CI children were able to detect /u/, /i/, /ɛ/, /ɔ/, and /a/ at the cortical level.

The latency of P1 turns out to be statistically comparable in CI relative to NH children when P1 had been evoked by /i/$_{std}$ in the context of /u/$_{dev}$ and of /ɛ/$_{dev}$, /i/$_{dev}$ in the context of /u/$_{std}$ and of /ɛ/$_{std}$, /u/$_{std}$, /u/$_{dev}$, /ɛ/$_{std}$, /ɛ/$_{dev}$, as well as /ɔ/$_{std}$ and /ɔ/$_{dev}$. This result suggests that vowel detection is not delayed in CI as compared to NH children. A single exception is represented by the latency of P1 when P1 had been evoked by /a/$_{std}$ and /a/$_{dev}$: in this case, the P1 latency appeared significantly shorter in CI relative to NH children. This weird result, is not new in the literature on CI users [cf. Torppa et al. 2012]: it does not suggest a faster vowel detection in CI as compared to NH children. Rather, it simply indicates that stimulation is likely to reach the auditory cortex of CI users faster than natural stimulation reaches the auditory cortex of NH individuals [cf. Picton 2011 for a review]. It is worth emphasizing that the latency of P1 is never significantly delayed in the CI examined relative to their NH peers, thus suggesting that CI children do not need a longer time interval for vowel detection.

The amplitude of P1 is statistically comparable in CI relative to NH children when P1 had been evoked by /ɔ/$_{std}$ and /a/$_{dev}$, but it is significantly reduced in CI relative to NH children in all the other contexts. These results clearly indicate that vowel detection tends be challenged, in CI relative to NH children.

Previous ERP studies on CI children exposed to languages other than Italian typically identified P1 in all the children implanted before 3.5 years [for speech-evoked P1, cf. Sharma et al. 2002abc, 2005, 2007, 2009; Gilley et al. 2008; Munivrana & Mildner 2013; for non-speech-evoked P1, cf. Torppa et al. 2012], but only in some deaf children implanted after 3.5 years [for speech-evoked P1, cf. Singh et al. 2004; Gilley et al. 2008; for non-speech-evoked P1, cf. Ponton et al. 2000; Ponton & Eggermont 2001], or even in no late-implanted children [Dinces et al. 2009]. These previous ERP studies found that the P1 response was typically characterized by an attenuated peak amplitude, or by a delayed peak amplitude,or even by both features as compared to NH children, thus suggesting that (speech) sound detection was often delayed and/or challenged in CI children. In the present study, vowel detection is never delayed in CI children, as suggested by the normal P1 latency; however, vowel detection is often likely to be challenged in CI as compared to NH children, as shown by the often reduced P1 amplitude.

With respect to scalp topography, as inferred from the voltage maps, the P1 response always presents a similar displacement in both groups of children: P1 is a robust positivity with fronto-central displacement at the bilateral level. Nevertheless, the response strength over the scalp areas, as inferred from the scalp activation patterns of the response, often appears clearly reduced in CI relative to NH children.

As for scalp distribution, P1 can be left-lateralized for latency or amplitude, or even equally distributed over both hemispheres, both in CI and NH children. To conclude, we can say that the left hemisphere may be more involved than the right one in vowel detection both in CI children, where it represents the hemisphere contralateral to the CI device, and in NH children. However, this does not hold systematically, and it may also happen that both hemispheres are equally involved in vowel detection.

7.5.2 The N1 response

Recall from 2.5.1, that the N1 response is a neural correlate of extraction of the acoustic-phonetic features which are relevant for linguistic categorization in the auditory cortex [cf. Pulvermüller & Shyrov, 2006; Näätänen et alii, 2011; Scharinger et alii, 2012].

The systematic presence of N1 in all the Italian CI children examined for the six vowel contrasts investigated suggests that all the CI children were able to correctly extract the acoustic-phonetic features which are relevant for categorization /u/, /i/, /ɛ/, /ɔ/, and /a/ at the cortical level.

The latency of N1 is statistically largely comparable in CI relative to NH children. This result indicate that extraction of the acoustic-phonetic features which are relevant for vowel categorization is generally not delayed in CI as compared to NH children. Two exceptions to the above-mentioned result are represented by N1 evoked by /i/$_{std}$ in the context of /ɛ/$_{dev}$ and by /ɔ/$_{dev}$ in the context of /a/$_{std}$. In the case of /i/$_{std}$ in the context of /ɛ/$_{dev}$, the P1 latency is prolonged in CI as compared to NH children. In the case of /ɔ/$_{dev}$ in the context of /a/$_{std}$, the P1 latency is shorter in CI as compared to NH children. As already put forward in 7.5.1, this last result does not suggest a faster vowel extract the acoustic-phonetic features which are relevant for categorization in CI children. Rather, it may indicate that stimulation may reach the auditory cortex of CI users faster than natural stimulation reaches the auditory cortex of NH listeners [cf. Picton 2011 for a review].

The amplitude of N1 is largely attenuated in CI relative to NH children, except when N1 had been evoked by /i/$_{dev}$ in the context of /u/$_{std}$ and of /ɛ/$_{std}$, /ɔ/$_{dev}$ in the context of /a/$_{std}$ and /ɔ/$_{std}$ in the context of /a/$_{dev}$. This finding suggests that extraction of the acoustic-phonetic features which are relevant for vowel categorization tends to be less accurate in CI as compared to NH children.

Previous ERP studies on CI children exposed to languages other than Italian were largely unable to able to identify N1 either in late-implanted children [for speech-evoked ERPs, cf. Singh et al. 2004; Sharma et al. 2005, 2007, 2009; Henkin et al. 2008; Dinces et al. 2009; for non-speech-evoked ERPs, cf. Ponton et al. 2000; Ponton & Eggermont 2001] or in early-implanted children [for non-speech-evoked ERPs, cf. Sharma et al. 2005, 2007, 2009; Torppa et al. 2012]. Some exceptions are represented by a few linguistic studies which identified N1 both in early-implanted [cf. Munivrana & Mildner 2013] and in late-implanted [Kileny et al. 1997; Beynon et al. 2002] children.These previous ERP studies found that the N1 response was typically characterized by a smaller peak amplitude or by a delayed peak amplitude in CI as compared to NH children, thus suggesting that extraction of the acoustic-phonetic features which are relevant for (speech) sound categorization was often delayed and/or challenged in CI children. In the present study, extraction of the acoustic-phonetic features which are relevant for vowel categorization is in some cases delayed in CI children relative to NH children, as suggested by the delayed N1 latency, but in other cases it takes place during a comparable time interval between CI and NH children. Nevertheless, this process is frequently challenged, as indicated by the reduced N1 amplitude in CI as compared to NH children.

With respect to scalp topography, as inferred from the voltage maps, the N1 typically presents a different scalp displacement in CI as compared to NH children for the pairs /i/$_{std}$-/ɛ/$_{dev}$, /ɛ/$_{std}$-/i/$_{dev,}$ and /ɔ/$_{std}$-/a/$_{dev}$: it is fronto-temporal for NH but front-central for CI children, or fronto-central for NH but front-temporal for CI children. A similar scalp displacement, on the other hand, characterizes the N1 topography of the pairs /i/$_{std}$-/u/$_{dev}$, /u/$_{std}$-/i/$_{dev}$, and /a/$_{std}$-/ɔ/$_{dev}$: N1 presents a fronto-temporal displacement both in NH and in CI children at the bilateral level. As for response strength, as inferred from the scalp activation patterns of the response, N1 typically presents a reduced scalp activation in CI relative to NH children.

As for scalp distribution, N1 is equally distributed over both hemispheres both in NH and in CI children, thus suggesting that both hemispheres tend to be equally committed in the exctraction of the acoustic-phonetic features which are relevant for vowel categorization.

7.5.3 The MMN response

Recall from 2.5.2 that MMN is regarded here as an indicator of representation of the acoustic-phonetic features which are relevant for vowel categorization in the auditory cortex (cf. Eulitz & Lahiri 2004; Pulvermüller & Shyrov, 2006; Näätänen et al. 2001, 2007, 2009, 2011; Scharinger et al. 2011, 2012; cf. Peltola 2004 and Sussmann et al. 2013 for a review).

The systematic presence of MMN in all the Italian CI children examined for the six vowel contrasts investigated indicates that all the CI children are able to successfully represent the acoustic-phonetic features which are relevant for vowel categorization in the auditory cortex .

The latency, the amplitude, and the area of MMN exhibited by CI children are always statistically comparable to those obtained from NH children, despite the reduced amplitude of P1 (cf. 7.5.1) and the delayed latency and the reduced amplitude of N1 (cf. 7.5.2). Our findings appear to suggest that, despite the differences in the peripheral input (e.g., natural hearing in NH children vs. electric hearing in CI children), and despite the fact that vowel detection as well as exctraction of the acoustic-phonetic features which are relevant for vowel categorization may be delayed or challenged, the brain of CI children is processing vowel phonemes in a very similar fashin to NH children [cf. Näätänen et al. 2012]. This result may appear weird at a first sight. On the one hand, our result is in contrast with previous studies finding delayed MMN latencies and reduced MMN amplitudes in CI relative to NH children, both in the case of late-implanted [cf. Watson et al. 2007] and of early-implanted [cf. Torppa et al. 2012; Ortmann et al. 2013] children, thus suggesting delayed and decreased auditory discrimination accuracy in CI users. On the other hand, our result is consistent with other reports suggesting that a difference between CI and NH children lies in the locus of MMN activation, rather than in MMN parameters [cf. Ponton et al. 2000; Watson et al. 2007; Bottari et al. 2014]. Infact, a closer look at MMN topography indicates that the main differences between CI and NH children concern MMN topography and response strentgh (as indexed by the voltage maps), rather than MMN values (as indexed by MMN latency, amplitude, and area).

With respect to scalp topography, the MMN systematically presents a different topography in CI as compared to NH children. A summary of the MMN topography is provided in Table 60.

	NH children		CI children	
Vowel contrast	Scalp topography	Hemisphere involvment	Scalp topography	Hemisphere involvment
/i/$_{std}$-/u/$_{dev}$	Fronto-central	both	Fronto-temporal	both
/u/$_{std}$-/i/$_{dev}$	Fronto-temporal	both	Fronto-central	both
/i/$_{std}$-/ɛ/$_{dev}$	Fronto-central	both	Central	right (ipsilateral)
/ɛ/$_{std}$-/i/$_{dev}$	Frontal and temporal	both right	Fronto-central	right (ipsilateral)
/a/$_{std}$-/ɔ/$_{dev}$	Fronto-central	right	Fronto-temporal	left (contralateral)
/ɔ/$_{std}$-/a/$_{dev}$	Fronto-temporal	both	Fronto-central	both

Table 60: Scalp topography of MMN in NH and CI children.

As for strength, MMN is usually characterized by a reduced scalp activation in CI as compared to NH children, except when MMN had been evoked by /i/$_{std}$-/u/$_{dev}$, whose the response strength is similar in CI and NH children, and when MMN had been evoked by /a/$_{std}$-/ɔ/$_{dev}$, whose response strength appears wider in CI relative to NH children.

As for scalp distribution, MMN the situation is different for NH and CI children. In NH children, MMN may be left-lateralized for amplitude and area, or just for amplitude, or even just for area (e.g., for /a/$_{std}$-/ɔ/$_{dev}$, cf. Table 49). Alternatively, MMN may be right-lateralized for amplitude, or even equally distributed over both hemispheres. In CI children, MMN generally is equally distributed over both hemispheres, but it may also be left-lateralized for latency. Thus, we can say that the left hemisphere may be more involved than the right one in vowel discrimination in the case of NH and CI children, even thug both hemispheres appear to generally be equally committed in vowel discrimination in CI children.

7.6 Chapter summary

The neurophysiological study presented so far shows that, with natural speech sounds, it is possible to get new pieces of information about the development, functionality, and plasticity of the auditory cortices during speech sound processing in CI children undergoing CI surgery during the sensitive period for central auditory pathway maturation and presenting good general auditory and speech intelligibility abilities. First, detection of isolated vowels is often less precise in CI vs. NH children. Second, exctraction of the acoustic-phonetic features which are relevant for vowel categorization is often delayed and less accurate in CI as compared to NH children. Third, representation of the acoustic-phonetic features which are relevant for vowel categorization is neither delayed, nor less accurate, nor of lower magnitude in CI relative to NH children. Fourth, the patterns of brain activation are often, but not systematically, different in CI as compared to NH children. Fifth, the response strength is nearly systematically reduced in CI relative to NH children. Sixth, both hemispheres were typically involved during vowel processing in CI children, while the left hemisphere was frequently more involved than the right one in CI children.

CHAPTER 8

Neurophysiological vowel processing II: The factors influencing the ERP responses

8.1 Introduction

As laid out in chapter 7, the CI and NH children participated in a neurophysiological experiment where the automatic processing of two pairs of high vowels (e.g., /i/$_{\text{std}}$ - /u/$_{\text{dev}}$ and /u/$_{\text{std}}$ - /i/$_{\text{dev}}$), of front vowels (e.g., /i/$_{\text{std}}$ - /ɛ/$_{\text{dev}}$ and /ɛ/$_{\text{std}}$ - /i/$_{\text{dev}}$), and of back vowels (e.g., /a/$_{\text{std}}$ - /ɔ/$_{\text{dev}}$ and /ɔ/$_{\text{std}}$ - /a/$_{\text{dev}}$) at the cortical level was investigated by recurring to the P1, N1, and MMN responses of the auditory ERP potentials.

The present chapter is devoted to cast light on those factors which are likely to consistently influence cortical processing of the Salento Italian vowels in a group of experienced pediatric CI users who received their unilateral CI before 3.5 years. The factors investigated are six: i) the vowel quality (cf. 8.2); ii) the Euclidean distance (cf. 8.2); iii) the direction of change in the distinctive feature specification (cf. 8.3); iv) the vowel acoustic-phonetic features (cf. 8.4); v) the age at CI surgery (cf. 8.5); and vi) the duration of CI stimulation, also referred to as 'time in sound' (cf. 8.6). The influence played by the above-mentioned factors is then discussed (cf. 8.7). A summary closes this chapter (cf. 8.8).

8.2 The vowel quality, the Euclidean distance, and the MMN values

To start with, we want to understand whether or not the MMN values were affected by the quality (e.g., high as compared to front as compared to back) or by the Euclidean distance (e.g., the acoustic distance in the F1-F2 space) of the eliciting vowels. Building on the findings by Horga & Liker (2006), Liker et al. (2007), and Baudonck et al. (2011) for vowel production, we wouls expect the MMN to peak earlier, with enhanced amplitude, and with wider area when MMN had been evoked by high and front as compared to back vowels. As for the Euclidean distance characterizing the vowel pairs, recall from 4.4.5 that it is almost equivalent for /ɛ/ vs. /i/ (e.g., 322 Mel) and for /a/ vs. /ɔ/ (and 304 Mel), whereas it is wider for /u/ vs. /i/ (847 Mel). The larger is the acoustic distance between vowels, the larger is the magnitude of deviance between them. Accordingly, we would expect the MMN to peak earlier, with larger amplitude, and with wider area when MMN had been evoked by high as compared to front and back vowels.

To understand whether or not MMN was sensitive to vowel quality or to the Euclidean distance, we regarded both pairs of high vowels as a single contrast, by collapsing together the MMN values evoked by /i/$_{\text{std}}$ - /u/$_{\text{dev}}$ and /u/$_{\text{std}}$ - /i/$_{\text{dev}}$. The same holds for both pairs of front and back vowels. The MMN values evoked by high, front, and back vowels were statistically evaluated with a *repeated-measure ANOVA*, separately for NH and CI children. The descriptive statistic analysis of the MMN values evoked by high, front, and back vowels are presented in Table 1 for NH children and in Table 3 for CI children; the inferential statistic analysis comparing the MMN values evoked by the three contrast types is presented in Table 2 for NH children and in Table 4 for CI children.

NH children							
Contrast types	Contrasts	Values	Mean	S.d.	Min	Max	Range
High vowels (E.d. = **847 Mel**)	/i/$_{std}$ - /u/$_{dev}$ and /u/$_{std}$ - /i/$_{dev}$	Lat. (ms)	**217**	**39**	160	288	128
		Ampl. (μV)	**-.80**	**.96**	-3.18	1.52	4.70
		Area (μV*ms)	**52**	**35**	8	162	154
Front vowels (E.d. = **322 Mel**)	/i/$_{std}$ - /ɛ/$_{dev}$ and /ɛ/$_{std}$ - /i/$_{dev}$	Lat. (ms)	**219**	**37**	160	288	128
		Ampl. (μV)	**-.85**	**.68**	-3.43	.69	4.13
		Area (μV*ms)	**45**	**30**	3	171	168
Back vowels (E.d. = **304 Mel**)	/a/$_{std}$ - /ɔ/$_{dev}$ and /ɔ/$_{std}$ - /a/$_{dev}$	Lat. (ms)	**215**	**38**	160	288	128
		Ampl. (μV)	**-.74**	**.90**	-3.25	1.09	4.34
		Area (μV*ms)	**47**	**33**	6	170	164

Table 1: Descriptive statistic analysis of the MMN values exhibited by NH children for all vowel contrasts.

NH children				
MMN values	High vowels (E.d. = **847Mel**)	Front vowels (E.d. = **322Mel**)	Back vowels (E.d. = **304Mel**)	Stat. Sig.
Lat. (ms)	217 ± 39	219 ± 37	215 ± 38	*F*(2, 13) = .210, *p* = .772
Ampl. (μV)	-.80 ± .962	-.85 ± .68	-.74 ± .90	*F*(1, 11) = .398, *p* = .615
Area (μV*ms)	52 ± 35	45 ± 30	47 ± 33	*F*(1, 12) = 1.487, *p* = .259

Table 2: Inferential statistic analysis of the MMN values exhibited by NH children for all vowel contrasts.

As expected, the *repeated-measure ANOVA* indicates that the MMN latency, amplitude, and area of NH children were statistically comparable, irrespective of whether MMN had been evoked by high, front, or back vowels as well as irrespective of whether the vowels of each pair were characterized by a smaller or a largeer Euclidean distance.

CI children							
Contrast types	Vowel contrasts	Values	Mean	S.d.	Min	Max	Range
High vowels (E.d. = **847 Mel**)	/i/$_{std}$ - /u/$_{dev}$ and /u/$_{std}$ - /i/$_{dev}$	Lat. (ms)	**216**	**13**	202	231	29
		Ampl. (μV)	**-.90**	**.56**	-2.05	-.19	1.87
		Area (μV*ms)	**61**	**21**	40	102	63
Front vowels (E.d. = **322 Mel**)	/i/$_{std}$ - /ɛ/$_{dev}$ and /ɛ/$_{std}$ - /i/$_{dev}$	Lat. (ms)	**219**	**9.22**	203	231	28
		Ampl. (μV)	**-.77**	**.34**	-1.20	-.42	.78
		Area (μV*ms)	**42**	**13**	28	59	30
Back vowels (E.d. = **304 Mel**)	/a/$_{std}$ - /ɔ/$_{dev}$ and /ɔ/$_{std}$ - /a/$_{dev}$	Lat. (ms)	**213**	**13**	191	227	36
		Ampl. (μV)	**-.46**	**.38**	-1.05	-.09	-96
		Area (μV*ms)	**50**	**12**	36	75	39

Table 3: Descriptive statistic analysis of the MMN values exhibited by CI children for all vowel contrasts.

CI children				
MMN values	High vowels (E.d. = **847 Mel**)	Front vowels (E.d. = **322 Mel**)	Back vowels (E.d. = **304 Mel**)	Stat. Sig.
Lat. (ms)	216 ± 13	219 ± 9	213 ± 13	*F*(2, 14) = .606, *p* = .558
Ampl. (μV)	**-.90 ± .56**	**-.77 ± .34**	**-.46 ± .38**	***F*(2, 12) = 3.835, *p* = .054**
Area (μV*ms)	**61 ± 21**	**42 ± 13**	**50 ± 12**	***F*(2, 12) = 4.639, *p* = .038**

Table 4: Inferential statistic analysis of the MMN values exhibited by CI children for all vowel contrasts.

The *repeated-measure ANOVA* indicates that there were no significant differences among the MMN latency values evoked by high, front, and back vowels in CI children as well. As for the MMN amplitude, the values evoked by the three vowel types were not far away from evoking statistically significant effects. With respect to MMN area, some significant differences among the area values evoked by high, front, and back vowels in CI children appeared to emerge. To better analyze these differences concerning the MMN amplitude and area values, we ran the estimated marginal means and the *post-hoc* tests (cf. Table 5 and Table 6 for amplitude as well as Table 7 and Table 8 for area).

Amplitude	Mean	S. E.	95% conf. int.	
			Lower bnd	Upper bnd
high	-,897	,199	-1,369	-,426
front	-,775	,119	-1,056	-,494
back	-,456	,133	-,772	-,141

Table 5. The estimated marginal means for amplitude of high, front, and back vowels in CI children.

(I) Ampl.	(J) Ampl.	Mean difference (I-J)	S. E.	Sig.[a]	95% conf. Int. for difference[a]	
					Lower bnd	Upper bnd
high	front	-,122	,184	1,000	-,699	,455
	back	-,441	,170	,106	-,971	,089
front	high	,122	,184	1,000	-,455	,699
	back	-,318	,135	,152	-,741	,104
back	high	,441	,170	,106	-,089	,971
	front	,318	,135	,152	-,104	,741

Based on the estimated marginal means.

a. Adjustement for multiple comparisons: Bonferroni.

Table 6. Pairwise comparisons for the estimated marginal means for amplitude of high, front, and back vowels in CI children.

As for MMN amplitude (cf. Table 4 above), the *post-hoc* tests revealed that, even though the MMN apparently presented a higher amplitude when MMN had been evoked by high (-.90μV) as compared to front (-.77μV) and to back (-.46μV) vowels, these small differences were not statistically significant.

Area	Mean	S.E.	95% conf. int.	
			Lower bnd	Upper bnd
high	61,166	7,445	43,562	78,770
front	41,770	4,474	31,190	52,350
back	50,479	4,377	40,130	60,828

Table 7. The sstimated marginal means for area of high, front, and back vowels in CI children.

(I) Area	(J) Area	Mean difference (I-J)	S. E.	Sig.[a]	95% conf. int. for difference[a]	
					Lower bnd	Lower bnd
high	front	19,396	6,705	,070	-1,574	40,366
	back	10,688	7,312	,562	-12,180	33,555
front	high	-19,396	6,705	,070	-40,366	1,574
	back	-8,709	4,863	,349	-23,917	6,499
back	high	-10,688	7,312	,562	-33,555	12,180
	front	8,709	4,863	,349	-6,499	23,917

Based on estimated marginal means a. Adjustement for multiple comparisons: Bonferroni.

Table 8. Pairwise comparisons for the estimated marginal means for area of high, front, and back vowels in CI children.

As for the MMN area (cf. Table 4 above), the smallest area was evoked by front vowels (e.g., 42µV*ms). Additionally, the area evoked by back vowels (e.g., 50µV*ms) was smaller as compared to that evoked by high vowels (e.g., 61µV*ms). The *post-hoc* tests (cf. Table 7 and Table 8 above) clarified that the finding that MMN area evoked by high vowels was wider as compared to the MMN area evoked by front vowels was not far away from being statistically significant (p = .070) as well as that the MMN area evoked by high vowels was not significantly wider as compared to the area evoked by back vowels (p = .562).

Taken together, the above-mentioned results indicate that the MMN values were insensitive to both vowel quality and to the Euclidean distance in NH children, in the sense that high, front, and back vowels were processed during a similar time window, as well as with comparable accuracy and size of neuronal activation. In CI children, on the other hand, the situation is not the same. On the one hand, the MMN latency and amplitude values were affected neither by vowel quality nor the Euclidean distance. The MMN area, on the other hand, turned out to be significantly wider for high as compared to front vowels, but to be statistically comparable in high and back vowels. These results for CI children might suggest that the MMN values were insensitive to the Euclidean distance, as indicated by the fact that MMN area was statistically comparable in high vowels characterized by a large Euclidean distance (e.g., 847 Mel) and in back vowels characterized by a small Euclidean distance (e.g., 304 Mel). Rather, the MMN area appeared partially constrained by vowel quality, since it was wider for high as compared to front vowels, but not for high as compared to back vowels.

The following section is devoted to the possible influence played by direction of change in the distintive feature specification on the MMN values.

8.3 The direction of change in the distinctive feature specification and the MMN values

As made precise in 5.3.4, along the lines of Eulitz & Lahiri (2004), Cornell et al. (2011), and Scharinger et al. (2012), we aimed at clarifying whether or not direction of change concerning the vowel distinctive feature specification was likely to constrain the processing of vowel pairs characterized by the same Euclidean distance. More particularly, along the lines of Eulitz & Lahiri (2004), Cornell et al. (2011), and Scharinger et al. (2012), we would like to cast light on whether the MMN peaks earlier and has enhanced amplitude, and wider area when the standard vowel is specified as [+] for a given distinctive feature and the deviant vowel is specified as [-] for the same distinctive feature. Should this be the case, we would expect the MMN evoked by the pair /u/$_{\mathrm{std}}$-/i/$_{\mathrm{dev}}$, where /u/ is specified as [+BACK, +ROUND] and /i/ is specified as [-BACK, -ROUND], to peak earlier and to have a larger amplitude and a wider area as compared to MMN evoked by /i/$_{\mathrm{std}}$-/u/$_{\mathrm{dev}}$. The same holds for the pairs /i/$_{\mathrm{std}}$-/ɛ/$_{\mathrm{dev}}$ and /ɛ/$_{\mathrm{std}}$-/i/$_{\mathrm{dev}}$. When direction of change is not unequivocal, as in the case of the back vowel pairs /a/$_{\mathrm{std}}$ -/ɔ/$_{\mathrm{dev}}$ and /ɔ/$_{\mathrm{std}}$ -/a/$_{\mathrm{dev}}$, where /a/ is specified as [+LOW, -ROUND], while /ɔ/ which is specified as [-LOW,+ROUND], we expect MMN to peak with comparable latency, amplitude, and area in both cases. In order to ascertain whether or not direction of change was easier-to-process in one direction (e.g., starting from /i/ and moving to /u/), or in the other direction (e.g., starting from /u/ and moving to /i/) in CI and NH children, we recurred to an independent *t*-test comparing the values of latency, amplitude, and area of MMN evoked by the two vowel pairs with opposite direction of change.

In the following, we will concentrate on high (cf. 8.3.1), front (cf. 8.3.2), and back (cf. 8.3.3) vowel pairs.

8.3.1 High vowels

Let us first consider the high vowel pairs /u/$_{\text{std}}$-/i/$_{\text{dev}}$ and /i/$_{\text{std}}$ -/u/$_{\text{dev}}$. During the elicitation of MMN (cf. 2.5.2), in the case of /u/$_{\text{std}}$-/i/$_{\text{dev}}$, the standard activates a phonological representation specified as [+] for the features [BACK] and [ROUND], thus generating a strong prediction concerning the specification of the same features in the deviant. These expectations are not fulfilled by the deviant, which is specified as [-] for the features [BACK] and [ROUND]. In the case of /i/$_{\text{std}}$ -/u/$_{\text{dev}}$, on the other hand, the standard activates a phonological representation specified as [-] for the features [BACK] and [ROUND] and, henceforth, it generates no prediction concerning the specification of the same features in the deviant. Along the lines of Eulitz & Lahiri (2004), Cornell et al. (2011), and Scharinger et al. (2012), we want to cast light on whether the MMN response elicited by the pair /u/$_{\text{std}}$-/i/$_{\text{dev}}$ is earlier, larger, and of higher magnitude as compared to that evoked by the pair /i/$_{\text{std}}$ -/u/$_{\text{dev}}$.

The independent *t*-test comparing the values of latency, amplitude, and area of MMN evoked by /i/$_{\text{std}}$-/u/$_{\text{dev}}$ to those of MMN evoked by /u/$_{\text{std}}$-/i/$_{\text{dev}}$ is presented in Table 9.

Children	MMN	/i/$_{\text{std}}$ -/u/$_{\text{dev}}$	/u/$_{\text{std}}$ -/i/$_{\text{dev}}$	Stat. Sig.
NH	Lat. (ms)	**226 ± 37**	**209 ± 38**	***t*(142)= 2.697, *p* = .008**
	Ampl. (uV)	-0.78 ± 1.01	-0.82 ± 0.91	*t*(142)= .257, *p* = .798
	Area (μV*ms)	52 ± 34	51 ± 35	*t*(142)= .102, *p* = .919
CI	Lat. (ms)	**228 ± 34**	**203 ± 32**	***t*(126)= 4.192, *p* < .001**
	Ampl. (uV)	-0.98 ± 1.50	-0.81 ± 1.55	*t*(126)= -.657, *p* = .513
	Area (μV*ms)	62 ± 60	67 ± 56	*t*(126)= -.412, *p* = .681

Table 9: The MMN values evoked by high vowels in NH and CI children.

As can be seen in Table 9, the MMN latency was significantly shorter when it had been evoked by /u/$_{\text{std}}$-/i/$_{\text{dev}}$ relative to /i/$_{\text{std}}$-/u/$_{\text{dev}}$, both for NH and for CI children. The MMN amplitude and area, on the other hand were statistically comparable for both contrasts in both groups of children.

We would like to conclude that, when the MMN response is evoked by high vowels, the MMN latency is shorter when direction of change goes from [+] to [-] as compared to when it goes from [-] to [+]. The MMN amplitude and area, on the other hand, are insensitive to direction of change.

8.3.2 Front vowels

Let us now focus on the front vowel pairs /i/$_{\text{std}}$ -/ɛ/$_{\text{dev}}$, and /ɛ/$_{\text{std}}$ -/i/$_{\text{dev}}$. In the case of /i/$_{\text{std}}$ -/ɛ/$_{\text{dev}}$, the standard vowel activates a phonological representation specified as [+] for the features [HIGH] and [ATR], thus generating a strong prediction concerning the specification of the same features in the deviant vowel. These expectations are not fulfilled by the deviant vowel, which is specified as [-] for the above-mentioned features. In the case of /i/$_{\text{std}}$ -/u/$_{\text{dev}}$, on the other hand, the standard activates a phonological representation specified as [-] for the features [HIGH] and [ATR], thus generating no prediction concerning the specification of the same features in the deviant. Building on Eulitz & Lahiri (2004), Cornell et al. (2011), and

Scharinger et al. (2013), we want to ascertain whether or not the MMN response elicited by the pair /i/$_{\text{std}}$ -/ɛ/$_{\text{dev}}$ is earlier, larger, and of higher magnitude as compared to that evoked by the pair /ɛ/$_{\text{std}}$ -/i/$_{\text{dev}}$.

The independent *t*-test comparing the values of latency, amplitude, and area of MMN evoked by /i/$_{\text{std}}$ -/ɛ/$_{\text{dev}}$ to those of MMN evoked by /ɛ/$_{\text{std}}$ -/i/$_{\text{dev}}$ is presented in Table 10.

Children	MMN	/i/$_{\text{std}}$ -/ɛ/$_{\text{dev}}$	/ɛ/$_{\text{std}}$ -/i/$_{\text{dev}}$	Stat. Sig.
NH	Lat. (ms)	**232 ± 34**	**205 ± 37**	***t*(142) = 4.613, *p* < .001**
	Ampl. (uV)	**-0.99 ± 0.78**	**-0.71 ± 0.53**	***t*(124) = 2.462, *p* = .015**
	Area (µV*ms)	46.97 ± 23	43,01 ± 14,27	*t*(141) = .782, *p* = .436
CI	Lat. (ms)	**225 ± 37**	**212 ± 37**	***t*(126) = 1.893, *p* = .061**
	Ampl. (uV)	-0.77 ± 0.75	-0.84 ± 0.70	*t*(126) = .488, *p* = .627
	Area (µV*ms)	42.03 ± 17	41.34 ± 17,12	*t*(126) = .110, *p* = .912

Table 10: The MMN values evoked by front vowels in NH and CI children.

As far as NH children are concerned, the MMN latency was significantly shorter when MMN had been evoked by /ɛ/$_{\text{std}}$-/i/$_{\text{dev}}$, whereas MMN amplitude was significantly larger when MMN had been evoked by /i/$_{\text{std}}$-/ɛ/$_{\text{dev}}$. The MMN area, on the other hand, appeared statistically comparable when evoked by both pairs of front vowels. With respect to CI children, the MMN latency was not far away from being significantly shorter when MMN had been evoked by /ɛ/$_{\text{std}}$-/i/$_{\text{dev}}$ as compared to to /i/$_{\text{std}}$-/ɛ/$_{\text{dev}}$. The MMN amplitude and area, on the other hand, resulted statistically comparable for both pairs of vowels.

To round off this section, when MMN had been evoked by front vowels, direction of change plays an interesting but equivocal influence on the MMN values. If the MMN latency appeared significantly shorter when direction of change went from [-] to [+] both in the case of NH and of CI children, the MMN amplitude resulted significantly wider when direction of change went from [+] to [-] just for NH children. Finally, the MMN area was insensitive to the influence played by direction of change for both groups of children.

8.3.3 Back vowels

Let us finally focus on the back vowel pairs /a/$_{\text{std}}$ -/ɔ/$_{\text{dev}}$, and /ɔ/$_{\text{std}}$ -/a/$_{\text{dev}}$. In the case of /a/$_{\text{std}}$ -/ɔ/$_{\text{dev}}$, the standard activates a phonological representation specified as [+LOW] and [-ROUND], thus generating a strong prediction concerning the specification of the feature [LOW] in the deviant. This expectation is not fulfilled by the deviant, which is specified as [-LOW] and [+ROUND]. In the case of /ɔ/$_{\text{std}}$ -/a/$_{\text{dev}}$, the standard activates a phonological representation specified as [-LOW] and [+ROUND], thus generating a strong prediction concerning the specification of the feature [ROUND] in the deviant. This expectation is not fulfilled by the deviant, which is specified as [+LOW] and [-ROUND]. Since direction of change is not unequivocal in back vowel pairs, we do not expect to find significant differences concerning the MMN values in one direction as compared to the other in both groups of children.

The independent *t*-test comparing the values of latency, amplitude, and area of MMN evoked by /a/$_{\text{std}}$ -/ɔ/$_{\text{dev}}$ to those of MMN evoked by /ɔ/$_{\text{std}}$ -/a/$_{\text{dev}}$ is presented in Table 11.

Children	MMN	/a/$_{\text{std}}$ -/ɔ/$_{\text{dev}}$	/ɔ/$_{\text{std}}$ -/a/$_{\text{dev}}$	Stat. Sig.
NH	Lat. (ms)	219 ± 43	210 ± 33	*t*(133) = 1.312, *p* = .192
	Ampl. (uV)	**-.563 ± .987**	**-.917 ± .775**	***t*(134) = 2.391, *p* = .018**
	Area (µV*ms)	47 ± 35	46 ± 31	*t*(142) =.053, *p* = .958
CI	Lat. (ms)	213 ± 33	212 ± 42	*t*(119) =.028, *p* = .977
	Ampl. (uV)	**-.667 ± 1.128**	**-.245 ± 1.109**	***t*(126) =.2,136 *p* = .035**
	Area (µV*ms)	53 ± 43	48 ± 38	*t*(126) =.771, *p* = .442

Table 11: The MMN values evoked by back vowels in NH and CI children.

The MMN latencies and area evoked by /a/$_{\text{std}}$ -/ɔ/$_{\text{dev}}$ and /ɔ/$_{\text{std}}$ -/a/$_{\text{dev}}$ were statistically comparable in both groups of children, thus fulfilling our expectations. The MMN amplitude, on the other hand, appeared significantly larger when MMN had been evoked by /ɔ/$_{\text{std}}$ -/a/$_{\text{dev}}$ for NH children, but significantly larger when MMN was evoked by /a/$_{\text{std}}$ -/ɔ/$_{\text{dev}}$ for CI children.

We would like to conclude that, when MMN had been evoked by back vowels, direction of change plays an interesting influence on MMN amplitude. In the case of NH children, the MMN amplitude was significantly larger when direction of change went from [-LOW, +ROUND] to [+LOW, -ROUND]. In the case of CI children, on the other hand, MMN amplitude was significantly larger when direction of change went from [+LOW, ROUND] to [-LOW, +ROUND].

8.4 The vowel acoustic-phonetic features and the N1 values

Recall 2.5.1 that the auditory N1 response of the ERPs signals detection and extraction of the vowel temporal and spectral properties (e.g., the formant values) which are particularly relevant for linguistic categorization. Interestingly, the N1 response of the ERPs (as well as its magnetic counterpart, the N1m) has been shown to be modulated by the vowel spectral properites in that different vowels elicited differential values of latency and amplitude of the N1 and of the N1m responses

In the present study, we wanted to cast light on whether the N1 values of latency and amplitude were likely to be modulated by the spectral properties of Salento Italian vowels and, more particularly, whether the results that we will find in Italian NH and CI children will be in agreement with those found by Manca (2014: 75-78) for Italian adults. To achieve this goal, we ran a first *repeated-measure ANOVA* on the N1 values of latency and a second *repeated-measure ANOVA* on the N1 values of amplitude for the NH (cf. Table 12) and the CI children (cf. Table 13, to Table 15), separately.

NH children						
N1 values	/i/$_{\text{std}}$[12]	/u/$_{\text{std}}$	/ɛ/$_{\text{std}}$	/a/$_{\text{std}}$	/ɔ/$_{\text{std}}$	Stat. Sig.
Lat. (ms)	185 ± 16	184 ± 16	189 ± 9	190 ±14	181 ± 14	*F*(3, 23) = 1.165, *p* = .343
Ampl. (µV)	-1.64 ± . 69	-1.27 ± .94	-1.73 ± .80	-1.23 ± .51	-1.23± .46	*F*(2, 19) = 1.642, *p* = .188

Table 12: Thr MMN values evoked by the five vowels used as standards in NH children.

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[12] We used the values of /i/$_{\text{std}}$ in the context of /u/$_{\text{dev}}$.

CI children						
N1 values	/i/$_{\text{std}}$[13]	/u/$_{\text{std}}$	/ɛ/$_{\text{std}}$	/a/$_{\text{std}}$	/ɔ/$_{\text{std}}$	Stat. Sig.
Lat. (ms)	181 ± 14	191 ± 17	187 ± 22	197 ± 18	187 ± 15	*F*(2, 13) = 1.713, *p* = .218
Ampl. (μV)	-.83 ± 40	-.90 ± .34	-1.20 ± .55	-.94 ± .47	-1.17 ± .38	*F*(3, 21) = 2.590, *p* = .079

Table 13: The MMN values evoked by the five vowels used as standards in CI children.

Amplitude	Mean	S. E.	95% conf.int.	
			Lower bnd	Upper bnd
/i/	-,833	,141	-1,166	-,501
/u/	-,901	,121	-1,188	-,614
/ɛ/	-1,204	,196	-1,667	-,740
/a/	-,940	,164	-1,329	-,551
/ɔ/	-1,172	,136	-1,494	-,850

Table 14. The estimated marginal means for the N1 latency evoked by /i, u, ɛ, ɔ, a/ in CI children.

(I) Ampl.	(J) Ampl.	Mean difference (I-J)	S. E.	Sig.[a]	95% conf. int. for difference[a]	
					Lower bnd	Upper bnd
/i/	/u/	,068	,120	1,000	-,414	,550
	/ɛ/	,370	,127	,228	-,143	,884
	/a/	,107	,151	1,000	-,503	,716
	/ɔ/	,339	,125	,298	-,163	,841
/u/	/i/	-,068	,120	1,000	-,550	,414
	/ɛ/	,302	,120	,398	-,181	,785
	/a/	,039	,160	1,000	-,607	,685
	/ɔ/	,271	,152	1,000	-,343	,885
/ɛ/	/i/	-,370	,127	,228	-,884	,143
	/u/	-,302	,120	,398	-,785	,181
	/a/	-,264	,138	,986	-,821	,294
	/ɔ/	-,032	,189	1,000	-,793	,729
/a/	/i/	-,107	,151	1,000	-,716	,503
	/u/	-,039	,160	1,000	-,685	,607
	/ɛ/	,264	,138	,986	-,294	,821
	/ɔ/	,232	,169	1,000	-,448	,912
/ɔ/	/i/	-,339	,125	,298	-,841	,163
	/u/	-,271	,152	1,000	-,885	,343
	/ɛ/	,032	,189	1,000	-,729	,793
	/a/	-,232	,169	1,000	-,912	,448

Based on estimated marginal means

a. Adjustement for multiple comparisons: Bonferroni.

Table 15. Pairwise comparisons for the estimated marginal means for N1 amplitude evoked by /i, u, ɛ, ɔ, a/ in CI children

The N1 response turned out to present comparable latency and amplitude values irrespective of the spectral characteristics of the five Salento Italian vowels, both in NH children (cf. Table 12 above) and in CI children (cf. Table 13 to Table 15 above).

The following section is dedicated to the influence played by age at surgery on the P1, N1, and MMN values.

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[13] Cf. footnote 1.

8.5 The age at CI surgery and the ERP values

One of the aims of the present study consisted in clarifying whether or not age at CI surgery was likely to influence the values of P1, N1, and MMN in a group of CI children implanted during the sensitive period for maturation of the auditory pathways, which is presumed to end between 3.5 years) [cf. Eggermont & Ponton 2003; Knudsen 2004; Sharma & Dorman 2006; Bishof 2007] and 4 years [cf. Krahl & Sharma 2012]. Recall from 4.2 that the mean age at surgery of the CI children examined was 2.8 years and that it ranged between 2.1 and 4.4 years. Seven out of eight the CI children examined received their unilateral CI before 3.5 years, whereas one child received its unilateral CI later at 4.5 years. However, as noted in 4.2, given that, with one exception, the children participating to the study received their CI early in their lives, we will consider the results of the present study as representative for early-implanted Italian children.

Deaf children implanted until 3.5 years usually receive the greatest benefit from CI stimulation in processing of speech and non-speech sounds, while deaf children implanted afterwards (up to 13 years) may receive significant benefit from CI stimulation in processing of speech and non-speech sounds, although much greater variation in auditory performance is acknowledged (cf. 3.10).

Building on the findings presented in 3.10, we have the following expectations for detection of single vowels (as indexed by P1), for detection and extraction of the acoustic spectral properties which are particularly relevant for linguistic categorization (as indexed by N1), and for extraction and representation of the acoustic spectral features which are meaningfull in linguistics terms (as indexed by MMN). First, we expect P1, N1, and MMN to peak later in deaf children implanted towards 4.4 years as compared to deaf children implanted towards 2.1 years. Second, we hypothesize that P1, N1, and MMN will present attenuated amplitude in deaf children implanted towards 4.4 years as compared to deaf children implanted towards 2.1 years. Third, we suppose that the area under the curve of MMN will be smaller in deaf children implanted towards 4.4 years relative to deaf children implanted towards 2.1 years. In the following, we will first concentrate on high (cf. 8.6.1), then on front (cf. 8.6.2), and finally on back (cf. 8.6.3) vowels.

8.5.1 High vowels

As far as /i/$_{\text{std}}$-/u/$_{\text{dev}}$ and /u/$_{\text{std}}$-/i/$_{\text{dev}}$ are concerned, a *bivariate correlation analysis* assessing the relationship between the P1, N1, and MMN values on the one hand (cf. Table 2 for P1 and N1 as well as Table 7 for MMN in 7.2) and the age at surgery on the other hand (e.g., 2.1 – 4.4 years) revealed significant negative correlations in CI children (cf. Table 16 for P1, Table 17 for N1, and Table 18 for MMN).

Age at surgery and the P1 values evoked by /i/ and /u/		
Vowels	Latency (ms)	Amplitude (μV)
/i/$_{\text{std}}$	*r* = .040, *p* = .757	*r* = .052, *p* = .685
/u/$_{\text{dev}}$	*r* = .239, *p* = .057	*r* = .053, *p* = .688
/u/$_{\text{std}}$	*r* = .079, *p* = .537	*r* = -.131, *p* = .301
/i/$_{\text{dev}}$	*r* = .185, *p* = .144	*r* = .033, *p* = .795

Table 16: Pearson correlations between age at surgery and the P1 values evoked by high vowels.

Age at surgery and the N1 values evoked by /i/ and /u/		
Vowels	Latency (ms)	Amplitude (μV)
/i/$_{std}$	r = -.096, p =.452	r =.121, p =.339
/u/$_{dev}$	r = -.053, p =.677	r = -.053, p = .677
/u/$_{std}$	r = -.070, p = .585	r = -.259, p = .059
/i/$_{dev}$	r = .027, p = .834	r = .250, p =. 238

Table 17: Pearson correlations between age at surgery and the N1 values evoked by high vowels.

Age at surgery and the MMN values evoked by /i/ and /u/			
Vowels	Latency (ms)	Amplitude (μV)	Area (μV*ms)
/i/$_{std}$-/u/$_{dev}$	r = .178, p = .160	r = -.177, p = .358	r = .042, p = .740
/u/$_{std}$-/i/$_{dev}$	r = -.065, p = .612	r = .305, p = .064	r = .220, p = .081

Table 18: Pearson correlations between age at surgery and the MMN values evoked by high vowels.

To round off this section, we would like to observe that, contrary to our expectations, age at surgery did not influence either the latency, or the amplitude, or even the area of P1, N1, and MMN in the Italian CI children examined. In other words, the ERP values appeared to be insensitive to age at surgery provided that surgery took place during the sensitive period for central auditory maturation.

8.5.2 Front vowels

With respect to /i/$_{std}$-/ɛ/$_{dev}$ and /ɛ/$_{std}$-/i/$_{dev}$, a first *bivariate correlation analysis* investigating the relationship between the P1 values on the one hand (cf. Table 22 in 7.3.1.1 and Table 32 in 7.3.2.1) and age at surgery on the other hand (e.g., 2.1 – 4.4 years) revealed no significant correlations (cf. Table 19).

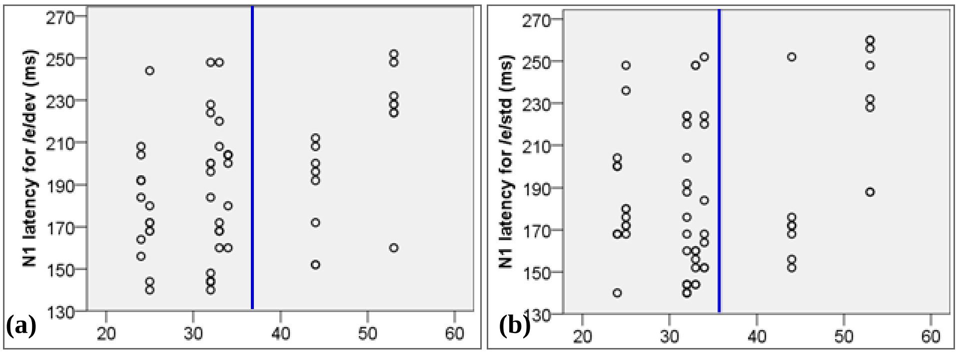
Age at surgery and the P1 values evoked by /i/ and /ɛ/		
Vowels	Latency (ms)	Amplitude (μV)
/i/$_{std}$	r = .137, p = .279	r = -.113, p = .373
/ɛ/$_{dev}$	r = .187, p = .140	r = -.144, p = .257
/ɛ/$_{std}$	r = .105, p = .410	r = -.125, p =.325
/i/$_{dev}$	r = .083, p =.513	r =.191, p = .131

Table 19: Pearson correlations between age at surgery and the P1 values evoked by front vowels.

A second *bivariate correlation analysis* shedding light on the relationship between the N1 values (cf. Table 22 in 7.3.1.1 and Table 32 in 7.3.2.1) and the age at surgery (e.g., 2.1 – 4.4 years), revealed significant correlations for the N1 latency evoked by /ɛ/$_{dev}$ and /ɛ/$_{std}$ (cf. Table 24 as well as Figure 1), but no significant correlations for the N1 amplitude and the N1 latency in the other cases (cf. Table 24).

Age at surgery and the N1 values evoked by /i/ and /ɛ/		
Vowels	Latency (ms)	Amplitude (μV)
/i/$_{std}$	r = -.102, p = .423	r = .241, p = .055
/ɛ/$_{dev}$	**r = . 380, p < .01**	r =.147, p =.258
/ɛ/$_{std}$	**r = .327, p = .008**	r =-.168, p =.185
/i/$_{dev}$	r = -.054, p =.673	r = -.056, p = .675

Table 20: Pearson correlations between age at surgery and the N1 values evoked by front vowels.



Months = Years.Months
20 = 1.8
30 = 2.6
40 = 3.4
50 = 4.2
60 = 5
70 = 5.8
80 = 6.6
90 = 7.4
100 = 8.2

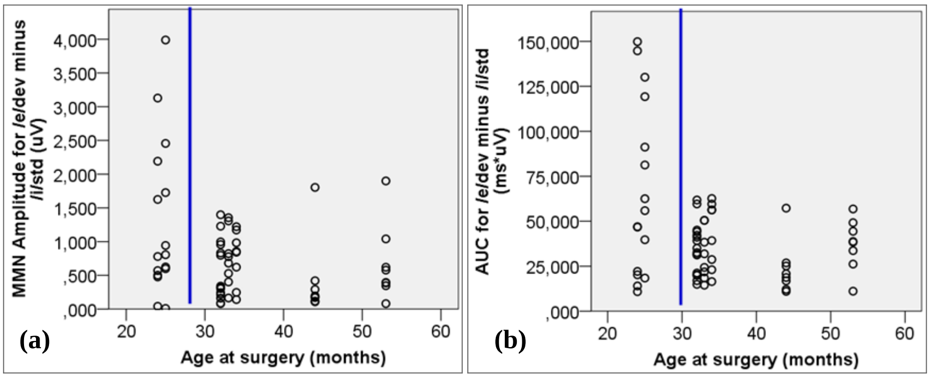
Figure 1: Age at surgery and the N1 latency evoked by /ɛ/as a deviant (a) and as a standard (b).

Figure 1 shows that the N1 latency evoked by /ɛ/, both as a deviant and as a standard, appeared significantly shorter in deaf children implanted before 3.4 years.

A third *bivariate correlation analysis* assessing the relationship between the MMN values (cf. Table 27 in 7.3.1.2 and Table 37 in 7.3.2.2) and the age at surgery (e.g., 2.1 – 4.4 years) returned significant correlations for the MMN values evoked by /i/$_{std}$-/ɛ/$_{dev}$, but not for the MMN values evoked by /ɛ/$_{std}$-/i/$_{dev}$ (cf. Table 25 and Figure 2) .

Age at surgery and the MMN values evoked by /i/ and /ɛ/			
Vowels	Latency (ms)	Amplitude (µV)	Area (µV*ms)
/i/$_{std}$-/ɛ/$_{dev}$	*r* = .150, *p* = .200	***r* = .265, *p* = .034**	***r* = -.313, *p* = .012**
/ɛ/$_{std}$-/i/$_{dev}$	*r* = -.020, *p* = .874	*r* = .063, *p* = .621	*r* = .059, *p* = 642

Table 21: Pearson correlations between age at surgery and the MMN values evoked by front vowels.



Months = Years.Months
20 = 1.8
30 = 2.6
40 = 3.4
50 = 4.2
60 = 5
70 = 5.8
80 = 6.6
90 = 7.4
100 = 8.2

Figure 2: Age at surgery and the MMN amplitude (a) and area (b).

If the MMN latency evoked by /i/$_{std}$-/ɛ/$_{dev}$ was not significantly influenced by earlier vs. later age at surgery, the MMN amplitude and area evoked by /i/$_{std}$-/ɛ/$_{dev}$, on the other hand, appeared significantly larger and wider in deaf children implanted before 2.6 years (cf. Table 21 and Figure 2 above).

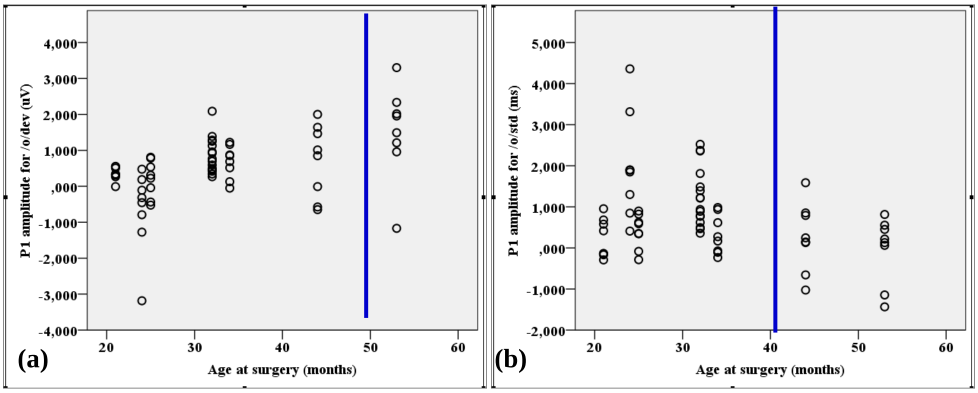
To conclude this section, we want to stress that, in contrast to our expectations, the P1 values evoked by front vowels were insensitive to earlier vs. later age at surgery. The N1 and the MMN values, on the other hand, were likely to be modulated by age at surgery, although not systematically. The N1 amplitude resulted larger in CI children undergoing surgery before 3,4 years, whereas the MMN amplitude and area were larger and wider in deaf chidlren implanted before 2.6 years.

8.5.3 Back vowels

As far as /a/$_{std}$-/ɔ/$_{dev}$ and /ɔ/$_{std}$-/a/$_{dev}$ are concerned, a first *bivariate correlation analysis* shedding light on the relationship between the P1 values on the one hand (cf. Table 42 in 7.4.1.1 and Table 52 in 7.4.2.1) and the age at surgery on the other hand (e.g., 2.1 – 4.4 years) , revealed significant correlations for the P1 amplitude evoked by /ɔ/, both as a standard and as a deviant, but no significant correlations for the P1 amplitude and the P1 latency in the other instances (cf. Table 22 as well as Figure 3), .

Age at surgery and P1 values evoked by /a/ and /ɔ/		
Vowels	Latency (ms)	Amplitude (μV)
/a/$_{std}$	r = .005, p = .966	r = .142, p = .263
/ɔ/$_{dev}$	r = -.197, p = .118	**r = .479, p < .001**
/ɔ/$_{std}$	r = -.024, p = .853	**r = -.317, p =.011**
/a/$_{dev}$	r = .051, p =.690	r = -.125, p = .323

Table 22: Pearson correlations between age at surgery and the P1 values evoked by back vowels.



Months	=	Years.Months
20	=	1.8
30	=	2.6
40	=	3.4
50	=	4.2
60	=	5
70	=	5.8
80	=	6.6
90	=	7.4
100	=	8.2

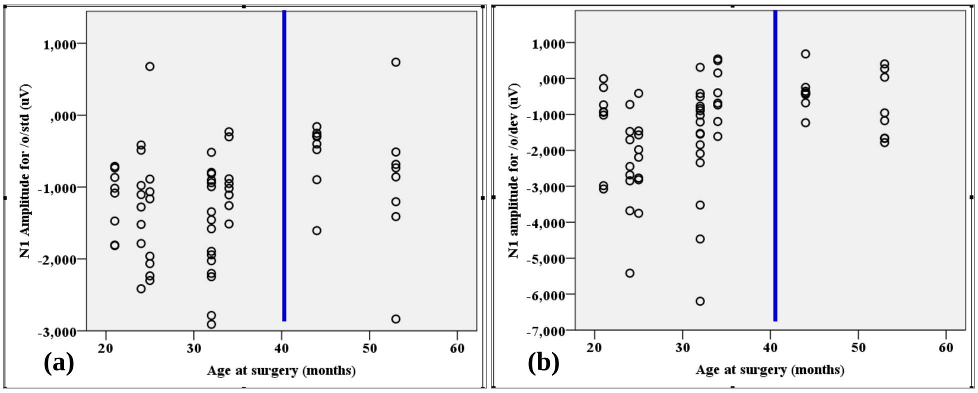
Figure 3: Age at surgery and the P1 amplitude evoked by /ɔ/ as a deviant (a) and as a standard (b).

If the P1 amplitude evoked by /ɔ/$_{dev}$ was larger in children implanted after 4.2 years as compared to children implanted earlier (cf. Figure 3a), the P1 amplitude evoked by /ɔ/$_{std}$ appeared larger in deaf children implanted before 3.4 years (cf. Figure 3b).

A second *bivariate correlation analysis* assessing the relationship between the N1 values on the one hand (cf. Table 42 in 7.4.1.2 and Table 52 in 7.4.2.1) and age at surgery on the other hand (e.g., 2.1 – 4.4 years), revealed a significant correlation for the N1 amplitude evoked by /ɔ/, both as a standard and as a deviant, but no significant correlation for the amplitude of N1 in the remaining contexts, as well as for the latency of N1 in all the contexts (cf. Table 23 and Figure 4) .

Age at surgery and the N1 values evoked by /a/ and /ɔ/		
Vowels	Latency (ms)	Amplitude (μV)
/a/$_{std}$	r = .181, p = .151	r = .029, p = .823
/ɔ/$_{dev}$	r = -.168, p = .185	**r = .353, p = .004**
/ɔ/$_{std}$	r = .066, p = .606	**r = .248, p =.049**
/a/$_{dev}$	r = -.115, p =.366	r =.103, p = .417

Table 23: Pearson correlations between age at surgery and the N1 values evoked by back vowels.



Months	=	Years.Months
20	=	1.8
30	=	2.6
40	=	3.4
50	=	4.2
60	=	5
70	=	5.8
80	=	6.6
90	=	7.4
100	=	8.2

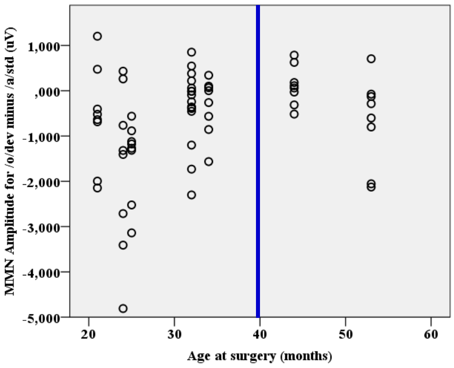
Figure 4: Age at surgery and the N1 amplitude evoked by /ɔ/ as a deviant (a) and as a standard (b).

Figure 4 suggests that the N1 amplitude evoked by /ɔ/, both as a deviant and as a standard, was significantly larger in deaf children implanted before 3.4 years.

A third *bivariate correlation analysis* shedding light on the relationship between the MMN values (cf. Table 47 in 7.4.1.2 and Table 57 in 7.4.2.2) and the age at surgery (e.g., 2.1 – 4.4 years), identified no significant correlations for the MMN latency and area (cf. Table 24). As for the MMN amplitude, a significant correlation was identified when MMN had been evoked by /a/$_{\text{std}}$-/ɔ/$_{\text{dev}}$, but not when it had been evoked by /ɔ/$_{\text{std}}$-/a/$_{\text{dev}}$ (cf. Table 24 and Figure 5) .

Age at surgery and MMN values evoked by /a/ and /ɔ/			
Vowels	Latency (ms)	Amplitude (µV)	Area (µV*ms)
/a/$_{\text{std}}$-/ɔ/$_{\text{dev}}$	*r* = .010, *p* = .939	***r* = .258, *p* = .039**	*r* = -.176, *p* = .165
/ɔ/$_{\text{std}}$-/a/$_{\text{dev}}$	*r* = .175, *p* = .166	*r* = .036, *p* = .775	*r* = .186, *p* = 177

Table 24: Pearson correlations between age at surgery and the MMN values evoked by back vowels.



Months	=	Years.Months
20	=	1.8
30	=	2.6
40	=	3.4
50	=	4.2
60	=	5
70	=	5.8
80	=	6.6
90	=	7.4
100	=	8.2

Figure 5: Age at surgery and the MMN amplitude evoked by /a/$_{\text{std}}$-/ɔ/$_{\text{dev}}$.

Figure 5 indicates that the MMN amplitude evoked by /a/$_{\text{std}}$-/ɔ/$_{\text{dev}}$ turned out to be significantly larger in deaf children implanted before 3.4 years.

To conclude this paragraph, we would like to note that, in agreement with our expectations, the P1, the N1, and the MMN amplitudes evoked by back vowels resulted significantly larger in children implanted before 3.4 years as compared to the deaf children implanted later. The ERP latencies and areas, on the other hand, were not constrained by earlier vs. later age at surgery.

8.6 The duration of CI use and the ERP values

The present study aimed at casting light on whether or not duration of CI use was likely to contrain the values of P1, N1, and MMN in a group of CI children implanted before 3.5 years. Recall from 4.2 that the mean duration of CI use in the deaf children examined was 6.3 years (e.g., 75 mts) and it ranged between 2.4 and 8.1 years. Building on the fact that the shortest duration of CI stimulation was of 2.4 years, we will consider the results of the present study as representative for experienced pediatric CI users.

As for vowel detection and extraction of vowel acoustic-spectral features, as indexed by P1 and N1, previous studies on CI children reported confusing results. On the one hand, shorter P1 latencies and larger P1 amplitudes evoked by musics were found in CI children implanted earlier in their lives (≤ 3.5 years), provided that they had been using their CI for at least 5 years [cf. Torppa et al. 2013]. On the other hand, no differences were found in the P1 and N1 values evoked by speech and non-speech sounds in children implanted before 3.5 years who had been using their unilateral CI for a period of at least 4 years [cf. Munivrana & Mildner 2013]. With respect to neural processing of pairs of linguistic and non-linguistic stimuli in CI children, the MMN latency appeared shorter and the MMN amplitude resulted larger in CI children implanted before 3.5 years and who had been using their CI for at least 5 years [cf. Torppa et al. 2013] or 6 years [cf. Ortmann et al. 2013].

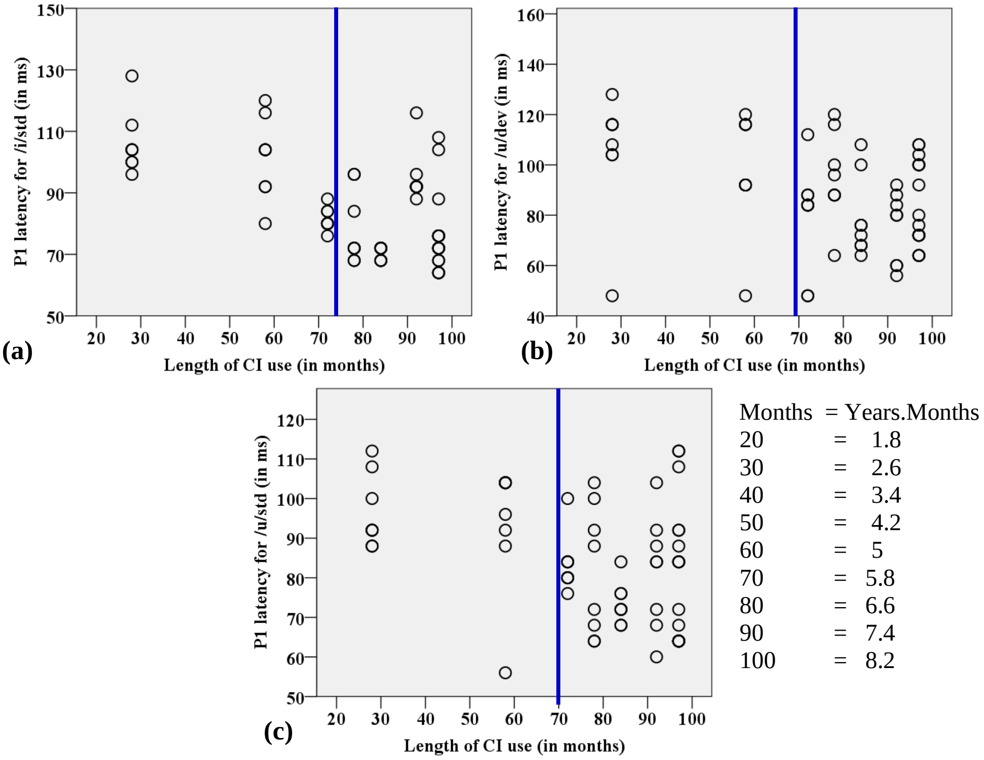
To recapitulate, it remains still unclear when exactly ERP latencies get significantly shorter, ERP amplitudes become significantly larger, and ERP area turns out to be significantly wider in the case of deaf children implanted during the optimal period for central auditory maturation. The present study will try to shed light on these points. Generally speaking, deaf children benefiting from longer duration of CI stimulation (i.e. towards 8.1 years) are expected to present shorter ERP latencies, larger ERP amplitudes, and wider ERP areas as compared to deaf children benefiting from a shorter duration of CI use (i.e. towards 2.4 years). In the following, we will first address high (cf. 8.6.1), then front (cf. 8.6.2), and finally back (cf. 8.6.3) vowels.

8.6.1 High vowels

As far as /i/$_{\text{std}}$-/u/$_{\text{dev}}$ and /u/$_{\text{std}}$-/i/$_{\text{dev}}$ are concerned, a first *bivariate correlation analysis* casting light on the relationship between the P1 values on the one hand (cf. Table 2 and Table 12 in 7,2,1) and duration of CI stimulation on the other hand (e.g., 2.4 – 8.1 years), revealed significant correlations only for the latency of P1, but not for its amplitude (cf. Table 25 and Figure 6).

Duration of CI use and the P1 values evoked by /i/ and /u/		
Vowels	Latency (ms)	Amplitude (μV)
/i/$_{\text{std}}$	**_r_ = -.587, _p_ < .001**	_r_ = -.050, _p_ = .695
/u/$_{\text{dev}}$	**_r_ = -.386, _p_ = .002**	_r_ = -.056, _p_ = .701
/u/$_{\text{std}}$	**_r_ = -.375, _p_ = .002**	_r_ = .040, _p_ = .755
/i/$_{\text{dev}}$	_r_ = -.094, _p_ = .458	_r_ = .002, _p_ = .986

Table 25: Pearson correlations between duration of CI stimulation and the P1 values evoked by high vowels.



Months = Years.Months
20 = 1.8
30 = 2.6
40 = 3.4
50 = 4.2
60 = 5
70 = 5.8
80 = 6.6
90 = 7.4
100 = 8.2

Figure 6: Duration of CI use and P1 latency evoked by /i/$_{std}$ (a), /u/ as a deviant (b), and as a standard (c).

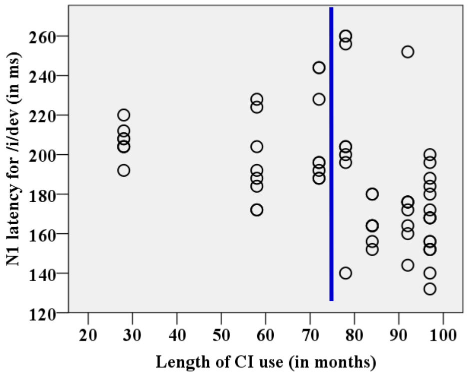
Figure 6 shows that the P1 latency evoked by /i/$_{std}$, /u/$_{dev}$, and /u/$_{std}$ appeared significantly shorter in deaf children benefiting from a duration of CI stimulation of at 5.8 years.

A second *bivariate correlation analysis* investigating the relationship between the N1 values (cf. Table 2 and Table 12 in 7,2,1) and the length of CI use (e.g., 2.4 – 8.1 years), returned no significant correlations, except for the N1 latency evoked by /i/ $_{dev}$ (cf. Table 26 and Figure 7).

Duration of CI use and the N1 values evoked by /i/ and /u/		
Vowels	Latency (ms)	Amplitude (µV)
/i/$_{std}$	$r = .056$, $p = .661$	$r = .069$, $p = .585$
/u/$_{dev}$	$r = -.063$, $p = .620$	$r = .046$, $p = .721$
/u/$_{std}$	$r = -.146$, $p = .250$	$r = .182$, $p = .151$
/i/$_{dev}$	**$r = -.433$, $p < .001$**	$r = .071$, $p = .575$

Table 26: Pearson correlations between duration of CI stimulation and the N1 values evoked by high vowels.

Figure 7 indicates that the N1 evoked by /i/$_{dev}$ peaked significantly earlier in deaf children benefiting from a duration of CI stimulation of at least 5.8 years.



Months = Years.Months
20 = 1.8
30 = 2.6
40 = 3.4
50 = 4.2
60 = 5
70 = 5.8
80 = 6.6
90 = 7.4
100 = 8.2

Figure 7: Length of CI use and the N1 latency evoked by /i/$_{dev}$.

A third *bivariate correlation analysis* assessing the relationship between the MMN values (cf. Table 7 and Table 17 in 7.2.2) and the length of CI use (e.g., 2.4 – 8.1 years) revealed no significant correlations (cf. Table 27).

Duration of CI use and the MMN values evoked by /i/ and /u/			
Vowels	Latency (ms)	Amplitude (µV)	Area (µV*ms)
/i/$_{std}$-/u/$_{dev}$	*r* = -.038, *p* = .766	*r* = -.084, *p* = .509	*r* = -.218, *p* = .083
/u/$_{std}$-/i/$_{dev}$	*r* = -.166, *p* = .190	*r* = .097, *p* = .448	*r* = -.190, *p* = .081

Table 27: Pearson correlations between age at surgery and the MMN values evoked by high vowels.

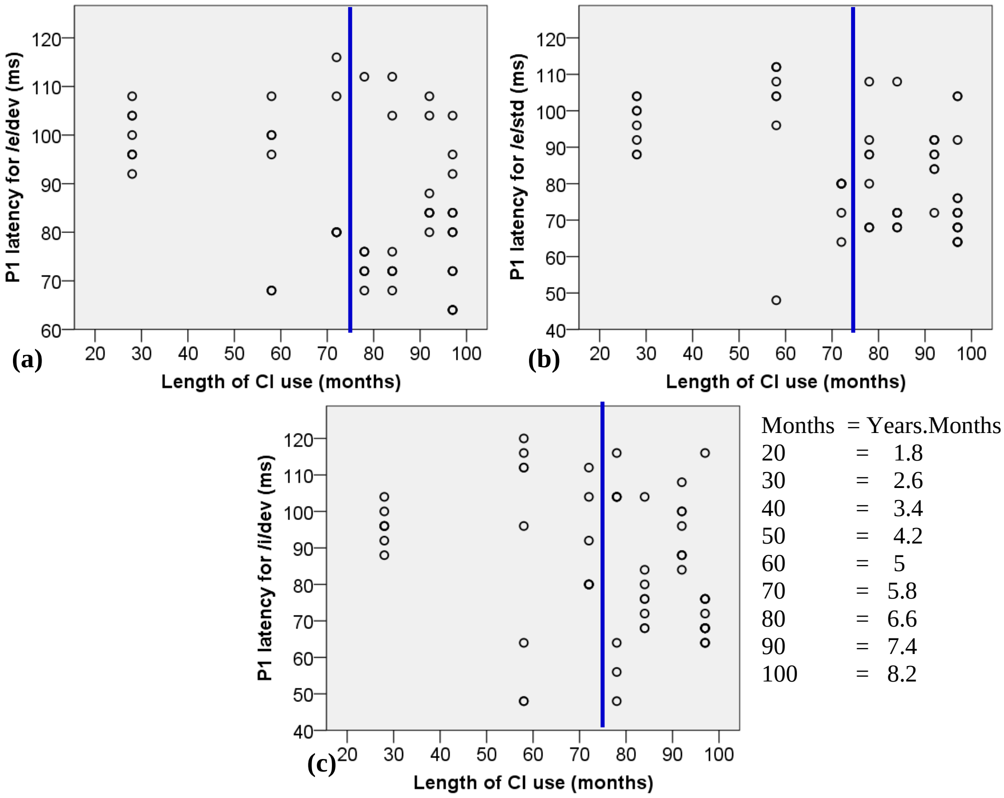
To recapitulate, the latency of P1 and N1 appeared significantly shorter in deaf children benefiting from a duration of CI stimulation of at least 5,8 years. The P1 and N1 amplitude, as well as all the MMN values, on the other hand, turned out to be comparable in all deaf children irrespective of the shorter (i.e. 2.4 years) or longer (i.e. 8.1 years) duration of CI stimulation.

8.6.2 Front vowels

With respect to /i/$_{std}$-/ɛ/$_{dev}$ and /ɛ/$_{std}$-/i/$_{dev}$, a first *bivariate correlation analysis* throwing light on the relationship between the P1 values (cf. Table 22 in 7.3.1.1 and Table 32 in 7.3.1.2) and the duration of CI stimulation (e.g., 2.4 – 8.1 years), revealed significant correlations only for the latency of P1, although not systematically, but not for its amplitude (cf. Table 28 and Figure 8).

Duration of CI use and the P1 values evoked by /i/ and /ɛ/		
Vowels	Latency (ms)	Amplitude (µV)
/i/$_{std}$	*r* = -.118, *p* = .354	*r* = .074, *p* = .562
/ɛ/$_{dev}$	***r* = -.400, *p* = .001**	*r* = .137, *p* =.282
/ɛ/$_{std}$	*r* = **-.473, *p* < .001**	*r* =-.094, *p* =.461
/i/$_{dev}$	*r* = **-.485, *p* < .001**	*r* = .200, *p* =135

Table 28: Pearson correlations between duration of CI stimulation and the P1 values evoked by front vowels.



Months	= Years.Months
20	= 1.8
30	= 2.6
40	= 3.4
50	= 4.2
60	= 5
70	= 5.8
80	= 6.6
90	= 7.4
100	= 8.2

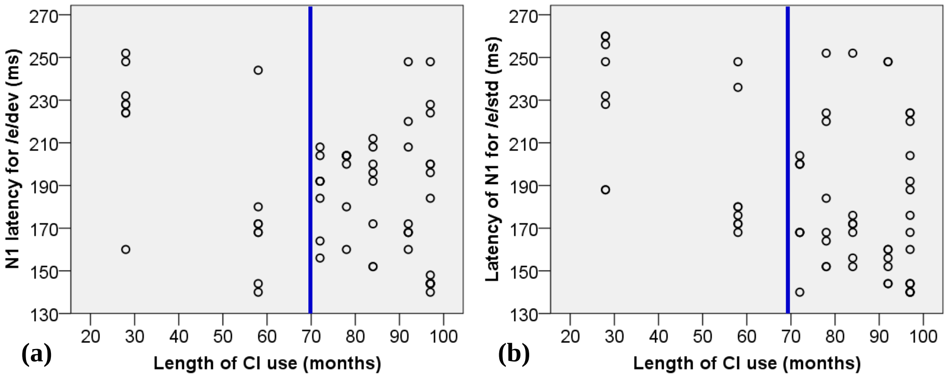
Figure 8: Duration of CI use and the P1 latency evoked by /ɛ/$_{\text{dev}}$ (a), /ɛ/$_{\text{std}}$ (b), and /i/$_{\text{dev}}$ (c).

Figure 8 suggests that the P1 latency evoked by /ɛ/$_{\text{dev}}$, /ɛ/$_{\text{std}}$, and /i/$_{\text{dev}}$ was significantly shorter in deaf children who had been using their unilateral CI for at least 5.8 years.

A second *bivariate correlation analysis* investigating the relationship between the N1 values (cf. Table 22 in 7.3.1.1 and Table 32 in 7.3.1.2) and the length of CI use (e.g., 2.4 – 8.1 years) returned no significant correlations for N1 amplitude (cf. Table 29), as well as some significant correlations for the N1 latency when N1 had been evoked by /ɛ/, but not when it had been evoked by /i/ (cf. Table 29 and Figure 9).

Duration of CI use and N1 values evoked by /i/ and /ɛ/		
Vowels	Latency (ms)	Amplitude (µV)
/i/$_{\text{std}}$	*r* = -.034, *p* =.792	*r* = .012, *p* = .927
/ɛ/$_{\text{dev}}$	***r* = -. 473, *p* < .01**	*r* = -.080, *p* =.565
/ɛ/$_{\text{std}}$	***r* = -.326, *p* = .009**	*r* = -.130, *p* =330
/i/$_{\text{dev}}$	*r* = .174, *p* =.170	*r* = .174, *p* =.170

Table 29: Pearson correlations between duration of CI stimulation and the N1 values evoked by front vowels.



Months	= Years.Months
20	= 1.8
30	= 2.6
40	= 3.4
50	= 4.2
60	= 5
70	= 5.8
80	= 6.6
90	= 7.4
100	= 8.2

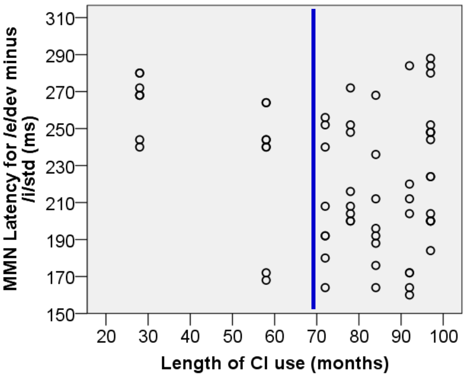
Figure 9: Duration of CI use and latency of N1 evoked by /ɛ/ as a deviant (a) and /ɛ/as a standard (b).

Once more, Figure 9 indicates that the latency of N1 evoked by /ɛ/ was significantly shorter in deaf children with a duration of stimulation of at least 5.8 years months.

A third *bivariate correlation analysis* assessing the relationship between the MMN values and (cf. Table 27 in 7.3.1.1 and Tabke 37 in 7.3.2.2) the length of CI use (e.g., 2.4 – 8.1 years) revealed no significant correlations for the MMN amplitude and area (cf. Table 30), but a significant correlation for the MMN latency, although not regularly (cf. Table 30 and Figure 10).

Duration of CI use and the MMN values evoked by /i/ and /ɛ/			
Vowels	Latency (ms)	Amplitude (µV)	Area (µV*ms)
/i/$_{std}$-/ɛ/$_{dev}$	***r* = -.339, *p* = .006**	*r* = .159, *p* = .209	*r* = -.198, *p* = .117
/ɛ/$_{std}$-/i/$_{dev}$	*r* = .177, *p* = .163	*r* = .176, *p* = .165	*r* = 189, *p* = .165

Table 30: Correlations between duration of CI stimulation and the MMN values evoked by front vowels.



Months	= Years.Months
20	= 1.8
30	= 2.6
40	= 3.4
50	= 4.2
60	= 5
70	= 5.8
80	= 6.6
90	= 7.4
100	= 8.2

Figure 10: Duration of CI use and the MMN latency evoked by /i/$_{std}$-/ɛ/$_{dev}$.

Figure 10 illustrates that the MMN evoked by the pair /i/$_{std}$-/ɛ/$_{dev}$ turned out to be significantly shorter in those children benefiting from a duration of CI stimulation of at least 5.8 years.

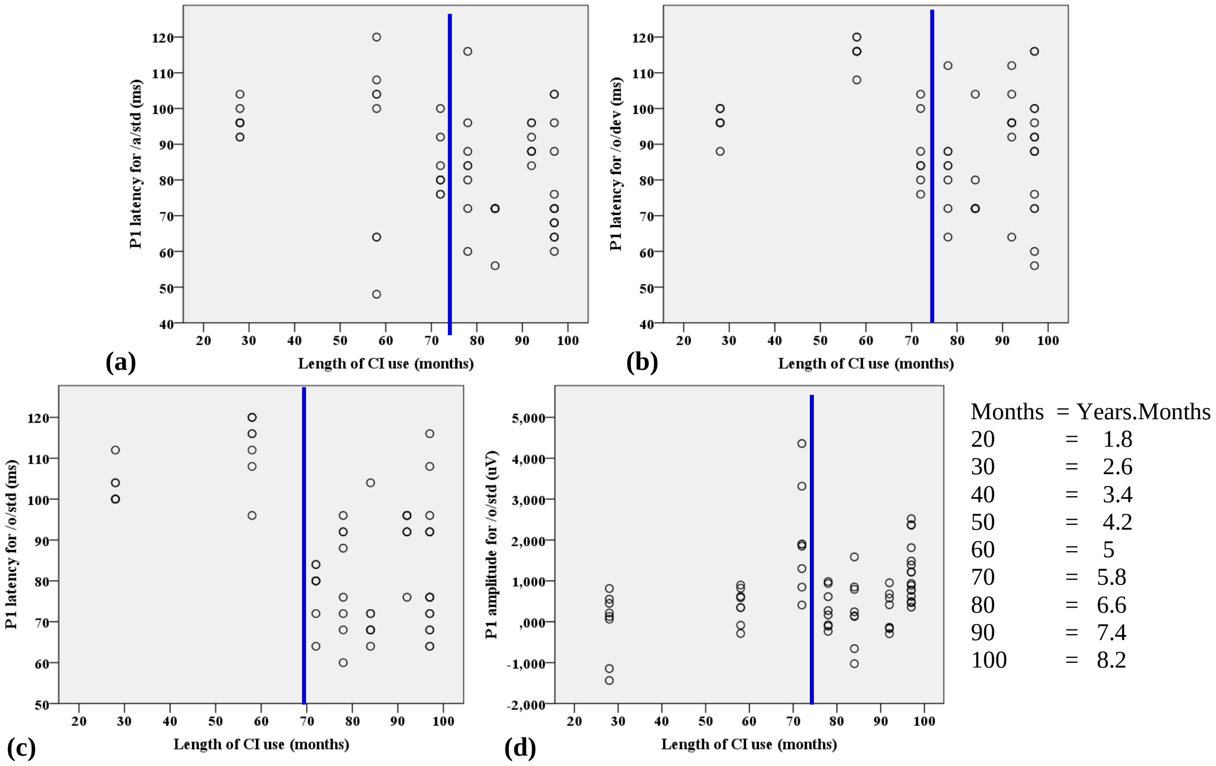
To round off this paragraph, the P1, N1, and MMN responses evoked by front vowels peaked significantly earlier in those deaf children benefiting from a duration of CI stimulation of at least 5.8 years. The ERP amplitudes and areas, on the other hand, were statistically comparable in all the deaf children examined, irrespective of the shorter (i.e. 2.4 years) or longer (i.e. 8.1 years) duration of CI stimulation.

8.6.3 Back vowels

As far as /a/$_{std}$-/ɔ/$_{dev}$ and /ɔ/$_{std}$-/a/$_{dev}$ are concerned, a first *bivariate correlation analysis* casting light on the relationship between the P1 values (cf. Table 42 in 7.4.1.1 and Table 52 in 7.4.1.2) and the duration of CI stimulation (e.g., 2.4 – 8.1 years), revealed significant correlations for the latency of P1, although not regularly, but not for its amplitude (cf. Table 31 and Figure 11).

Duration of CI use and the P1 values evoked by /a/ and /ɔ/		
Vowels	Latency (ms)	Amplitude (µV)
/a/$_{std}$	***r* = -.389, *p* = .001**	*r* = -.219, *p* = .082
/ɔ/$_{dev}$	***r* = -.322, *p* = .009**	*r* = -.145, *p* = .253
/ɔ/$_{std}$	***r* = -.492, *p* = .01**	***r* = -.273, *p* = .029**
/a/$_{dev}$	*r* = -.110, *p* = .386	*r* = -.046, *p* = .716

Table 31: Pearson correlations between duration of CI stimulation and the P1 values evoked by back vowels.



Months = Years.Months
20 = 1.8
30 = 2.6
40 = 3.4
50 = 4.2
60 = 5
70 = 5.8
80 = 6.6
90 = 7.4
100 = 8.2

(a) (b) (c) (d)

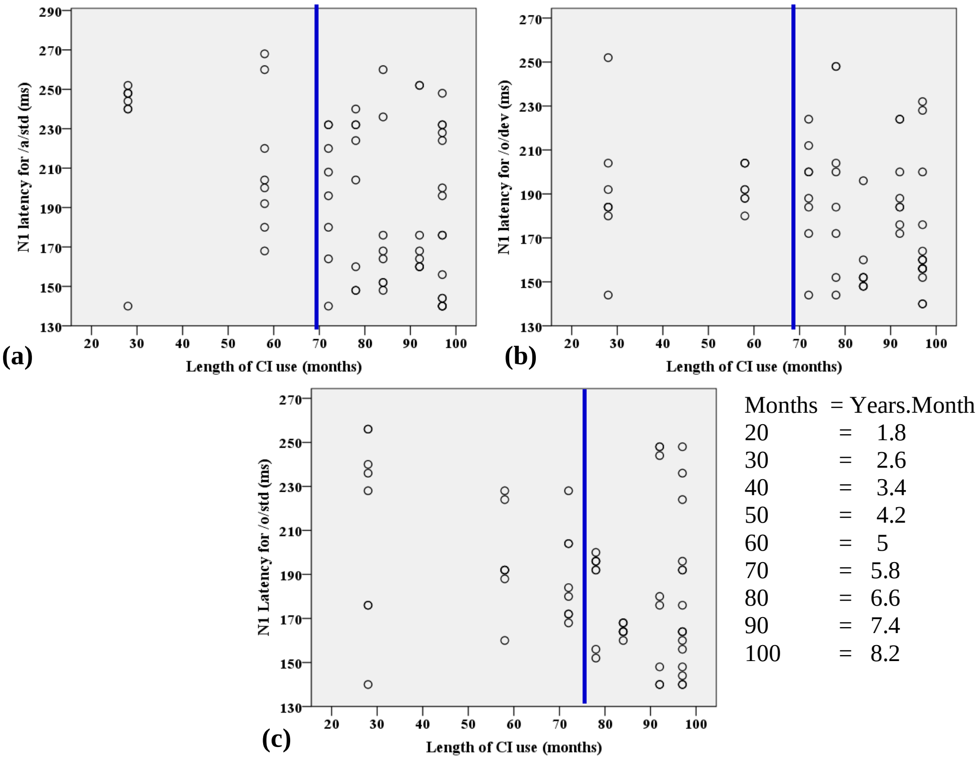
Figure 11: Duration of CI use and the P1 latency evoked by /a/$_{std}$ (a), /ɔ/$_{dev}$ (b), and /ɔ/$_{std}$ (c). Duration of CI use and the P1 amplitude evoked by /ɔ/$_{std}$ (d).

The latency of P1 was likely to be significantly shorter in deaf children who had been using their unilateral CI for at least 5 years (cf. Figure 11a), whereas it was consistently significantly shorter in deaf children benefiting from a duration of CI stimulation of at least 5.8 years (cf. Figure 11b and Figure 11c). Likewise, the amplitude of P1 resulted significantly wider in deaf children who had been using their CI for at least 5.8 years (cf. Figure 11d).

A second *bivariate correlation analysis* assessing the relationship between the N1 values values (cf. Table 42 in 7.4.1.1 and Table 52 in 7.4.1.2) and the length of CI use (e.g., 2.4 – 8.1 years) returned no significant correlations for N1 amplitude, but some significant correlations for N1 latency when N1 had been evoked by /ɔ/$_{dev}$, /ɔ/$_{std}$, and /a/$_{dev}$, but not when N1 had been evoked by /a/$_{std}$, (cf. Table 32 and Figure 12).

Duration of CI use and the N1 values evoked by /a/ and /ɔ/		
Vowels	Latency (ms)	Amplitude (µV)
/a/$_{std}$	***r* = -.405, *p* = .001**	*r* = .095, *p* = .456
/ɔ/$_{dev}$	***r* = -.246, *p* = .050**	*r* = .060, *p* = .637
/ɔ/$_{std}$	***r* = -.342, *p* = .006**	*r* = -.145, *p* = .252
/a/$_{dev}$	*r* = -.042, *p* = .740	*r* = -.103, *p* = .419

Table 32: Pearson correlations between duration of CI stimulation and the N1 values evoked by back vowels.



Months	= Years.Months
20	= 1.8
30	= 2.6
40	= 3.4
50	= 4.2
60	= 5
70	= 5.8
80	= 6.6
90	= 7.4
100	= 8.2

Figure 12: Duration of CI use and latency of N1 evoked by /ɔ/$_{\text{dev}}$ (a), /ɔ/$_{\text{std}}$ (b), and /a/$_{\text{dev}}$ (c).

Figure 12 suggests that the latency of N1 was significantly shorter in deaf children with a duration of CI stimulation of at least 5.8 years.

A third *bivariate correlation analysis* assessing the relationship between the MMN values (cf. Table 27 in 7.3.1.2 and Table 37 in 7.3.2.2) and the length of CI use (e.g., 2.4 – 8.1 years) revealed no statistically significant correlations (cf. Table 33).

Duration of CI use and MMN values evoked by /a/ and /ɔ/			
Vowels	Latency (ms)	Amplitude (μV)	Area (μV*ms)
/a/$_{\text{std}}$-/ɔ/$_{\text{dev}}$	*r* = .220, *p* = .080	*r* = .214, *p* = .089	*r* = -.167, *p* = .187
/ɔ/$_{\text{std}}$-/a/$_{\text{dev}}$	*r* = -.166, *p* = .191	*r* = -.204, *p* = .105	*r* = .222, *p* = .085

Table 33: Correlations between duration of CI stimulation and the MMN values of evoked by back vowels.

To resume, the P1 and N1 responses elicited by back vowels tended to peak significantly earlier in those deaf children benefiting from a duration of CI stimulation of at least 5.8 years as compared to those children benefiting from a shorter duration of CI stimulation. The amplitude of P1 and N1 as well as all the values of MMN, on the other hand, turned out to be in sensitive to duration of CI stimulation.

8.7 Discussion

In deaf children with unilateral CI devices, the automatic processing of single vowels as well as vowel pairs at the cortical level, as indexed by the P1, N1, and MMN responses in turn, is likely to be potentially constrained by a variety of factors, such as the vowel quality, the Euclidean distance, the direction of change in the distintive feature specification, the acoustic-phonetic features of the eliciting vowels, the age at surgery, and the duration of CI use. These factors may influence the ERP values to a different extent. First, we explored whether and how the vowel quality, the Euclidean distance, the direction of change, and the difficulty degree, were likely to affect the MMN values. Second, we studied whether and to what extent the acoustic-phonetic features of the eliciting vowelsinfluenced the N1 values. Third, we investigated whether and how age at surgey and length of CI use constrained the values of P1, N1, and MMN. In the following, we will first concentrate on the factors influencing the P1 (cf. 8.7.1), the N1 (cf. 8.7.2), and the MMN (cf. 8.7.3) response.

8.7.1 The factors constraining the P1 response

As repeatedly observed throughout this thesis, the auditory P1 response is a correlate of sound detection at the cortical level as well as a marker for the maturation of the central auditory pathways [Sharma, A. et al. 2002abc, 2005b, 2007, 2009; Gilley et al. 2008]. We investigated whether and to what extent age at surgery and duration of CI stimulation were likely to contrain the P1 values of latency and amplitude evoked in deaf children undergoing surgery during the sensitive period for central auditory maturation.

As for age at surgery (range: 2.1 – 4.4 years), the P1 values turned out to be largely insensitive to the earlier (e.g., towards 2.1 years) or later (e.g., towards 4.4 years) age at surgery. This systematically holds for the P1 latency evoked by high, front, and back vowels, as well as for the P1 amplitude evoked by high and front vowels. In the case of back vowels, on the other hand, the P1 amplitude was likely to be significantly larger in those deaf children undergoing surgery before 3.4 up to 4.2 years, although not regularly.

With respect to duration of CI stimulation (range: 2.4 – 8.1 years), the P1 latency evoked by high, front, and back vowels was significantly shorter in deaf children benefiting from a CI use of at least 5.8 years as compared to those children benefiting from a shorter CI use. The P1 amplitude, on the other hand, was never influenced by the longer vs. shorter duration of CI stimulation when P1 had been evoked by high and front vowels. Intriguingly,the P1 amplitude turned out to be wider in those deaf children who had been using their unilateral CI for at least 5.8 years, as above highlightened for the P1 latency, only when P1 had been evoked by back vowels.

Previous studies monitored the P1 values evoked by speech [cf. Sharma A. et al. 2002abc, 2007; Gilley et al. 2008; Munivrana & Mildner 2013; for a review, Sharma A. & Dorman 2006] and non-speech sounds [cf. Torppa et al. 2012] in deaf children implanted before 3.5 years. With respect to age at surgery, these studies did not monitor whether, in the case of children implanted during the period of maximal plasticity of the auditory pathways, earlier vs. later age at surgery was likely to affect the values of P1. As for the influence played by duration of CI use, on the one hand, CI children implanted before 3.5 years and who had been using their CI for at least 5 years (range: 2.6 – 10.8 years) presented shorter P1 latencies and larger P1 amplitudes evoked by musics as compared to children with a shorter time in sound [cf. Torppa et al. 2013]. On the other hand, no significant differences were found in the P1 values evoked by speech and non-speech sounds in children implanted before 3.5 years who had been using their unilateral CI for at least 4 years (range: 4.1 years . 6.6 years) [cf. Munivrana & Mildner 2013].

In our data concerning age at surgery, the fact the latency of P1 is categorically insensitive to age at surgery suggest that the CI children investigated are able to detect high, front, and back vowels irrespective of the earlier vs. the later age at surgery. The finding that the amplitude of P1 is insensitive to age at surgery when P1 had been evoked by high and front vowels appears to indicate that earlier age at surgery does not promote accuracy in detection of high and front vowels. The finding that the P1 amplitude is significantly wider in those deaf children implanted before 3.4 up to 4.2 years when P1 had been evoked by back vowels happens to signal that earlier age at surgery may be crucial for accuracy in detection of back vowels.

In our data concerning duration of CI stimulation, the fact that the P1 latency evoked by all vowels is significantly shorter in deaf children benefiting from a CI use of at least 5.8 years indicates a more efficient synaptic transfer and more efficient auditory pathways as compared to those children benefiting from a shorter CI use [cf. Sharma et al. 2007]. The finding that the P1 amplitude was never affected by the longer vs. shorter duration of CI stimulation when P1 had been evoked by high and front vowels is likely to indicate that high and front vowels are detected with comparable accuracy by all CI children irrespective of the duration of CI stimulation. The finding that the amplitude of P1 evoked by back vowels is wider in those deaf children who had been using their unilateral CI for at least 5.8 years as compared to the other children indicates that the P1 amplitude evoked by back vowels is significantly affected by duration of CI stimulation.

To round off this section, we would like to conclude that the P1 values are constrained by an age at surgery smaller than 3.4 up to 4.2 years, but by a duration of CI stimulation of at least 5.8 years.

8.7.2 The factors constraining the N1 response

As frequently observed, the auditory N1 response encodes detection and extraction of spectral properties which are particularly relevant for linguistic categorization [for N1, cf. Pulvermüller & Shyrov 2006; Rinne 2006; Näätänen et al. 2011; Manca 2014: 75-78; for N1m, cf. Roberts et al. 2000, 2004; Obleser et al. 2003, 2004; Titinen et al. 2005; Scharinger et al. 2011, 2012]. The N1 response has been shown to be modulated by the vowels' spectral properties [in the above-mentioned studies We studied whether and to what extent the vowel acoustic-phonetic features, age at surgery, and duration of CI stimulation potentially influence the N1 values of latency and amplitude evoked in deaf children undergoing surgery before 3.5 years.

With respect to the vowel acoustic-phonetic features, the N1 response presents comparable latency and amplitude values irrespective of the spectral characteristics of the five Salento Italian vowels. This holds both for CI and for NH children. Our results are in contrast with the above-mentioned studies. In particular, a recent study by Manca (2014: 75-78) on the modulation exerted by the spectral characteristics of the Salento Italian vowels on the latency and the amplitude values of the N1 response in adult NH speakers has reported different findings consistent with a significant modulation of the N1 values depending on the vowels' spectral characteristics. As for the N1 latency, the back vowels /a/ and /u/ elicited a later response as compared to the front vowels /ɛ/ and /i/ and to the back vowel /ɔ/. With respect to the N1 amplitude, the high vowels /u/ and /i/ elicited a greater amplitude with respect to the low vowel /a/ and the mid vowels /ɛ/ and /ɔ/ [cf. Manca 2014]. In languages other than Italian, a consistent modulation of the N1m values depending on the vowel spectral characteristics had been reported as well. First, the back vowels /o/ and /u/ were found to elicit later N1m responses than non-back vowels, thus suggesting that N1m latency inversely traks F1 [cf. Roberts et al. 2000, 2004, and Titinen et al. 2005 for English vowels; cf. Obleser et al. 2004 for German vowels; cf. Scharinger et al. 2011 for Turkish vowels]. Second, the high vowels i/ and /u/ turned out to elicit later N1m responses than non-high vowels, thus revealing a significant interaction of tongue body height and tongue place of articulation [cf. Obleser et al. 2004 for German vowels; Scharinger et al. 2011 for Turkish vowels]. Third, as far as non-back vowels are concerned, the low vowel /a/ elicited a significantly faster response than the mid-high vowel /e/ as well as /e/ elicited a significantly faster response than the high vowel /i/ [cf. Obleser et al. 2003]. Fourth, as for N1m amplitude, it appeared to inversely track both F1 and F2, by increasing with decreasing formant valuesm in that the largest N1m amplitudes were observed for the high back vowel /u/ [cf. Scharinger et al. 2011 for Turkish vowels].

We hypothesize that the absent modulation of the N1 values depending on the spectral characteristics of Salento Italian vowels in the NH and CI children examined here may be due to the developmental patterns of the N1 response. The N1 response reflects auditory cortical activation resulting from intra- and inter-hemispheric activity [cf. Mäkela & Hari 1992; Mäkela & McEvoy 1996]. However, cortico-cortical connections continue to mature from infance into the adolescence. This might be the reason why N1 is often not readily observed before 9 years of age either in NH children [cf. Čeponiene et al. 1998, 2002; Ponton et al. 2000; Gilley et al. 2005; Sussmann et al. 2008] or in CI children, both in late-implanted [for speech-evoked ERPs, cf. Singh et al. 2004; Sharma et al. 2005, 2007, 2009; Henkin et al. 2008; Dinces et al. 2009; for non-speech-evoked ERPs, cf. Ponton et al. 2000; Ponton & Eggermont 2001] and in early-implanted [for speech-evoked ERPs, cf. Sharma et al. 2005, 2007, 2009; for non-speech evoked ERPs, cf. Torppa et al. 2012]. children A few exceptions are represented by the studies of Kileny et al. [1997], Beynon et al. [2002], and Munivrana & Mildner [2013], which identified N1 in early-implanted and in late-implanted children, respectively, but which did not investigate the modulation of the N1 response depeding on the vowel spectral cues.

Returning to our data, we suppose that the fact that the N1 response is not readily modulated by the spectral characteristics of the Salento italian vowels in the CI children (age range at testing: 6.7 — 10.7 years, with 5 children below 9 years of age) and in the NH children (age range at testing: 4.3 – 10.8 years, with 7 children below 9 years of age) may be ascribed to the fact that the N1 response in pediatric subjects is not mature until adolescence. It is also be plausible that the number of children involved into our study is too small (n = 8 CI and n = 9 NH children) for us to be able to monitor the possible modulation of the N1 response building on the vowels' F1 and F2 values of the eliciting vowels.

As for the age at surgery (range: 2.1 – 4.4 years), the values of N1 are differently constrained by age at surgery depending on the vowel quality. When N1 had been evoked by high vowels, the N1 latency and amplitude result insensitive to age at surgery. When N1 had been evoked by front vowels, the N1 latency is significantly shorter in deaf children implanted before 3.4 years, whereas the N1 amplitude is not modulated by the earlier vs. later age at surgery, When N1 had been evoked by back vowels, the N1 amplitude appears significantly larger in deaf children implanted before 3.4 years, whereas its latency is unaffected by age at surgery,

With respect to the duration of CI stimulation (range: 2.4 – 8.1 years), the N1 response is likely to peak significantly earlier when it had been evoked by high, front, and back vowels in deaf children benefiting from a duration of CI stimulation of at least 5.8 years as compared to those deaf children benefiting from a shorter CI use.

Previous studies monitoring the N1 values in CI children implanted early [cf. Munivrana & Mildner 2013] or late in their life [cf. Kileny et al. 1997; Beynon et al. 2002]. Age at surgery ranged between 3 and 4 years for Munivrana & Mildner (2013), and between 5.3 and 12.5 years for Beynon et al. (2002), whereas it was not specified in Kileny et al. (1997). These studies did not monitor whether earlier vs. later age at surgery was likely to constrain the values of N1. As for the influence played by duration of CI use, on the one hand, no significant differences emerged in the N1 values in children implanted before 3.5 years who had been using their unilateral CI for at least 4 years (range: 4.1 years . 6.6 years) [cf. Munivrana & Mildner 2013] as well as in late-implanted children who had been using their CI for at least 5.3 years [cf. Beynon et al. 2002], whereas the possible influence of duration of CI stimulation on the N1 values had not been investigated in late-implanted children who had been using their CI for a period ranging between 7 mts and 7 years [cf. Kileny].

In our data concerning age at surgery, the N1 latency or amplitude are likely to be constrained by age at surgery when N1 had been evoked by front and back vowels, in that the N1 response peaked earlier or with larger amplitude in deaf children implanted before 3.4 years. When N1 had been evoked by high vowels, on the other hand, the N1 values of latency and amplitude are comparable in all children irrespective of the age at surgery.

In our data concerning duration of CI stimulation, contrary to previous studies the N1 response is likely to peak significantly earlier when it had been evoked by high, front, and back vowels in deaf children benefiting from a duration of CI stimulation of at least 5.8 years, thus possibly indicating a more efficient detection and extraction of the vowel acoustic-phonetic characteristics as well as more efficient auditory pathways as compared to as compared to those children benefiting from a shorter CI use [cf. Sharma et al. 2007]. The finding that the N1 amplitude is never constrained by the longer vs. shorter duration of CI stimulation irrespective of vowel quality may suggest that the acoustic-phonetic characteristics of high, front, and back vowels are detected and extracted with comparable accuracy irrespective of the shorter (e.g., 2.4 years) or the longer (e.g., 8.1 years) duration of CI stimulation.

To conclude this section, we would like to observe the N1 values are likely to be constrained by an age at surgery smaller than 3.2 years and by a duration of CI stimulation of at least 5.8 years.

8.7.3 The factors constraining the MMN response

Along the lines of Lahiri & Reetz (2002, 2010), Eulitz & Lahiri (2004), and Sussman et al. (2003, 2013), in the present thesis, MMN is regarded as indicating the successful extraction and representation of the auditory regularities characterizing the standard vowels and which are meaningfull in linguistics terms (e.g., the acoustic spectral and temporal features) at the cortical level, especially in the case of deaf children. We studied whether and to what extent the vowel quality, the Euclidean distance, the direction of change, the age at surgery, and the duration of CI stimulation were likely to influence the MMN values of latency, amplitude, and area evoked in deaf children undergoing surgery during the period of maximal plasticit for the central auditory pathways.

When analyzing vowel quality and the Euclidean distance, the two pairs of high vowels (e.g., /i/$_{\text{std}}$ - /u/$_{\text{dev}}$ and /u/$_{\text{std}}$ - /i/$_{\text{dev}}$) were regarded as a single contrast, the two pairs of front vowels (e.g., /i/$_{\text{std}}$ - /ɛ/$_{\text{dev}}$ and /ɛ/$_{\text{std}}$ - /i/$_{\text{dev}}$) were considered as a single contrast, and the two pairs back vowels (e.g., /a/$_{\text{std}}$ - /ɔ/$_{\text{dev}}$ and /ɔ/$_{\text{std}}$ - /a/$_{\text{dev}}$) were analyzed as a single contrast. With respect to vowel quality, the MMN values result insensitive to vowel quality in the case of NH children, thus suggesting that NH children process high, front, and back vowels during a comparable time interval, as well as with a comparable accuracy, and with a comparable size of neuronal activation. In the case of CI children, the MMN latency and amplitude turn out to be insensitive to vowel quality, The MMN area, on the other hand, is not far away from being significantly wider when MMN had been evoked by high as compared to front vowels, whereas MMN area evoked by high and back vowels resulted comparable. Previous studies had found that back vowels were more difficult to produce for pediatric CI users [cf. Horga & Liker 2006; Liker et al. 2007; Baudonck et al. 2011] as well as more difficult to perceive for adult CI users [cf. Harnsberger et al. 2001]. Our data do not indicate that back vowels are more-difficult to process at the cortical level for CI children; rather, high, front, and back vowels are processed during a similar time window and with comparable accuracy by CI children, as indicated by the MMN latency and amplitude, in turn. As for the size of neuronal activation, as indexed by MMN area, high vowels are cortically processed with higher accuracy as compared to front vowels, but with comparable accuracy as compared to back vowels. With respect to the Euclidean distance characterizing vowel pairs, the larger is the acoustic distance between vowels, the larger is the magnitude of deviance between them. It is almost equivalent for the front vowels /ɛ/ vs. /i/ (e.g., 322 Mel) and for the back vowels /a/ vs. /ɔ/ (and 304 Mel), whereas it is wider for the high vowels /u/ vs. /i/ (847 Mel). In NH children, the MMN results insensitive to the Euclidean distance since comparable MMN values had been elicited by the front and the back vowel pairs, characterized by a small Euclidean distance, and by the high vowel pairs, characterized by a large Euclidean distance. The same holds for CI children with respect to the MMN values of latency and amplitude, thus indicating that CI children process vowel pairs during a comparable time window and with a similar precision irrespective of the magnitude of deviance characterizing the vowels. As for the MMN area, the area evoked by high vowels (with E. d. = 847 Mel) and in back vowels (E. d. = 304 Mel) is statistically comparable irrespective of the different Euclidean distance characterizing the two vowel pairs; the area evoked by high vowels (with E. d. = 847 Mel) is wider as compared to the area evoked by front vowels (with Euclidean distance = 322 Mel). These findings appear to suggest that the MMN area is sensitive to vowel quality (e.g., high and back as compared to front vowels), rather than to the larger vs. smaller Euclidean distance. Previous studies on CI children [cf. Henkin et al. 2008], CI adults [cf. Okusa et al. 1999; Kelly et al. 2005], and NH adults [cf. Titinen et al. 1995; Dietsch & Luce 1997; Obleser et al. 2003; Peltola 2003, 2007] have found the MMN to peak earlier and to present a larger amplitude when it had been evoked by vowel contrasts presenting a larger Euclidean distance as compared to vowel contrasts characterized by a smaller Euclidean distance [for exceptions, cf. Horvàth et al. 2008]. Should MMN values be sensitive to the Euclidean distance, one would expect the MMN to peak earlier, with larger, amplitude, and with wider area when it had been evoked by high vowels, which are characterized by a large Euclidean distance (e.g., 847 Mel) as compared to front and back vowels, which are characterized by a smaller Euclidean distance (322 Mel and 304 Mel, respectively). However, our results do not agree with the afore-mentioned studies; rather, our findings are in line with Horvàth et al. (2008), in showing that the Euclidean distance is not a crucial factor in constraining vowel processing at the cortical level.

As for direction of change in distinctive feature specification, we wanted to cast light on whether direction of change was likely to constrain the MMN values. More specifically, we want to clarify whether MMN peaks earlier and it has larger amplitude and wider area when the standard vowel is specified as [+] for a given distinctive feature and the deviant vowel is specified as [-] for the same distinctive feature. Should this be the case, we would expect the MMN evoked by the vowel pair /u/$_{std}$-/i/$_{dev}$, where /u/ is specified as [+BACK, +ROUND] and /i/ is specified as [-BACK, -ROUND], and the vowel pair /i/$_{std}$-/ɛ/$_{dev}$, where /i/ is specified as [+HIGH, +ATR] and /ɛ/ is specified as [+HIGH, +ATR], to peak earlier and to have a larger amplitude and a wider area as compared to MMN evoked by /i/$_{std}$-/u/$_{dev}$ and /ɛ/$_{std}$-/i/$_{dev}$, where the standard vowels are specified as [-] and the deviant vowels are specified as [+] for the above-mentioned phonological features. When direction of change is not unequivocal, as in the case of the back vowel pairs /a/$_{std}$ -/ɔ/$_{dev}$ and /ɔ/$_{std}$ -/a/$_{dev}$, where /a/ is specified as [+LOW] and [-ROUND], while /ɔ/ which is specified as [-LOW] and [+ROUND], we expect MMN to peak with comparable latency, amplitude, and area in both cases. Our findings for direction in the distinctive feature specification are not completely clear. First, when MMN had been evoked by high vowels, the MMN latency appears shorter when direction of change went from [+] to [-], whereas the MMN amplitude and area result insensitive to direction of change, both in NH and in CI children. Second, when MMN had been evoked by front vowels, the MMN latency appears shorter when direction of change went from [-] to [+] both in the case of NH and of CI children, whereas the MMN amplitude resulted significantly wider when direction of change went from [+] to [-] just for NH children. The MMN area, on the other hand, is insensitive to direction of change in front vowels. Third, when MMN had been evoked by back vowels, the MMN amplitude is significantly larger when direction of change went from [-LOW] and [+ROUND] to [+LOW] and [-ROUND] in NH children, whereas the reverse case holds for CI children. Previous investigations by Eulitz & Lahiri (2004), Cornell et al. (2011), and Scharinger et al. (2012) had shown that MMN was likely to peak earlier and with enhanced amplitude when the standard vowels was specified as presenting a given phonological feature and the deviant vowel was unspecified for the same distinctive feature, whereas MMN peaked later and with reduced amplitude when the standard vowel was unspecified for the same feature and the deviant vowel is specified as presenting it. Our data do not corroborate the findings by Eulitz & Lahiri (2004), Cornell et al. (2011), and Scharinger et al. (2012), thus indicating that direction of change does not unequivocally affect the MMN values either in NH and in CI children.

As for age at surgery (range: 2.1 – 4.4 years), the values of MMN are differently constrained by age at surgery depending on the vowel quality. When MMN had been evoked by high vowels, all its values result insensitive to age at surgery. When MMN had been evoked by front vowels, the MMN latency is insensitive to age at surger, whereas its amplitude and area result larger and wider in deaf children implanted before 2.6 years. When MMN had been evoked by back vowels, the MMN latency and area are not affected by age at surgery, whereas the MMN amplitude is larger in deaf children implanted before 3.4 years.

With respect to duration of CI stimulation (range: 2.4 – 8.1 years), when MMN had been evoked by high and back vowels, its values are not constrained by duration of CI stimulation. When MMN had been evoked by front vowels, the MMN amplitude and area were insensitive to duration of CI stimulation, whereas the MMN latency areshorter in deaf children benefiting from a CI use of at 5.8 years.

Previous studies on cortical processing of pairs of linguistic and non-linguistic stimuli in deaf children implanted during the period of maximal plasticity of their auditory pathways, achieved the following results: the MMN latency appeared shorter and the MMN amplitude was larger in CI children implanted before 3.5 years and who had been using their CI for at least 5 years (range: 2.6 – 10.8) [cf. Torppa et al. 2013] or 6 years (range: 6.1 - 15.3 years) [cf. Ortmann et al. 2013]. Our data indicate that shorter MMN latencies are likely to be found in deaf children who had been using their CIs for at least 5.8 years, i.e. slightly after with respect to Torppa et al. (2013), but slightly before with respect to Ortmann et al. (2013). Our results suggest a more efficient extraction and representation of the auditory regularities (e.g., the acoustic spectral and temporal features) of the (standard) vowels at the cortical level, especially in the case of experienced pediatric CI users.

To round off this section, we would like to concluce that the MMN values are likely to be constrained by an age at surgery smaller than 2.6 up to 3.4 years, but by a duration of CI stimulation of at least 5.8 years.

8.8 Chapter summary

The present chapter investigated the factors which were likely to influence cortical processing of the Salento Italian vowels in a group of experienced pediatric CI users who had undergone surgery before 3.5 years.

As for vowel detection, as indexed by P1, we investigated whether and to what degree age at surgery and duration of CI stimulation affected the P1 values of latency and amplitude. With respect to detection and extraction of the vowel acoustic-phonetic features, as indexed by N1, we studied whether and to what extent the vowel acoustic-phonetic features, age at surgery, and duration of CI stimulation were likely to contrain the N1 values of latency and amplitude. As far as extraction and representation of the vowel acoustic-phonetic features are concerned, we explored whether and how vowel quality, the Euclidean distance, the direction of change, the age at surgery, and the duration of CI use played a role on the MMN values of latency, amplitude, and area.

Out of the seven factors investigated, only three turned out to consistently contrain vowel processing in Italian pediatric CI users. First, vowel quality influenced MMN area which was wider for high as compared to high vowels. Second, age at surgery affected typically the ERP amplitude, and rarely the ERP latency and area: the former is shorter and the latter are larger in deaf children implanted before 2.6 years up to 3.2 years. Third, duration of CI stimulation played a role only on the ERP latency, and never on the ERP amplitude and area: The ERP latency resulted shorter in deaf children who had been benefiting from a duration of CI use of at least 5.8 years.

CHAPTER 9

Processing of single vowels and of vowel pairs in Italian pediatric cochlear-implant users: Joint evidence from behavioral and neurophysiological findings

9.1 Introduction

This chapter summarizes, discusses, and interprets the main findings achieved throughout the present research in chapter 6 to chapter 8.

The main results achieved for the processing of single vowels and of vowel pairs at the behavioral level and at the neurophysiological level in CI children are first extensively recapitulated (cf. 9.2) for detection (cf. 9.2.1) and processing (cf. 9.2.2) of single vowels as well as for processing of vowel pairs (cf. 9.2.3). Subsequently, the role played by age at surgery (cf. 9.2.4) and of duration of CI stimulation (cf. 9.2.5) on vowel processing at the behavioral and the neurophysiological levels is addressed. After having recapitulated the main results achieved so far, we provide an interpretation for them (cf. 9.3), i.e. for the systematic presence of MMN in the CI children (cf. 9.3.1), for the non-systematic left-lateralization of the ERP responses in the CI children (cf. 9.3.2), for the behavioral lower percentages and *d'* values as well as for the neurophysiological prolonged ERP latencies, the reduced ERP amplitudes, the different patterns of response displacement on the scalp, of 'degree' of brain area activation, and of hemisphere involvment in the children with CI devices (cf. 9.3.3), and, finally, for the fact that some vowel pairs turned out to be easier to process behaviorally and neurophysiologically for the CI children (cf. 9.3.4). We conclude this chapter by interpreting the above-mentioned neurophysiological results as demonstrating that (i) CI children are partially impaired for the processing of single vowels only at the neurophysiological level, whereas they are partially impaired for the processing of vowel pairs only at the behavioral level (cf. 9.3.5); ii) CI children are partially impaired in the detection of of single vowels and in the processing of single vowels, which are auditory processes, but not in the processing of vowel pairs which is a cognitive process (cf. 9.3.6).

9.2 Result summary

In the following, we will sum up the main findings achieved throughout the present research for the following aspects: i) detection of single vowels at the neurophysiological level (cf. 9.2.1); ii) the processing of single vowels at the behavioral and the neurophysiological levels (cf. 9.2.2); iii) the processing of vowel pairs at the behavioral and the neurophysiological levels (cf. 9.2.3); iv) the role played by the earlier vs. later age at surgery (cf. 9.2.4); and v) the role played by the longer vs. shorter duration of CI stimulation (cf. 9.2.5).

9.2.1 Detection of single vowels at the neurophysiological level in children with cochlear implants as compared to normal-hearing children

Detection of single vowels in CI children has been investigated here only at the neurophysiological level, by recurring to the P1 response of the auditory ERPs (cf. 7.2.1.1, 7.2.2.1, 7.3.1.1, 7.3.2.1, 7.4.1.1, 7.4.2.1, 7.5, 8.5, 8.6, and 8.7.1). As frequently observed throughout the present thesis, the P1 response indicates (speech) sound detection at the cortical level and, especially in the case of CI children who had experienced a period of auditory deprivation before surgery, the P1 response is regarded as a marker for the maturation of the central auditory pathways [cf. Sharma et al. 2002abc, 2005b, 2007, 2009; Gilley et al. 2008; for a review, Sharma & Dorman 2006].

Recall from 3.8.1 and 3.8.2 that previous ERP studies monitoring the P1 response in CI children managed in identifying the P1 response in all the deaf children implanted during the sensitive period for central auditory development (≤ 3.5 up to 4 years) [cf. Sharma et al. 2002abc, 2005, 2007, 2009; Gilley et al. 2008; Chang et al. 2012; Torppa et al. 2012; Munivrana & Mildner 2013], but only in some deaf children implanted after the sensitive period for central auditory development [cf. Ponton et al. 2000; Ponton & Eggermont 2001; Sharma et al. 2002; Singh et al. 2004; Gilley et al. 2008], or even in no late-implanted children [Dinces et al. 2009]. As laid out in 3.10, in deaf children implanted late in their lives, the cortical responses were often abnormal with respect to their prolonged latencies, their reduced amplitudes, or because of their polyphasyc morphology. These cortical patterns are usually regarded as the ‘natural’ consequences of a prolonged lack of auditory sensation experienced before CI surgery (cf. Figure 1) [cf. Sharma et al. 2009; Sharma & Dorman 2006].

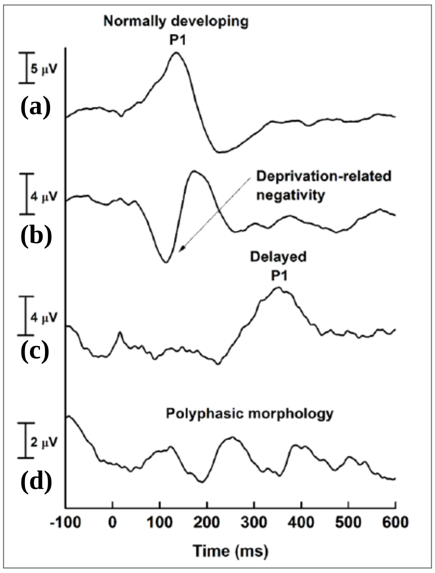


Figure 1: Examples of P1 waveforms for a normally-developing central auditory pathway (a), an unstimulated central auditory system (b), a partially stimulated auditory system (c), and a re-organized auditory cortex (d). From Sharma et al. (2009: 281).

Additionally, as made precise in 3.10, in children implanted during the sensitive period for auditory maturation, the P1 latency usually reached the normal values observed in age-matched NH peers during the first six or eight months after CI surgery. However, this did not hold for late-implanted children [cf. Sharma et al. 2002abc; Sharma et al. 2009; Sharma & Dorman 2006].

Previous studies focusing on children implanted before 3.5 years (cf. 3.8.1.1 and 3.8.2.1) have reported the P1 response to be typically characterized by a smaller peak amplitude, or by a delayed peak amplitude, or even by both features as compared to NH children, thus suggesting that detection of linguistic (cf. 3.8.1) and of non-linguistic (cf. 3.8.2) sounds was often delayed and/or challenged in CI children. The influence played by earlier vs. later age at surgery on the P1 values in deaf children implanted during the period of maximal plasticity of the auditory pathways had not been investigated in previous studies [cf. Sharma A. et al. 2002a, 2005, 2007, 2009; Gilley et al. 2008; Chang et al. 2012; Torppa et al. 2012; Munivrana & Mildner 2013; for a review, Sharma A. & Dorman 2006]. As for the influence played by duration of CI stimulation on the values of P1 (cf. 3.12), it did not apper to consistently constrain the values of P1: if the P1 response appeared to peak earlier and with enhanced amplitude in CI children implanted before 3.5 years and who had been using their implant for at least 5 years [cf. Torppa et al. 2013], this did not hold for early-implanted children who had been using their CI for at least 4 years [cf. Munivrana & Mildner 2013].

In our analysis of the P1 response, we concentrated on the following values: its latency, its amplitude, its scalp topography, its scalp lateralization, and its ‘degree’ of brain area activation. More particularly, we compared the P1 values and parameters found in the CI children to those found in NH children to understand whether or not the CI children appeared to lag behind their age-matched NH peers.

First of all, the P1 response was systematically found in all the Italian CI children examined, both for the standard and for the deviant vowels. This finding, which is in agreement with the previous studies on early-implanted CI children (cf. 3.8.1.1. and 3.8.2.1) indicates that, despite the initial period of auditory deprivation experienced by the Italian CI children, they were able to detect /u/, /i/, /ɛ/, /ɔ/, and /a/, both as standards and as deviants, at the cortical level.

The latency of P1 was comparable in CI relative to NH children when P1 had been evoked by the high vowels /u/, /i/, /ɛ/, and /ɔ/, occurring both as standards and as deviants. As for /a/, occurring both as a standard and as a deviant, the P1 response apparently peaked earlier in CI as compared to NH children. From the former finding, we infer that detection of the high and front vowels is never delayed in CI as compared to NH children, which is in contrast with the results from previous studies (cf. 3.8.1 and 3.8.2). From the latter finding, which, although in contrast with the results of some previous studies, is not new in the literature [cf. Torppa et al. 2012; cf. Picton 2011 for a review], we infer that electrical stimulation is likely to reach the auditory cortex of CI users faster than natural stimulation reaches the auditory cortex of NH individuals. Interestingly, the latency of P1 is never significantly delayed in the CI examined relative to their NH peers, thus suggesting that early-implanted children do not need a prolonged time interval for vowel detection.

The amplitude of P1 was comparable in CI relative to NH children when P1 had been evoked by /ɔ/$_{\text{std}}$ and /a/$_{\text{dev}}$, but significantly reduced in CI relative to NH children in all the other contexts. From these findings, which are in agreement with previous studies (cf. 3.8.1 and 3.8.2), we deduce that vowel detection is frequently challenged for accuracy, either occasionally or systematically, in CI children (cf. 9.3.3 for discussion).

With respect to the scalp topography and the response strength, the P1 response appears as a robust positivity with fronto-central displacement at the bilateral level both in CI and NH children. Nevertheless, the ‘degree’ of brain area activation often appears reduced in CI relative to NH children, thus indicating a reduced strength of the P1 response in CI children (cf. 9.3.3 for discussion).

As for distribution over both hemispheres of the P1 response, it could be left-lateralized (for latency or for amplitude) or equally distributed over both hemispheres both in CI and NH children. The former result indicates that the left hemisphere is in some instances more involved than the right one in vowel detection, whereas the latter result suggests that both hemispheres can be equally involved in vowel detection. These patterns are found both in CI and NH children. In spite of being evoked by vowels, the P1 response does not result consistently left-lateralized in all children (cf. 9.3.2 for discussion).

To conclude, we would say that the Italian CI children examined can be regarded as successfully-implanted CI users with respect to vowel detection in the auditory cortex.

9.2.2 Processing of single vowels at the behavioral and neurophysiological levels in children with cochlear implants as compared to normal-hearing children

Processing of single vowels was investigated at the behavioral level and at the neurophysiological levels. At the behavioral level, children frequency in correct categorization of isolated vowels was measured as group percentages for each vowel phoneme (cf. 6.2, 6.4, 6.5, 6.6.1, 6.6.3, and 6.6.4). At the neurophysiological level, extraction of the vowel acoustic-phonetic features which are relevant for linguistic categorization was monitored by examining the N1 response of the auditory ERPs (cf. 7.2.1.1, 7.2.1.2, 7.3.1.1, 7.3.1.2, 7.4.1.1, 7.4.1.2, 7.5.2, 8.4, 8.5, 8.6, 8.7.2). In the following, we will first deal with the behavioral results (cf. 9.3.1), then with the neurophysiological results (cf. 9.3.2), and finally with the joint results (cf. 9.3.3)

9.2.2.1 Behavioral results

At the behavioral level, the Italian CI children correctly identified /i/, /ɛ/, /u/, /ɔ/, and /a/ with comparable frequency irrespective of vowel quality, thus suggesting that there are no easier-to-categorize vowels for CI children (cf. 9.3.5 for discussion). Even though CI devices primarily facilitate speech perception, they are of crucial importance for deaf individuals to develop several aspects concerning speech production as well, such as its overall intelligibility, its suprasegmental features, the production of vowels and consonants, and so on. Therefore, perception and production of speech sounds are two different, but closely related abilities. Our results concerning vowel categorization appeared in contrast to previous studies on the acoustic properties of vowels produced by adult [cf. Neumayer et al. 2010], adolescent [cf. Löfqvist et al. 2010; Neumayer et al. 2010], and pediatric [cf. Horga & Liker 2006; Liker et al. 2007; Baudonck et al. 2011] CI users, finding that they produce mid and back vowels with lower accuracy as compared to the other vowels, and thus implicitly suggesting that mid and back vowels are more difficult to produce for CI users.

9.2.2.2 Neurophysiological results

Previous ERP studies monitoring the N1 response in CI children were not able to find this auditory response both in late-implanted children (cf. 3.8.1.2 and 3.9.1.2) and in early-implanted children (cf. 3.8.1.1 and 3.9.1.1). A few exceptions to this situation are represented by the studies by Munivrana & Mildner [2013] on early-implanted children as well as by the studies by Kileny et al. [1997], Beynon et al. [2002], and Burdo et al. [2006] on late-implanted children. These few previous ERP studies found that the N1 response was typically characterized by a smaller amplitude or by a delayed amplitude in CI as compared to NH children, thus suggesting that detection and extraction of the acoustic-phonetic features which are crucial for linguistic or non-linguistic categorization was often delayed and/or challenged for accuracy in CI children.

In the present study, the N1 response was regularly identified in all the Italian CI children, both for the standard and for the deviant vowels. This finding, which is in agreement with a few previous ERP studies, suggests that even though the cortico-cortical connections resulting into the intra- and inter-hemispheric activity giving rise to N1 activity are not completely mature until the adolescence [cf. Mäkela & Hari 1992; Mäkela & McEvoy 1996], they have reached a certain degree of maturation in the CI children examined here (mean age at testing: 9.1 years, range: 6.7 – 10.7 years), allowing them detection and extraction of the acoustic-phonetic features which are linguistically relevant for categorization of /u/, /i/, /ɛ/, /ɔ/, and /a/, occurring both as standards and as deviants. [14]

The N1 latency was largely comparable in CI relative to NH children. Nevertheless, two exceptions have to be mentioned. First, the N1 latency appeared delayed in CI relative to NH children when N1 had been evoked by /i/$_{\text{dev}}$ in the context of /ɛ/$_{\text{std}}$. Second, the N1 response appeared to peaked earlier in CI as compared to NH children when N1 had been evoked by /ɔ/$_{\text{dev}}$. On the one hand, we deduce that extraction of the acoustic-phonetic features which are linguistically relevant for vowel categorization is typically not delayed in CI as compared to NH children, which is in contrast with the results of previous studies. On the other hand, we infer that extraction of the acoustic-phonetic features which are linguistically relevant is rarely delayed or faster in the CI children examined. As already suggested for the P1 response (cf. 9.2), this last result may follow from the fact that electrical stimulation is likely to reach the auditory cortex of CI users faster than natural stimulation reaches the auditory cortex of NH individuals, thus rarely giving place to a faster extraction of the vowel acoustic-phonetic features (cf. 9.3.3 for discussion).

The N1 amplitude was largely attenuated in CI relative to NH children, except when N1 had been evoked by /ɔ/, occurring both as a standard and as a deviant, as well as by /i/$_{\text{dev}}$, occurring both in the context of /u/$_{\text{std}}$ and of /ɛ/$_{\text{std}}$. Henceforth, we infer that extraction of the acoustic-phonetic features is likely to be challenged for accuracy in CI children, as already put forward by previous studies, although not regularly (cf. 9.3.3 for discussion).

With respect to the scalp topography, the N1 response was found to present a similar displacement over brain areas in CI and NH children only when N1 had been evoked by the vowels characterizing the pairs /i/$_{\text{std}}$-/u/$_{\text{dev}}$, /u/$_{\text{std}}$-/i/$_{\text{dev}}$, and /a/$_{\text{std}}$-/ɔ/$_{\text{dev}}$: in these contexts N1 always presented a fronto-temporal displacement. When N1 had been evoked by /i/$_{\text{std}}$-/ɛ/$_{\text{dev}}$, /ɛ/$_{\text{std}}$-/i/$_{\text{dev}}$, and /ɔ/$_{\text{std}}$-/a/$_{\text{dev}}$, on the other hand, N1 presented either fronto-temporal scalp displacement for NH and fronto-central scalp displacement for CI children, or the reverse patterns, but always at the bilateral level. As for the ‘degree’ of brain area activation, N1

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[14] It is possible that previous studies on pediatric CI users were not able to find the N1 response because they used a too short ISI. For N1 elicitation, a quite long ISI (e.g., ≥ 800ms) is needed [cf., among others, Čeponiene et al. 2002; Gilley et al. 2005; Sussman et al. 2008].

typically presented reduced response strength in CI relative to NH children (cf. 9.3.3 for discussion).

With respect to distribution over both hemispheres, the N1 response tended to be equally distributed over both hemispheres both in CI and NH children, except for rarely being right-lateralized for amplitude in NH children or left-lateralized for latency in CI children. In sum, both hemispheres tend to equally contribute to extraction of the acoustic-phonetic features which are linguistically relevant for vowel categorization. As already observed for P1 (cf. 9.2), in spite of being evoked by vowels, the N1 response do not result consistently left-lateralized either in CI or in NH children (cf. 9.3.2 for discussion).

With respect to the vowels' acoustic-phonetic features, the N1 response evoked by the five Salento Italian vowels in CI and NH children presented comparable latencies and amplitudes irrespective of the different spectral characteristics of the single vowels. This finding is in contrast with previous studies showing modulation of the N1 parameters depending on the F1, F2, and F3 values of the eliciting vowel in adult NH subjects (cf. 2.5.1). We interpret the absent modulation of the N1 values based on the spectral characteristics of the Salento Italian vowels in all the children examinated as suggesting that the N1 response was not completely mature by the age of 9.1 years (range: 6.7 – 10.7 years) in CI children as well as by the age of 7.6 years (range: 4.3 - 10.9 years) in NH children. To be more precise, the systematic presence of N1 indicates that the N1 response had reached a certain maturation degree which enabled CI and NH children to extract the acoustic-phonetic features which are relevant for vowel categorization. Nevertheless, the absent modulation of the N1 response building on the acoustic-phonetic feature of the single vowels in CI and NH children was likely to suggest that the N1 response was not completely mature by the age of 9.1 years in CI children and by the age of 7.6 years in NH children, since it will continue to mature until adolescence [cf. Mäkela & Hari 1992; Mäkela & McEvoy 1996].

To conclude, we would say that the Italian CI children examined in the present study can be regarded as successfully-implanted CI users with respect to vowel categorization at the behavioral level as well as with respect to detection and extraction of the acoustic-phonetic features which are meaningful for vowel categorization at the neurophysiological level.

9.2.2.3 Joint findings from the behavioral and neurophysiological levels

The joint interpretation of the behavioral (cf. 9.2.2.1) and the cortical (cf. 9.2.2.2) data indicates that, despite the initial period of auditory deprivation experienced by the Italian CI children examined (range: 2.1 -4.4 years), they manage to correctly identify front (e.g., /i/ and /ɛ/) and back (e.g., /u/, /ɔ/, and /a/) vowels at the behavioral level as well as they succeeded in detecting and extracting of the acoustic-phonetic features which are linguistically relevant for categorization of front (e.g., /i/ and /ɛ/) and back (e.g., /u/, /ɔ/, and /a/) vowels at the cortical level.

At the behavioral level, vowel categorization is not challenged for accuracy in CI as compared to NH children. At the cortical level, extraction of the acoustic-phonetic features which are relevant for vowel categorization is never delayed in CI as compared to NH children. Nevertheless, the accuracy and the response strength are often reduced in CI relative to NH children as well as the patterns of brain area activation and distribution over both hemispheres were (at least partially) different in CI as compared to NH children.

The acoustic-phonetic features of the Salento Italian vowels do not turn out to modulate either the behavioral percentages or the cortical N1 values of latency and amplitude, thus suggesting that front and back as well as low, mid-low, and high vowels are categorized with comparable frequency at the behavioral level as well as during a similar time window and with comparable accuracy at the cortical level.

To sum up, we can say that, despite the initial auditory deprivation period experienced by the Italian CI children examined, the CI stimulation (at least partially) restored the hearing sensation and promoted the auditory pathways maturation for processing of single vowels at the behavioral and neurophysiological levels.

9.2.3 Processing of vowel pairs at the behavioral and neurophysiological levels in children with cochlear implants as compared to normal-hearing children

The processing of vowel pairs was investigated at the behavioral level and at the neurophysiological levels. At the behavioral level, children frequency in correct discrimination of vowel pairs was measured as group percentages for each vowel phoneme, whereas children accuracy in correct discrimination of vowel pairs was measured as *d'* scores (cf. 6.3). At the neurophysiological level, extraction and representation of the vowel auditory regularities and irregularities which are meaningful in linguistics terms (e.g. the formant values) in the auditory cortex during processing of vowel pairs was investigated by recurring to the MMN response of the auditory ERPs (cf. 7.2.1.2, 7.2.2.2, 7.3.1.2, 7.3.2.2, 7.4.1.2, 7.4.2.2, 7.5.3, 8.2, 8.3, 8.5, 8.6, and 8.7.3).

9.2.3.1 Behavioral results

At the behavioral level, the pediatric CI users succeeding in discriminating five same-vowel pairs (e.g., /i/-/i/, /u/-/u/, /a/-/a/, /ɛ/-/ɛ/, and /ɔ/-/ɔ/) and six different-vowel pairs (e.g., /u/-/i/, /i/-/u/, /ɛ/-/i/, /i/-/ɛ/, /a/-/ɔ/and /ɔ/-/a/).

Different patters emerged for discrimination of the same-vowel pairs: i) the pairs /u/-/u/, /i/-/i/, and /ɔ/-/ɔ/ were discriminated with comparable frequency and accuracy by CI and NH children; ii) the pairs /ɛ/-/ɛ/ and /a/-/a/ were correctly discriminated by CI children with a slight lower frequency and accuracy as compared to NH children. This finding is in partial agreement with previous acoustic studies (cf. 3.13) and it demonstrates that, if mid and back vowels were systematically more difficult to produce for CI children [cf. Horga & Liker 2006; Liker et al. 2007; Baudonck et al. 2011] they are not systematically more difficult to discriminate for the CI examined here, in that /ɛ/-/ɛ/ is more-difficult to discriminate for CI as compared to NH children, but the same does not hold for /ɔ/-/ɔ/.

As far as discrimination of different-vowel pairs is concerned, the pairs /u/-/i/, /ɛ/-/i/, and /a/-/ɔ/ were discriminated with higher frequency and accuracy as compared to the pairs /i/-/u/, /i/-/ɛ/, and /ɔ/-/a/ by Italian CI with respect to NH children, thus implicitly suggesting that the former are easier-to-process as compared to the latter. Neither direction of change in the distintive feature specification nor the Euclidean distance appeared to consistently constrain the discrimination of different-vowel pairs. With respect to direction of change in the distintive feature specification characterizing the easier-to-process vowel pairs, different patterns emerge. As for high vowels, /u/ is specified as [+BACK, + ROUND], whereas /i/ is specified as [-] for the same features (cf. 4.4.4), Our finding that /u/-/i/ is processed with higher frequency and accuracy as compared to /i/-/u/ apparently suggests that direction of change from [+] to [-] is easier to process relative to the opposite direction of change in the case of high vowel pairs. As for front vowels, /ɛ/ is specified as [-HIGH, -[ATR], while /i/ is specified as [+] for the same features. The finding that /ɛ/-/i/ is processed with higher frequency and accuracy as compared to /i/-/ɛ/, apparantly indicates that direction of change from [-] to [+]results easier to process relative to the opposite direction of change in the case of front vowels. As for back vowels, /a/ is specified as [+LOW, -ROUND], whereas /ɔ/ is specified as [-LOW, +ROUND]. Our finding that /a/-/ɔ/ is processed with higher frequency and accuracy relative to /ɔ/-/a/ at first sight indicates that the configuration [+LOW, -ROUND] might be easier to process as compared to the opposite configuration. With respect to the Euclidean distance characterizing the easier-to-process vowel pairs, it was larger for /u/-/i/ and /i/-/u/ (e.g., 847 Mel), but smaller for /ɛ/-/i/ and /i/-/ɛ/ (e.g., 322 Mel) as well as for /a/-/ɔ/ and /ɔ/-/a/ (e.g., 304 Mel). To conclude, neither the direction of change in the distinctive feature specification nor the Euclidean distance cannot account for the fact that some vowel pairs are easier-to-process at the behavioral level as compared to other vowel pairs (cf. discussion in 9.3.4).

9.2.3.2 Neurophysiological results

Previous ERP studies monitoring the MMN response in deaf children implanted after 3.5 or 4 years were able to identify the MMN response only in successfully-implanted children [for speech-evoked MMN, cf. 3.8.2; for non-speech-evoked MMN, cf. 3.9.2], whereas those studies concentrating on the MMN in deaf children implanted before 3.5 years systematically identified the MMN response in all the children [for speech-evoked MMN, cf 3.8.1; for non-speech-evoked MMN, cf. 3.9.1]. These studies usually found delayed MMN latencies and/or reduced MMN amplitudes in CI relative to NH children, both in the case of late-implanted and of early-implanted children, thus suggesting that extraction and representation of the auditory acoustic-phonetic regulatiries of the vowels at the cortical level was frequently delayed in time and was characterized by decreased accuracy in pediatric CI users. Other studies reported that crucial differences between CI and NH children are to be searched in the scalp topography and in the MMN response strength, rather than in the MMN values. In fact, even though the MMN values often resulted comparable in CI and NH children, the scalp topography was likely to involve (partially) different brain areas as well as response strength was often diminuished in the former as compared to the latter [cf. Ponton et al. 2000; Watson et al. 2007; Bottari et al. 2014]. Despite the fact that the benefits of CI stimulation on deaf children are best studied by combining auditory ERPs investigating automatic speech sound processing at the neurophysiological level together with task-oriented linguistic tests exploring speech sound processing at the behavioral level, except for they study by Ortmann et al. (2013), which combined the MMN response at the neurophysiologic with speech sound discrimination at the behavioral level, no previous studies adopted both measures to achieve a full picture of auditory processing of pairs of speech sounds in pediatric CI users. In the case of early-implanted children, the possible influence played by earlier vs. later age at surgery on the MMN values had not been investigated by previous studies [cf. Torppa et al. 2012; Ortmann et al. 2013]. As for duration of CI stimulation, the MMN latency appeared shorter and the MMN amplitude was larger in CI children implanted before 3.5 years and who had been using their CI for at least 5 years (range: 2.6 – 10.8) [cf. Torppa et al. 2013] or 6 years (range: 6.1 - 15.3 years) [cf. Ortmann et al. 2013].

In the present study, the MMN response was regularly identified in all the Italian CI children examined for the six vowel pairs. This finding, which is in agreement with previous studies on early-implanted children, suggests that CI children are able to successfully process pairs of high (e.g., /u/$_{std}$-/i/$_{dev}$ and /i/$_{std}$-/u/$_{dev}$), front (e.g., /i/$_{std}$-/ɛ/$_{dev}$ and /ɛ/$_{std}$-/i/$_{dev}$), and back (e.g., /a/$_{std}$-/ɔ/$_{dev}$ and /ɔ/$_{std}$-/a/$_{dev}$) vowels at the cortical level (cf. 9.3.1).

Despite the often reduced amplitude of the P1 response (cf. 9.2.3.1) and the frequently delayed latency and reduced amplitude of the N1 response (cf. 9.2.3.2) in CI children, the MMN values of latency, amplitude, and area exhibited by the CI children were nearly systematically comparable to those obtained from NH children (see discussion in 9.3.5). A single exception is represented by the area evoked by /ɔ/$_{std}$-/a/$_{dev}$, which turned out to be significantly smaller in CI as compared to NH children. Our findings seem to indicate that extraction and representation of the vowel auditory regularities which are contrastive in linguistics terms in the auditory cortex during processing of vowel pairs was neither delayed, not challenged or of lower magnitude in CI as compared to children. This result, which disagrees with previous studies reporting the MMN to peak later and with attenuated amplitude in CI relative to NH children, both in the case of late-implanted and of early-implanted children, appears to indicate that, despite the differences at the level of the peripheral input (e.g., natural vs. electric hearing), and despite the fact that vowel detection and extraction of the acoustic-phonetic features which are relevant for vowel categorization can be delayed or challenged, the brain of CI children process vowel phonemes in a very similar fashion to NH children [cf. Näätänen et al. 2012]. However, as we will soon discuss, the main differences between CI and NH children concern the MMN scalp topography, its brain area ctivation, and its distribution over both hemipsheres, rather than the MMN values [cf. Ponton et al. 2000; Watson et al. 2007; Bottari et al. 2014] (cf. 9.3.5 for discussion).

With respect to scalp topography, the MMN response systematically presented different topographical patterns in CI as compared to NH children. First, when it presented fronto-temporal displacement in NH children, it systematically presented fronto-central displacement in CI children, and the reverse holds as well. Second, in CI children MMN tended to have fronto-central displacement, whereas both fronto-central and fronto-temporal displacements can be found in NH children. These findings suggest (at least partially) different patterns of brain area activation in CI as compared to NH children (cf. 9.3.5 for discussion). A fronto-temporal displacement of the MMN is usually associated with a 'phonological' MMN, which is typically evoked by speech sounds, whereas a fronto-central displacement of the MMN is typically associated with a 'purely acoustic' MMN [e.g., Eulitz & Lahiri 2004; Pulvermueller & Shtyrov 2006], However, since both distributional patterns are found in both groups of children, these may be due to the maturation of the auditory pathways in pediatric subjects, not to the 'nature' of the MMN response.

As for the 'degree' of brain area activation, the MMN response appeared characterized by a reduced strength in CI as compared to NH children (i.e. for the pairs /u/$_{std}$-/i/$_{dev}$, /i/$_{std}$-/ɛ/$_{dev}$, /ɛ/$_{std}$-/i/$_{dev}$, and /ɔ/$_{std}$-/a/$_{dev}$), while having a similar strength in CI and NH children in the remaining contexts. This result suggests that, not only were the brain activation patterns different in CI vs. NH children, but also that the degree of involvement of the brain areas activated is reduced in CI relative to NH children (cf. 9.3.5 for discussion).

The distribution of MMN over both hemispheres appeared different for CI and NH children. In CI children, MMN generally resulted equally distributed over both hemispheres (e.g., for /i/$_{\text{std}}$-/u/$_{\text{dev}}$, /u/$_{\text{std}}$-/i/$_{\text{dev}}$, /i/$_{\text{std}}$-/ɛ/$_{\text{dev}}$, and /ɛ/$_{\text{std}}$-/i/$_{\text{dev}}$), while being left-lateralized for latency only in two instances (e.g., for /a/$_{\text{std}}$-/ɔ/$_{\text{dev}}$ and /ɔ/$_{\text{std}}$-/a/$_{\text{dev}}$). In NH children, MMN was frequently left-lateralized for amplitude and/or area (e.g., for /i/$_{\text{std}}$-/u/$_{\text{dev}}$, /i/$_{\text{std}}$-/ɛ/$_{\text{dev}}$, /ɔ/$_{\text{std}}$-/a/$_{\text{dev}}$, and /a/$_{\text{std}}$-/ɔ/$_{\text{dev}}$), while rarely being right-lateralized for amplitude (e.g., for /ɛ/$_{\text{std}}$-/i/$_{\text{dev}}$), or equally distributed over both hemispheres (e.g., for /u/$_{\text{std}}$-/i/$_{\text{dev}}$). From the former finding, we can infer that both hemispheres are usually equally committed in the processing of different-vowel pairs in CI children, whereas the left hemisphere tends to be more involved in the processing of different-vowel pairs in the case on NH children (cf. 9.3.2 for discussion).

As for the possible modulation exerted by vowel quality on the MMN values, previous acoustic studies monitoring the vowel perception and production in CI users had found that mid back vowels were more difficult to produce for pediatric CI users as well as more difficult to perceive for adult CI users (cf. 3.13). In the present study, vowel quality does not turn out to constrain the processig of vowel pairs, in that pairs of high, front, and back vowels are cortically processed during a similar time window and with comparable accuracy by CI children. A single exception is represented by the size of neuronal activation, as indexed by MMN area, which is higher for high vowels as compared to front (but not back) vowels, thus suggesting that more neurons are involved in the processing of the high as compared to the front vowel pairs.

With respect to the Euclidean distance characterizing the vowel pairs, it is almost equivalent for the front vowels /ɛ/ vs. /i/ (e.g., 322 Mel) and the back vowels /a/ vs. /ɔ/ (e.g., 304 Mel), whereas it is wider for the high vowels /u/ vs. /i/ (847 Mel). Previous studies on CI children, CI adults,and NH adults,found the MMN to peak earlier and to present a larger amplitude when MMN had been evoked by vowel contrasts presenting a larger Euclidean distance as compared to vowel contrasts characterized by a smaller Euclidean distance (cf. 4.4.5). Our data are in contrast to the above-mentioned studies but in line with Horvàth et al. (2008), in showing that the Euclidean distance is not a crucial factor in constraining vowel processing at the cortical level in pediatric CI and NH subjects.

With respect to direction of change in the feature distinctive feature specification (cf. 4.6.2), previous investigations had shown that MMN was likely to peak earlier and with enhanced amplitude when the standard vowels was specified as presenting a given phonological feature and the deviant vowel was unspecified for the same distinctive feature as compared to the opposite situation. As for high vowels, /u/ is specified as [+BACK, +ROUND], whereas /i/ is specified as [-BACK, -ROUND] (cf. 4.4.4). Our data concerning the MMN response elicited by high vowels partially corroborate the findings of the above-mentioned studies, since the MMN elicited by /u/$_{\text{std}}$-/i/$_{\text{dev}}$ peaked earlier, but with comparable amplitude and area, as compared to the MMN elicited by /i/$_{\text{std}}$-/u/$_{\text{dev}}$. This finding suggests that high vowel pairs may be processed faster when the standard vowel is specified as [+] for a given phonological feature and the deviant vowel is specified as [-] for the same distinctive feature. Accuracy and size of neuronal activation during processing of high vowel pairs, on the other hand, do not appear constrained by direction of change in the distinctive feature specification. As for front vowels, recall that /i/ is specified as [+HIGH, +ATR], whereas /ɛ/ is specified as [-HIGH, -ATR] (cf. 4.4.4). Our data concerning the MMN response elicited by front vowel pairs, instead, do not corroborate the findings of the above-mentioned studies, since, contrary to our expectations, the MMN elicited /ɛ/$_{\text{std}}$-/i/$_{\text{dev}}$ peaked earlier, but with similar amplitude and area, as compared to the MMN elicited by /i/$_{std}$-/ɛ/$_{dev}$. This result indicates that front vowel pairs may be processed faster when the standard vowel is specified as [-] for a given phonological feature and the deviant vowel is specified as [+] for the same distinctive feature. Accuracy and size of neuronal activation during processing of front vowel pairs, on the other hand, are not constrained by direction of change in the distinctive feature specification.

To round off this section, we would say that the CI children examined here may be regarded as successfully-implanted CI users with respect to processing of vowel pairs at the behavioral and at the neurophysiological levels.

9.2.3.3 Joint findings from the behavioral and neurophysiological levels

The joint interpretation of the behavioral (cf. 9.2.3.1) and the cortical (cf. 9.2.3.2) data concerning the processing of different-vowel pairs reveals, despite the initial period of auditory deprivation experienced by the Italian CI children examined (range: 2.1 -4.4 years), they manage to correctly process pairs of different-vowels at the behavioral level as well as they succeeded in successfully developing the vowel neural representation in the auditory cortex by correctly representing the repetitive acoustic-phonetic features which are of crucial importance for vowel categorization in linguistic terms.

At the behavioral level, discrimination of the vowel pairs /i/-/u/, /i/-/ɛ/, and /ɔ/-/a/ is characterized by a lower frequency and accuracy in CI as compared to NH children, whereas discrimination of the vowel pairs /u/-/i/, /ɛ/-/i/, and /a/-/ɔ/ is characterized by comparable frequency and accuracy in both groups of children. At the cortical level, representation of the acoustic-phonetic features which are contrastive for vowel categorization and the consequent successful development of vowel neural representation in the auditory cortex is never delayed, nor less accurate, nor of lower magnitude in CI as compared to NH children. Nevertheless, the scalp topography is systematically different and the response strength is always reduced in CI as compared to NH children. Additionally, the distributional patterns over both hemispheres are often different in CI as compared to NH children, with both hemispheres being equally involved in the processing of different-vowel pairs in CI children, but with the left hemisphere often being more involved than the right one in NH children. Additionally, the pairs /u/-/i/ and /ɛ/-/i/ are cortically processed faster as compared to /i/-/u/ and /i/-/ɛ/ by both groups of children. As for back vowels, the pair /ɔ/-/a/ is processed with higher accuracy by NH children, whereas the reverse pair holds for CI children. Taken altogether, these finding suggest that processing of different-vowel pairs is (at least) partially impaired at the behavioral and cortical levels in CI children as well as that the pattern of brain activation, response strength and hemisphere involvment are not the same in CI as compared to NH children.

The vowel quality (e.g., high vs. front vs. back) plays no role either on the behavioral percentages and *d'* values or on the MMN values: pairs of high, front, and back vowels are processed with comparable frequency and accuracy at the behavioral level as well as by recurring to a similar time window, accuracy, and size of neuronal activation at the cortical levels by CI children. Likewise, the Euclidean distance (e.g., larger vs. smaller) is irrelevant for behavioral and neurophysiological vowel processing: both vowel pairs characterized by a large Euclidean distance (e.g. pairs of high vowels) and vowel pairs characterized by a small Euclidean distance (e.g. pairs of front and back vowels) are processed with comparable frequency and accuracy at the behavioral level as well as by recurring to a similar time window, accuracy, and size of neuronal activation at the cortical levels by CI children. Direction of change in distintive feature specification does not appear to unequivocally contrain processing of vowel pairs in CI children. On the one hand, pairs of high vowels are correctly processed with higher frequency ad accuracy at the behavioral level as well as faster at the cortical level when direction of change goes from [+] to [-]. On the other hand, pairs of front vowels were correctly processed with higher frequency ad accuracy at the behavioral level as well as faster at the cortical level when direction of change goes from [-] to [+].

To sum up, we can say that, despite the initial auditory deprivation period experienced by the Italian CI children examined, the CI stimulation (at least partially) restored the hearing sensation and promoted the auditory pathways maturation for behavioral discrimination of vowel pairs as well as for the successful extraction and representation of the acoustic-phonetic features which are crucial for vowel categorization at the cortical level.

9.2.4 The effect of earlier vs. later age at surgery on vowel processing at the behavioral and neurophysiological levels

The deaf children examined in the present study underwent cochlear implantation in the age range between 2.1 and 4.4 years (cf. 4.3 for additional demographic details on the CI children selected). Given that the sensitive period of maximal plasticity for central auditory maturation is presumed to end between 3.5years [cf. Eggermont & Ponton 2003; Knudsen 2004; Sharma & Dorman 2006; Bishof 2007] and 4 years [cf. Krahl & Sharma 2012] and given that seven out of the eight CI children monitored received their unilateral CI devices before the age of 3.5 years, we are considering the findings achieved here as being representative for deaf children undergoing the CI surgery during the optimal age range for achieving the better language outcomes. It is worth mentioning that, to the best of our knowledge, the present study is the first one which wants to ascertain whether, in the case of early-implanted children, earlier (e.g., towards 2.1 years) vs. later (e.g., towars 4.4 years) age at surgery is likely to constrain vowel processing at the behavioral and cortical levels.

At the behavioral level, age at surgery turns out to be irrelevant for frequency in correct vowel categorizatrion as well as for frequency and accuracy in correct discrimination of same- and different-vowel pairs. Thus, CI children implanted later (e.g., towards 4.4 years) managed to correctly categorize all single vowels and all vowel pairs with comparable frequency and accuracy relative to CI children implanted earlier (e.g., towards 2.1 years) in their life.

At the neurophysiological level, age at surgery appears to differently constrain the ERP values. As for the latency values, the latencies of P1 and MMN turn out to be categorically insensitive to age at surgery, whereas the latency of N1 was largely insensitive to age at surgery, except when N1 had been evoked by /ɛ/, occurring both as a standard and as a deviant. In this case, the N1 latency is shorter in deaf children undergoing the CI surgery before 3.5 years. The findings concerning the ERP latencies indicate that, in the case of early-implanted children, detection (as indexed by P1) and processing of single vowels (as indexed by N1), as well as processing of vowel pairs (as indexed by MMN) at the cortical level are not delayed in those children implanted later (e.g., towards 4.4 years) as compared to those children implanted earlier (e.g., towards 2.1 years) in their lives. With respect to amplitude values, the amplitudes of P1, N1, and MMN result largely insensitive to age at surgery. Systematic exceptions to these situations are represented by the amplitudes of P1 and N1 when these ERP responses had been evoked by /ɔ/. Another exception is represented by the amplitude of MMN, when MMN had been evoked by the pairs /a/-/ɔ/ and /i/-/ɛ/. In these contexts, the ERP amplitudes are larger in deaf children undergoing the CI surgery before 3.5 years. The findings achieved here for the ERP amplitudes suggest that, in early-implanted children, detection (as indicated by P1) and processing (as indicated by N1) of high and front vowels in isolation as well as processing of pairs of high and front vowels (as indicated by MMN) are not less precise in CI children implanted later (e.g., towards 4.4 years) relative to CI children implanted earlier (e.g., towards 2.1 years). Nevertheless, detection and processing of back vowels in isolation together with processing of pairs of back vowels are often more precise in CI children undergoing surgery before 3.5 years as compared to CI children implanted later. As far as the area under the curve of MMN is concerned, age at surgery plays no role on this value. It may therefore be concluded that size of neuronal activation needed for processing of pairs of high, front, and back vowels is not reduced in CI children implanted towards 4.4 years of age as compared to children implanted towards 2.1 years of age.

To round off this section, we would like to observe that, in most contexts, earlier age at surgery promotes neither faster nor more accurate processing of single vowels and of vowel pairs at the cortical level. Nevertheless, in the case of back vowels, processing of single vowels and of vowel pairs is likely to be faster and more accurate in children who underwent CI surgery before 3.5 years as compared to children implanted later.

9.2.5 The effect of longer vs. shorter duration of implant stimulation on vowel processing at the behavioral and neurophysiological levels

The deaf children monitored here are early-implanted children who had been using their unilateral CI for at least 2.4 years. Since the mean duration of CI stimulation was 6.3 years (range: 2.4 - 8.1 years), the eight CI children monitored were regarded as experienced CI users. Previous studies investigating the ERP responses in deaf children implanted before 3.5 years have found the following patters (cf. 3.12). The P1 response peaked earlier and with enhanced amplitude in deaf children who had been using their CI for at least 5 years [cf. Torppa et al. 2012], but not in those children who had been using their CI for at least 4 years [cf. Munivrana & Mildner 2013]. The N1 response was not found to peak earlier or with larger amplitude in deaf children with a duration of CI stimulation of at least 4 years [cf. Munivrana & Mildner 2013]. The MMN response peaked earlier and with larger amplitude in deaf children who had experienced a duration of CI stimulation of at least 5 years [cf. Torppa et al. 2012] or 6 years [cf. Ortmann et al. 2013].

Given that the mean duration of CI stimulation is 6.3 years, and that duration of CI stimulation ranges between 2.4 and 8.1 years in the children monitored here, we wanted to shed light on whether we can replicate the findings achieved by Torppa et al. (2012) and Ortmann et al. (2013), or whether a duration of CI stimulation shorter of 5 years is likely to make processing of single vowels and of vowel pairs faster and more accurate both at the behavioral and at the neurophysiological level.

At the behavioral level, duration of CI stimulation plays no role either on frequency in correct vowel categorizatrion or on frequency and accuracy in correct discrimination of same- and different-vowel pairs. These findings indicate that CI children benefiting from a shorter duration of CI stimulation (e.g., towards 2.4 years) manage to correctly categorize all single vowels and to discriminate all vowel pairs with comparable frequency and accuracy relative to CI children benefiting from a longer duration of CI stimulation (e.g., towards 8.1 years).

At the neurophysiological level, duration of CI stimulation turns out to differently constrain the ERP values. As for the ERP latencies, the P1 latency is always systematically shorter in deaf children with a CI use of at least 5.8 years, whereas the N1 latency is systematically shorter in deaf children benefiting from a CI use of at least 5.8 years, when N1 had been evoked by /ɛ/ and /ɔ/, but not when N1 had been evoked by /u/, /i/, and /a/. In the case of MMN, its latency is insensitive to duration of CI use when MMN had been evoked by high and back vowels, but it was shorter in deaf children who had been using their CI for at least 5.8 years when MMN had been evoked by front vowels. Take together, the findings concerning the ERP latencies indicate that, in the case of early-implanted children, detection of single vowels (as indexed by P1) is systematically faster in those children benefiting from a longer duration of CI stimulation of at least 5.8 years relative to those children benefiting from a shorter duration of CI stimulation. Extraction (as indexed by N1) and representation (as indexed by MMN) of the acoustic-phonetic features which are relevant for vowel categorization at the cortical level, on the other hand, are likely to be faster in those children benefiting from a duration of CI stimulation of at least 5.8 years relative to those children benefiting from a shorter duration of CI stimulation (e.g., towards 2.4 years). With respect to ERP amplitudes, the amplitudes of N1 and MMN are categorically insensitive to duration of CI stimulation, whereas the amplitude of P1 is nearly categorically insensitive to duration of CI stimulation, except for /ɔ/. The findings concerning the amplitudes indicate that those children benefiting from a shorter duration of CI use (e.g., 2.4 years) are less accurate neither in detection (as indexed by P1) and categorization (as indexed by N1) of the Salento Italian vowels in isolation nor in the processing of vowel pairs (as indexed by MMN) as compared to those children benefiting from a longer duration of CI use (e.g., 8.1 years). Finally, duration of CI stimulation plays no influence on the area of MMN, thus suggesting that size of neuronal activation during processing of vowel pairs is similar in all deaf children, irrespective of the longer or shorter duration of CI stimulation.

To recapitulate, we would like to observe that detection of single vowels is categorically faster, whereas extraction and representation of the acoustic-phonetic features which are relevant for vowel categorization at the cortical level are often faster in those children benefiting from a longer duration of CI stimulation of at least 70 months (e.g., 5.8 years). Detection of single vowels as well as extraction and representation of the acoustic-phonetic features which are relevant for vowel categorization at the cortical level are equally precise in all the children monitored irrespective of the longer or shorter duration of CI stimulation. These findings agree with previous studies [cf. Torppa et al. 2012; Ortmann et al. 2013] in suggesting that the processing of single vowels and of vowel pairs are faster in deaf children who had been benefiting from a duration of CI stimulation between 5 and 6 years. Nevertheless, our finding indicate that, contrary to previous studies [cf. Torppa et al. 2012; Ortmann et al. 2013], accuracy in processing of single vowels and of vowel pairs is not higher in deaf children who had been using their CI for at least 5 or 6 years. This last aspect may follow from the linguistic rehabilitation strategies used by the different speech therapists.

9.3 Result interpretation

In the following, we will provide an interpretation for the main results achieved in the present study: i) the systematic presence of the MMN response in CI children (cf. 9.3.1); ii) the non-systematic left-lateralization of the ERPs in CI children (cf. 9.3.2); iii) the often lower values found in CI children at the behavioral level as well as the delayed and attenuated parameters often found in the same children at the neurophysiological level (cf. 9.3.3); iv) the fact that some vowel pairs are easier-to-process behaviorally and neurophysiologically for CI children (cf. 9.3.4); v) the evidence that the behavioral and the neurophysiological levels of processing present different impairments in CI (cf. 9.3.5); and vi) the fact that, at the cortical level, CI children are partially impaired only at the auditory, not at the cognitive, level (cf. 9.3.6).

9.3.1 The systematic presence of MMN in children with implants

Along the lines of the a few previous studies [cf. Eulitz & Lahiri 2004; Sussman et al. 2003, 2013], here (cf. 2.5.2) we interpret the presence of the MMN response as indicating recognition of an acoustic-phonetic (i.e., with pronounced formants) vowel as a native phoneme (i.e., as a meaningfull linguistic sound) in the hearer's native language as well as signaling the successful extraction and representation of the auditory regularities characterizing the standard vowel (e.g., the acoustic spectral and temporal features) as well as of the auditory irregularities characterizing the deviant vowel (e.g., the acoustic and spectral features differentiating the deviant from the standard) at the cortical level in the auditory system.

In this perspective, the key factors influencing deviance detection in the auditory scene are two: the cortical extraction of the standard regularities from the ongoing acoustic-phonetic input and the cortical representation of these regularities in memory [Sussman et al. 2003, 2013]. Following Näätänen (2001) and Eulitz & Lahiri (2004), among others, we assume MMN elicitation to consists of the following steps (cf. 2.5.2). First, the standard vowel creates a central sound representation, corresponding to the standard vowel's neural trace stored in the auditory cortex. Neural traces are assemblies of cortical cells forming the memory trace for learned cognitive representations relative to the automatically processed speech sounds at the cortical level. Vowel neural traces convey information about the vowel phoneme's phonological representation in terms of distintive features. Second, the deviant vowel creates a percept corresponding to the deviant vowel phoneme's neural trace stored in the auditory cortex. Third, the MMN is automatically elicited when the phonological representation of the deviant vowel, which is part of the vowel's neural trace, is compared against the phonological representation of the standard vowel, and the different specification for a couple of phonological features is automatically observed at the cortical level.

The formation of the neural traces of phonemes in the child's auditory cortex can only be driven by speech input [cf. Cheour et al. 2000]. In this view, the systematic presence of the MMN response in the CI children examined here appears to indicate that, despite the initial auditory deprivation, the regular CI use and the auditory training for language learning allow auditory pathway maturation in early-implanted children for the succesful development of the neural representations of the Salento Italian vowel phonemes in linguistically significant terms (i.e. with respect to their correct specification of the phonological features [HIGH],

[LOW], [BACK], [ROUND], and [ATR]), as well as activation of these neural representations when the correspondent vowel phonemes are passively heard.

Since the correct specification of the above-mentioned phonological features is directly derived from the spectral frequencies extracted from the acoustic-phonetic input, and given that each distintive feature serves as an instruction for a particular action of one of the movable articulators of the vocal apparatus (i.e. the tongue blade, body, and root, the soft palate, the larynx, the lips, and the jaw [cf. Halle 2002; Poeppel et al. 2008]), we are making here the following assumptions. First, we are assuming that the regular CI use enables the auditory pathways of early-implanted children to extract the spectral frequencies which are relevant for linguistic categorization from the ongoing acoustic-phonetic input. Second, following the above-mentioned previous studies, we are assuming that the spectral frequencies are coded in terms of distintive features at the neural level, with adequate specification as [+] (e.g. [+BACK]) or as [-] (e.g., [-BACK]). Third, at the articulatory level, we are assuming that, after activation of the vowel neural traces, the adequate distintive feature specifications are put into practice by activating the the corresponding configurations of the vocal organs, which have been learned by CI children during linguistic training and oral rehabilitation.

To conclude, we would like to observe that the systematic presence of the MMN response in the CI children examined here may be considered as an index of how vowel neural representations have been successfully developed in terms of distintive feature specification in the auditory cortex and, hence, that MMN can be regarded as an index that these vowel phonemes have been successfully learned by CI children. This last finding is also indirectly confirmed by the correct vowel categorization and the correct discrimination of same- and different-vowel pairs at the behavioral level.

9.3.2 The non-systematic left-lateralization of the ERPs in children with cochlear implants

Recall from 2.2.4, that functional asymmetries characterize the auditory cortices: the left auditory cortex has a greater temporal sensitivity, whereas greater spectral sensitivity characterizes the right auditory cortex [cf. Zatorre et al. 2002; Dorsaint-Pierre et al. 2006]. These functional asymmetries have been grounded on asymmetries at the anatomical [cf. von Economo & Horn 1930; Geschwind & Levitsky 1968; Penhume et al. 1996, 2003] and the cellular [cf. Seldon 1981ab, 1982; Hulster & Gazzaniga 1996] level in the left hemisphere relative to the right one and they have been assumed to be responsible for a more efficient processing of rapidly changing temporal information, which is relevant for speech sound processing, thus indicating that certain aspects of speech decoding depend critically on the left auditory cortex [cf. Zatorre et al. 2002; Dorsaint-Pierre et al. 2006]. Scalp distribution and the eventual lateralization of the P1, N1, and MMN responses evoked by vowels were investigated in all children to get a deeper understanding of the response distribution over both hemispheres and of hemisphere involvment during vowel processing in CI and NH children.

The P1 and N1 responses, indexing detection of vowels and extraction of the acoustic-phonetic features which are crucial for vowel categorization in linguistic terms, in turn, usually appeared equally distributed over both hemispheres both in NH and in CI children, thus indicating that both hemispheres were equally committed in detection and processing of single vowels. Only rarely were the P1 and N1 responses left-lateralized, mostly for latency, both in NH and in CI children. In the case of CI children, the fact that P1 and N1 were rarely left-lateralized indicates that the hemisphere contralateral to the implanted ear is hardly ever likely to be more involved in detection and processing of single vowels. In NH subjects, the frequent equal involvement of both hemispheres in detection and processing of single vowels is in agreement with previous research indicating that the earlier stages of processing (e.g., sound detection and categorization) depend on core auditory areas at the bilateral level [cf. Binder et al. 2000; Hickok & Poeppel 2000; Zatorre et al. 2002]. Likewise, the non-systematic left-lateralization of detection and of categorization of single vowels in NH children is in line with previous studies finding no left-lateralization for P1 and N1 evoked by speech sounds [cf. Sharma et al. 1997; Čeponiene et al. 2001, 2005, 2008; Gilley et al. 2005; Bruder et al. 2010]. For exceptions, see Golding et al. [2006]. As for monaural stimulation, it is well-known that activity in the auditory cortex is typically lateralized [cf. Jancke et al. 2002], with shorter ERP latencies and greater ERP amplitudes evoked by non-linguistic stimuli on the hemisphere contralateral to the stimulated ear [cf. Wolpaw & Penry 1977] in the case of NH adults [cf. Hine & Debener 2007], of unilaterally deaf adults without CI [cf. Ponton et al. 2001; Khosla et al. 2003; Hine et al. 2008], and of adults CI users [cf. Sandmann et al. 2009], although not regularly [cf. Vasama & Mäkelä 1997; Sheffler et al. 1998]. In the case of CI children, the absent left-lateralization of P1 and N1 evoked by speech sounds is widely acknowledged as well [cf. Beynon et al. 2002; Singh et al. 2004; Sharma et al. 2009; Munivrana & Mildner 2013].

For the MMN response, its scalp distribution has so far be shown to usually (but not systematically) reflect the nature of the stimulus, with the MMN being left-lateralized (e.g., elicited with a larger amplitude and a wider area in the left auditory cortex) for language stimuli, but right-lateralized (e.g., elicited with a larger amplitude and a wider area in the right auditory cortex) for non-linguistic stimuli. The MMN lateralization has been explained by the activation of (at least partially) different neural populations in the auditory cortices in response to different types of auditory changes (cf. Alho et al. 1998a; Rinne et al. 1999a; Näätänen et al. 1997, 2007; Tervaniemi et al. 1999, 2000a; Shestakova et al. 2002b; Pulvermueller et al. 2003; Shtyrov et al. 2005). The acoustic change-detection process, giving rise to the “acoustic MMN”, is bilaterally generated to any deviant stimulus and it tendentially has right-dominant distribution (cf. Zatorre et al. 1992; Paavilainen et al. 1997; Naatanen 2001). The phoneme-change detection process, giving rise to the “phonetic/phonological MMN”, on the other hand, is often generated in the left hemisphere only when the deviant stimulus is a native phoneme, implicating the presence of permanent phoneme traces for native phonemes in the left auditory cortex. The left-hemispheric MMN component crucially depends on the presence of the long-term memory traces (i.e. learned neuronal representations conceptualized as large connected neuron ensembles) for the native phonemes, which are able to identify the invariant phoneme-identity code amongst wide acoustic variation (cf. Näätänen 2001; Näätänen et al. 1997, 2007; Pulvermueller & Shrytov 2006).

As far as the MMN scalp distribution in the present research is concerned, although typically being equally distributed over both hemispheres both in the CI and in the NH children monitored here, it is likely to be left-lateralized for latency, amplitude, or area in both groups of children, although not systematically. These findings indicate that, even though both hemispheres are usually involved in the processing of vowel pairs, it could also happen that the left hemisphere shows a deeper degree of involvment in some instances, mostly in NH children. It is worth observing that, in the CI children examined, the left ear is the one contralateral to the implanted ear. Previous researches have reported left-hemispheric lateralization of MMN in response to native phonemes [cf. Mazoyer et al. 1993; Kim et al. 1997; Dehaene et al. 1997; Shafer et al. 2004], although not systematically in normal, right-handed adult individuals [cf. Näätänen, 2001; Pulvermüller & Shyrov 2006], especially when speech sounds are placed in a grammatical context [cf. Shtyrov et al. 2005], or when subjects are attending to the auditory stimuli [cf. Imaizumi et al. 1997]. As far as pediatric subjects are concerned, in NH children, MMN evoked by native speech sounds was in some cases right- [cf. Novak et al. 1989; Molfese & Burger-Judish 1991; Csepe 1995], in other cases left-lateralized for amplitude [cf. Dehaene-Lambertz & Dehaene 1994; Dehaene-Lambertz & Baillet 1998; Dehaene-Lambertz 2000; Csepe 1995], or even not lateralized at all [cf. Shestakova et al. 2002; Sharma M. et al. 2006; Bruder et al. 2010]. MMN evoked by non-native speech sounds, on the other hand, did not appear lateralized [cf. Shestakova et al. 2003; Rinker et al. 2010; Bruder et al. 2010; Davids et al. 2011]. With respect to pathologic children, MMN evoked by native speech sounds was hardly ever found to be left-lateralized for amplitude in CI children [cf. Ortmann et al. 2013], while it was lateralized neither in CI users [cf. Singh et al. 2004] nor in children suffering from SLI [cf. Davids et al. 2011] or from reading disorders [cf. Sharma M. et al. 2006].

In the light of the above-mentioned studies, the fact that left-lateralization of MMN was not systematic in NH and CI children monitored here is not to be considered a surprising result. One the one hand, one could interpret the absence of systemactic left-lateralization for MMN as indicating that just the acoustic MMN component is actually active during processing of some vowel pairs and that all children are cortically processing /u/, /i/, /ɛ/, /ɔ/, and /a/ as non-linguistic sounds, rather than as phonemes. When MMN appears left-lateralized, on the other hand, one may consider the left-lateralization as an index of the fact that the purely phonological MMN is actually taking place.

Even though the left-hemispheric enhancement of MMN is believed to depend on the presence of the long-term memory traces of native phonemes in the left auditory cortex (cf. 2.2.4), in the light of the discussion presented in 9.3.1, we interpret the absence of the systematic left-lateralization of MMN in all the children studied here not as meaning that they did not develop the neuronal representations of /u/, /i/, /ɛ/, /ɔ/, and /a/ in the left auditory cortex, especially because all children were able to identify and discriminate /u/, /i/, /ɛ/, /ɔ/, and /a/ at the behavioral level, although with different ‘degrees’ of frequency and accuracy for CI as compared to NH children. Rather, we suggest that the absence of the systematic left lateralization of vowel-evoked MMN may be due to the following aspects in themselves as well as to their interaction: i) vowel phonemes being presented in isolation, rather than being placed in a grammatical context [cf. Hickok & Poeppel 2000; Binder et al. 2003; Shtyrov et al. 2005]; ii) the passive condition required here for automatic vowel processing [cf. Imaizumi et al. 1997]; iii) the developmental differences in the MMN scalp topography and distribution between adults and children [cf. Martin et al. 2003]; iv) the neural processes underlying discrimination of isolated vowels in the auditory cortices not being yet mature by 9.1 years for CI and 10.9 years for NH children [cf. Steinschneider & Dunn 2002; Martin et al. 2003]; and v) the cortical long-term memory representations of native phonemes being primarily – but not exclusively – located in the left auditory cortex [cf. Kujala 2006].

9.3.3 How to account for the differences emerging between CI and NH children in processing of single vowels and of vowel pairs at the behavioral and neurophysiological levels?

As for processing of single vowels and of vowel pairs, some clear differences emerge between CI and NH children. At the behavioral (i.e. conscious) level, the percentages which is a correlated of frequency in correct vowel identification and discrimination as well as the *d'* values indexing accuracy in correct vowel discrimination were often lower in CI as compared to NH children. At the neurophysiological (i.e. automatic) level, prolonged N1 latencies, attenuated P1 and N1 amplitudes, as well as different patterns of scalp topography and distribution as well as of brain area activation for P1, N1, and MMN were often observed in CI as compared to NH children. We interpret these differences characterizing detection and the processing of single vowels as well as the processing of vowel pairs in CI relative to NH children to follow from the factors mentioned below as well as to their interplay.

We consider the sometimes lower behavioral percentages and *d'* values as well as the often attenuated amplitudes of P1 and N1 together with the often prolonged latency of N1 at the neurophysiological level as being the 'natural' consequence of the attenuated, incomplete, and degraded auditory feedback provided by (unilateral) CI devices to individuals affected by SNHL (cf. 3.5). In other words, unilateral CI devices cannot substitute normal hearing from the point of view of the extraction, transformation, and transmission of the acoustic-phonetic, relevant, fine-structured information characterizing vowels, thus often leading to incomplete perception of the acoustic-phonetic features of vowels in CI users [cf. Ponton et al. 2000; Harnsberger et al. 2001; Moore 2003; Singh et al. 2004]. Recall from 3.13, that the incomplete perception of the acoustic-phonetic features (e.g., the formant values, especially F1 and F2, which are of crucial importance for vowel categorization) of vowels in CI users usually leads them to develop acoustic vowel spaces which are reduced (e.g., smaller along the F1/F2 plane), compressed (e.g., with vowel phonemes concentrated on a relatively small region of the F1/F2 plane), and fronted (e.g., with higher F2 values) as expected, both in perception [cf. Smith 1975; Harnsberger et al. 2001] and in production [cf. Lane et al. 2001; Ménard et al. 2007; Schenk et al. 2003; Neumayer et al. 2010; Horga & Liker 2006; Liker et al. 2007; Löfqvist et al. 2010]. By extending to pediatric CI users the findings achieved by Harnsberger et al. [2001] for adult CI users, we hypothesize that the reduced frequency in categorization of single vowels at the behavioral level, the less accurate detection and categorization of single vowels at the cortical level, and the reduced frequency and accuracy in the discrimination of vowel pairs only at the behavioral level in the CI children examined are likely to depend on the reduced discrimination of the F1 and F2 values as well as on the arrangment and overlap of the vowel categories in their perceptual spaces. For all the above-mentioned factors, processing of single vowels and of vowel pairs may be challenging in CI users [cf. Drennan & Rubinstein 2008] both at the behavioral and at the neurophysiological levels. As a consequence, CI users may have to develop a perceptual strategy [cf. Sandmann et al. 2009] allowing them to rely on the reduced cues of sound properties and on other cues (e.g., visual cues, cf. 9.3.5) to optimally process speech sounds. However, it may also be that the attenuated amplitudes of P1 and N1 follow from the reduced auditory sensory memory and phonological awareness as a consequence of the initial auditory deprivation experienced by the CI children examined [cf. Watson et al. 2007; Ortmann et al. 2013].

We hypothesize that the often different patterns of brain area activation relative to P1, N1, and MMN, the systematically reduced response strength of P1, N1, and MMN, as well as the absent left-lateralization of P1, N1, and MMN in CI children may be due to the following factors: i) the partial reorganization of the auditory cortex following the initial auditory deprivation period experienced by CI children [cf. Finney et al. 2001; Sharma et al. 2005; Gilley et al. 2008; Kral & Sharma 2012; cf. 3.11]; ii) possible alterations in the contribution of the ERP generators following CI surgery [cf. Watson et al. 2007]; and iii) the adaptation of the auditory cortex to electrical monaural stimulation as provided by unilateral CI devices [cf. Debener et al. 2008].

To sum up, our data confirm that unilateral CI devices, although partially restoring the auditory sensations in congenitally deaf children through electrical hearing, cannot substitute normal hearing. In fact, even the best CI users do not hear normally, since the signal they receive through the stimulation provided by the CI device is degrated, at least to a certain degree.

9.3.4 Why are some vowel pairs easier to process behaviorally and neurophysiologically for children with cochlear implants?

The way language is organized and processed by CI and, in general, deaf children falls along a continuum going from fully visual to predominantly (or fully) auditory. It is for this reason that CI users without additional handicaps, and especially congenitally-deafened or prelingually-deafened ones, tend to heavily rely both on auditory (e.g., the “invisible” acoustic-phonetic) cues and on visual (e.g., the “visible” or “salient” visual cues associated with articulation of speech sounds by watching the talker’s face) cues for language comprehension during communication interactions [cf., Erber 1975; McConkey Robins 2006: 158, 160; Desai et al. 2008; Huyse et al. 2013, among many others].

After implantation, some CI children manage to rely almost completely on auditory cues during comunicative interactions, while relying on visual cues only in extremely noisy situations. In fact, visual cues, when available, are essentially unaffected by noise [cf. Goh et al. 2001; Clark 2003; Schorr et al. 2005; Rouger et al. 2007]. These children are usually labeled as “star performers”. Other CI children, on the other hand, remain highly dependent on visual cues to “augment” what they hear. These children are usually termed “poor performers”. The most-frequently mentioned factors to account for the higher or lower degree to which CI children rely on visual cues after implantations may be classified as “external” vs. “internal” factors. By “external” factors, we refer to those factors which are not determined by the child himself/herself, such as age at implantation, duration of CI stimulation, etiology of deafness, residual hearing, neural plasticity, parental support, and educational environment. By “internal” factors, we define those factors which cannot be determined by the child himself/herself, such as temperament, tolerance, frustration, volition, personality, internal motivations, and so on.

CI users predominantly relying on auditory cues can not only easily hold a face-to-fact conversation, a simple task since both auditory and visual cues are available, but they also manage to comunicate on the telephone, a difficult task because there are no visual cues available to CI users as well as because the acoustic signal itself tends to be highly degraded. On the other hand, CI users heavily relying on visual cues, tend to be able to communicate in face-to-face conversations, where both auditory and visual cues are available, but they are unable to comunicate on the telephone, where there are no visual cure available and where they can only rely to a (highly) degraded auditory signal [cf. Dorman et al. 1993; Gstoettner et al. 1997; Harnsberger et al. 2001].

We have extensively adressed the importance of visual cues for CI users, since we believe that they may explain some findings concerning the processing of vowel pairs achieved in the present research. Recall from 9.2.3, that the vowel pairs /u/-/i/, /ɛ/-/i/, and /a/-/ɔ/ turned out to be easier-to-process as compared to the reverse pairs for CI children both at the behavioral level, where they were discriminated with a higher frequency and accuracy, as indicated by the higher percentages and *d'* values, and at the cortical level level, where they were processed with a shorter latency of MMN in the case of /u/-/i/ and /ɛ/-/i/, but with a larger amplitude of MMN in the case of /a/-/ɔ/. It is not possible to explain the easiness in processing of /u/-/i/, /ɛ/-/i/, and /a/-/ɔ/ as compared to /i/-/u/, /i/-/ɛ/, and /ɔ/-/a/ by recurring to the Euclidean distance, which is the same in both pairs of high, front, and back vowels as well by recurring to direction of change in the distintive feature specification (cf. 8.3). We hypothesize that the finding that the pairs /u/-/i/, /ɛ/-/i/, and /a/-/ɔ/ are processed more easily at the behavioral and cortical levels by CI children may be explained by considering the visual cues associated with vowel production, especially those related to the articulation of the first vowel in each pair.

Let us first consider the high vowel pairs. During articulation of both /u/ and /i/, the tongue body is raised with respect to its rest position along the vertical axis, the jaw is in its rest position, and the tongue root is avanced with respect to its rest position. What differentiate /u/ from /i/ at the articulatory level is represented by the configurations of the lips and of the tongue body along the horizontal axis. The lips are constricted (or rounded) with a consequent narrowing of the lip orifice during production of /u/, while they are straight (or unrounded) during articulation of /i/. The tongue body is retracted towards the velum during production of /u/, while it is advanced away from the velum during articulation of /i/. Correspondances among the configurations assumed by the articulators of the vocal apparatus, the acoustic-phonetic characteristics, and the distintive feature specification distinguishing /u/ from /i/ are provided in Table 1.

High vowels					
/u/			/i/		
Articulatory configurations	Acoustic-phonetic characteristics	Distinctive feature specification	Articulatory configurations	Acoustic-phonetic characteristics	Distinctive feature specification
Lips are constricted.	F3 value	[+ROUND]	Lips are straight.	F3 value	[-ROUND]
The tongue body is retracted towards the velum.	Small F2 value: 665 Hz.	[+BACK]	The tongue body is advanced away from the velum.	Large F2 value: 2333Hz.	[-BACK]

Table 1: Correspondances among the configurations assumed by the articulators of the vocal apparatus, the acoustic-phonetic characteristics, and the distintive feature specification distinguishing /u/ from /i/.

The configuration assumed by the lips (e.g., rounded vs. unrounded) is a clearly visible for CI users, whereas the position maintained by the tongue body (advanced vs. retracted) is hidden from the view. In Italian, back vowels are always produced with rounded lips (except for /a/, cf. 4.4.3 and 4.4.4). Given that the tongue body position is hidden from the view, whereas the lip configuration is clearly visible, the Italian pediatric CI users are thought to rely on this visual cue to infer vowel place in the case of high vowels auditorily presented. More generally, we hypothesize that the Italian CI children monitored have learned during the auditory training the configurations assumed by the articulators of the vocal apparatus during articulation of the Salento Italian high vowels. When processing auditorily presented pairs of high vowels at the behavioral and neurophysiological levels, these children recall the visual cue on which they rely to distinguish between high vowels, i.e. the configuration of the lips which are rounded for /u/ but unrounded for /i/. In other words, we believe that what makes /u/-/i/ easier-to-process (as compared to /i/-/u/) is the saliency associated to the visual cue associated to the first vowel in the pair, i.e. the fact that the lips are costricted for /u/ (but straight for /i/). See also the lip configuration in Figure 3.

Figure 3: Lips are rounded during articulation of /u/ (a) but straight during articulation of /i/ (b).

Given the fact that /u/-/i/ is processed faster at the neurophysiological level and with higher frequency and accuracy at the behavioral level as compared to /i/-/u/ by the NH children as well, we infer that visual cues are salient not only for deaf children, but also for NH children, even though the latter do not crucially rely on the visual cues for language comprehension during communication interactions.

Let us now consider the front vowel pairs. During articulation of both /ɛ/ and /i/, the tongue body is retracted away from the velum along the horizontal axis; additionally, the lips are unrounded. What differentiates /ɛ/ from /i/ is represented by the height of the tongue body, the degree of lowering of the jaw, and the advancement of the tongue root. As for the tongue body height, the tongue body is in its rest position during production of /ɛ/, whereas it is raised above its rest position during articulation of /i/. With respect to the tongue root, it is advanced with respect to its resty position for /i/, while it is in its neutral position for /ɛ/. As for the jaw, it is in its rest position (e.g., it is closed) for /i/, but it is slightly lowered for /ɛ/. Correspondances among the configurations assumed by the articulators of the vocal apparatus, the acoustic-phonetic characteristics, and the distintive feature specification distinguishing /ɛ/ from /i/ are provided in Table 2.

Front vowels					
/ɛ/			/i/		
Articulatory configurations	Acoustic-phonetic characteristics	Distinctive feature specification	Articulatory configurations	Acoustic-phonetic characteristics	Distinctive feature specification
Tongue body is in its rest position.	Middle F1 value: 539 Hz	[-HIGH]	Tongue body is raised above its rest position..	Low F1 value: 268Hz	[+HIGH]
Jaw is slightly lowered.			Jaw is closed.		
Tongue root is in its neutral position.	-	[-ATR]	Tongue root is advanced with respect to its rest position.	-	[+ATR]

Table 2: Correspondances among the configurations assumed by the articulators of the vocal apparatus, the acoustic-phonetic characteristics, and the distintive feature specification distinguishing /ɛ/ from /i/.

The degree of lowering (e.g., lowered vs. raised) of the jaw is clearly visible for CI users, whereas the tongue body height and tongue root advancement cannot be seen since the tongue is largely hidden from the view. As a consequence, CI users relying on visual cues during speech sound processing can actually only rely on the lowering of the jaw to infer vowel height in the case of front vowels. More generally, we put forward that the Italian CI children monitored have learned during the auditory training the configurations assumed by the articulators of the vocal apparatus during articulation of the Salento Italian front vowels. When auditorily processing pairs of high vowels at the behavioral and neurophysiological levels, the CI children are assumed to recall the visual cue on which they rely to distinguish between front vowels, i.e. the position of the jaw which is slightly lowered for /ɛ/, thus allowing the inferior teeth to partially be seen, but closed for /i/, thus preventing the inferior teeth from partially be seen. We suggest that what makes /ɛ/-/i/ easier-to-process (as compared to /i/-/ɛ/) is the saliency assigned to the visual cue associated to the first vowel in the pair, i.e. the fact that the jaw is lowered for /ɛ/ (but raised for /i/). See also the position of the jaw in Figure 4.

Figure 4: Jaw is slightly lowered during articulation of /ɛ/ (a) but closed during articulation of /i/ (b).

Given the fact that /ɛ/-/i/ is processed faster at the neurophysiological level and with higher frequency and accuracy at the behavioral level as compared to /i/-/ɛ/ by the NH children as well, we infer that visual cues are salient not only for deaf children, but also for NH children, even though the latter do not crucially rely on the visual cues for language comprehension during communication interactions.

Let us finally consider the back vowel pairs. During articulation of both /a/ and /ɔ/, the tongue body along the horizontal axis is retracted towards the velum both for /a/ and for /ɔ/;

additionally, the tongue root is in its rest position both for /a/ and for /ɔ/. What differentiates /a/ from /ɔ/ is represented by the tongue body height, the degree of lowering of the jaw, and the lip configuration. As for the tongue body height, it is lowered below its rest position for /a/, whereas it is in its rest position for /ɔ/. With respect to the degree of lowering of the jaw, the jas is completeley lowered during production of /a/, while it is slightly lowered during production of /ɔ/. Finally, as for the lip configuration, lips are unrounded for /a/ but rounded for /ɔ/. Correspondances among the configurations assumed by the articulators of the vocal apparatus, the acoustic-phonetic characteristics, and the distintive feature specification distinguishing /a/ from /ɔ/ are provided in Table 3.

Back vowels					
/a/			/ɔ/		
Articulatory configurations	Acoustic-phonetic characteristics	Distinctive feature specification	Articulatory configurations	Acoustic-phonetic characteristics	Distinctive feature specification
Tongue body is lowered below its rest position.	Large F1 value: 805 Hz.	[+LOW]	Tongue body is in its rest position.	Middle F1 value: 573 Hz	[+LOW]
Jaw is completely lowered.			Jaw is slightly lowered.		
Lips are unrounded.	Not too small F2 value: 1212 Hz	[+ROUNDED]	Lips are rounded.	Small F2 value: 846 Hz	[ROUNDED]

Table 3: Correspondances among the configurations assumed by the articulators of the vocal apparatus, the acoustic-phonetic characteristics, and the distintive feature specification distinguishing /a/ from /ɔ/.

The degree of lowering of the jaw (e.g., completely lowered for /a/ vs. partially lowered for /ɔ/) as well as the configuration of the lips (e.g., unrounded for /a/ but rounded for /ɔ/) are clearly visible for CI users, whereas the tongue body height cannot be seen since the tongue is largely hidden from the view. As a consequence, CI users relying on visual cues during speech sound processing can rely on two visual cues to infer height in back vowels, i.e. the degree of lowering of the jaw and the lip configuration. We suggest that the Italian CI children monitored have learned during the auditory training the configurations assumed by the articulators of the vocal apparatus during articulation of the Salento Italian back vowels. When processing pairs of back vowels at the behavioral and neurophysiological levels, they recall the visual cue on which they rely to distinguish between front vowels, i.e. the degree of lowering of the jaw and the lip configuration. We suggest that what makes /a/-/ɔ/ easier-to-process (as compared to /ɔ/-/a/) is the saliency assigned to the visual cue concerning the degree of lowering of the jaw associated to the first vowel in the pair, i.e. the fact that the jaw is completely lowered for /a/ (but partially lowered for /ɔ/). See also the position of the jaw in Figure 5.

Figure 5: Jaw is completely lowered during articulation of /a/ (a) but partially lowered during articulation of /ɔ/ (b).

On the other hand, we suppose that the degree of lip rounding does not contrain vowel processing, since the degree of lip roundung is lower in /ɔ/ as compared to /u/. For the different degrees of lip rounding in /ɔ/ (partial rounding) as compared to /u/ (complete rounding), see Figure 6.

Figure 6: Partial lip rounding during articulation of /ɔ/ (a) but complete rounding during articulation of /u/ (b).

After having extensively demonstrated that processing of vowel pairs at the behavioral and neurophysiological levels in CI appears constrained by the most salent visual cues assigned to the first vowel in the pairs during auditory training, i.e. the configurations of the lips during processing of high vowel pairs and the degree of lowering of the jaw during processing of front and back vowel pairs, we will now conclude this chapter with a final interpretation of the findings presented so far which represents a new contribution in the literature on speech sound processing in pediatric CI users.

9.3.5 The behavioral and the neurophysiological levels of processing present different impairments in children with cochlear implants

The processing of single vowels and of different-vowel pairs were investigated both at the behavioral and at the cortical level in the present study.

With respect to the correct processing of single vowels, it is often less accurate (as indicated by the often attenuated N1 amplitudes) and only rarely delayed (as suggested by the rarely prolonged N1 latencies) in CI as compared to NH children at the cortical level (cf.

9.2.2.2). On the contrary, the processing of single vowels is neither less frequent (as indicated by the percentages) nor less accurate (as suggested by the *d'* values) in CI relative to NH children at the behavioral level (cf. 9.2.2.1).

As for the correct processing of different-vowel pairs, it appears less frequent (as indicated by the lower percentages) and less accurate (as suggested by the lower *d'* values) in CI relative to NH children at the behavioral level (cf. 9.2.3.1). On the contrary, the processing of different-vowel pairs is neither delayed (as indicated by the MMN latencies), nor less precise (as suggested by the MMN amplitudes), nor even of lower magnitude (as indicated by the MMN area) in CI as compared to NH children (cf. 9.2.3.2). Rather, the main differences concerning the processing of different-vowel pairs in CI relative to NH children concern the scalp topography of the MMN, the degree of brain area activation, as well as the dislocation of the MMN over both hemispheres.

Taken together, the above-mentioned results suggest that the main difference existing between the behavioral and the neurophysiological levels of processing in CI children consist in the fact that the processing of different-vowel pairs is partially impaired for frequency and accuracy only at the behavioral level, whereas the processing of single vowels is partially impaired, mostly for accuracy, and rarely for the time interval required, only at the neurophysiological level. We provide the following interpretations for the findings detailed so far.

First, the processing of single vowels does not happen to be impaired for frequency and accuracy at the behavioral level, whereas it appears partially impaired, mostly for accuracy and rarely for the time interval required, only at the neurophysiological level. As for the behavioral level, the vowel categorization task was task-oriented (cf. 4.5) in that the CI children had first to carefully listen to the vowels in isolation and then they had to categorize them by clicking on laptop panels labeled as “A”, “E”, “I”, “O”, or “U”. We suspect that the design of the vowel categorization task and the fact that the CI children simply had to select the correct panel for vowel categorization could have facilitated the vowel categorization task, thus obscuring the possible differences between CI and NH children. At the neurophysiological level, on the other hand (cf. 4.6), the CI children did not have to perform any vowel categorization task; rather they were asked to concentrate on a self-selected movie for subsequently resuming it to the researcher, in order to direct their attention away from the vowel stimuli presented in the background. That is, at the neurophysiological level, we tested how efficiently the brain used the electric information delivered through the CI device to automatically extract the acoustic-phonetic features which are relevant for vowel categorization, without relying on panels labeled with the five vowel phonemes.

Second, the processing of different-vowel pairs turns out to be partially impaired for frequency and accuracy only at the behavioral level, but not at the neurophysiological level. As for the behavioral level, during the vowel-discrimination task (cf. 4.5), the CI children were asked to carefully listen to both same-vowel and different-vowel pairs and to tell whether they had just listened to a same-vowel pair or a different-vowel pair by clicking on a laptop panel labeled as “SAME”, in the case they had just heard a same-vowel pair, but on a panel labeled as “DIFFERENT”, provided that they had just heard a same-vowel pair. We think that this second behavioral task was more difficult as compared to the first behavioral task for the CI children, because of the fact that the panels were simply labeled as “SAME” vs. “DIFFERENT”, rather than with the exact vowel symbols. It is possibly for this reason that correct discrimination is less frequent and less precise in the CI as compared to the NH children. At the neurophysiological level (cf. 4.6), once more the CI children did not have to perform any vowel discrimination task; rather they were asked to concentrate on a self-selected movie for subsequently resuming it to the researcher. That is, at the neurophysiological level, we tested how efficiently the brain used the electric information delivered through the CI device to automatically represent the acoustic-phonetic features which are relevant for vowel categorization of the frequent and the rare vowels, without relying on panels labeled as "SAME" or "DIFFERENT". The fact that the CI children were neither slower, nor less accurate in the processing of vowel pairs at the cortical level, indicate that despite the often degraded auditory input delivered through the CI device, they manage to represent the acoustic-phonetic features which are relevant for vowel categorization and, hence, to activate the vowel neural traces stored in the auditory cortex (cf. discussion in 9.3.6).

The fact that the results obtained at the behavioral level do not completely match with those obtained at the neurophysiological level may be due to the fact that, as observed by Knudsen (2004), the behavioral measures are likely to underestimate the magnitude as well as the persistence of the effects derived by early auditory deprivation on neural circuits during the sensitive period for the maturation of auditory pathways, at least in some instances. The reason for this state of affairs is that behavior results from the information that has previously been processed through hierarchies of neural circuits in the brain operating in parallel. Among these circuits, those operating at higher levels in the hierarchy still remain plastic and, thus, they tend to obscure irreversible changes in those circuits operating at lower levels, whereas automatic processing at the neural level may be more precise than conscious processing at the behavioral level and, more generally, that neurophysiological processing tends to be more precise than we think or than we are aware of [cf. Allen et al. 2000; Knudsen 2004].

In other words, cortical processing precedes behavioral processing, in that vowel phonemes are first automatically processed by the neural circuits and then they are consciously processed at the behavioral level. Processing of single vowels is first automatically processed at the cortical level, where we often find the CI children to be slower and less precise as compared to the NH children, and then at the behavioral level, where the differences between CI and NH children are no longer visible. Likewise, processing of vowel pairs is first automatically processed at the cortical level, where we find no salient differences between the CI and the NH children, and then at the behavioral level, where we often find the CI children to be less precise and less accurate in the discrimination of different-vowel pairs. The results of the present research make clear that the behavioral level tends to underestimate the differences between CI and NH children for the processing of single vowels, whereas the neruophysiological level is likely to obscure the differences between CI and NH children for the processing of vowel pairs. Once more, the present study highlights that both behavioral and neurophysiological measures are of crucial importance to draw the complete picture for vowel processing in experienced CI children receiving their CI device before 3.5 years.

9.3.6 During cortical vowel processing, children with cochlear implants are partially impaired only at the auditory, not at the cognitive, level

With respect to detection and processing of single vowels as well as to the processing of vowel pairs at the cortical level, throughout the chapters 7 and 8, it has been repeatedly observed that the impact of SNHL and electrical hearing through CI stimulation is deeper on detection and on the processing of single vowels as compared to the processing of vowel pairs.

Detection of single vowels (cf. 9.2.1) is never delayed in CI children; rather, it is often less precise in CI as compared to NH children. Beside this, the brain area activation and the hemisphere involvement during vowel detection are likely to be different in CI relative to NH children as well as the response strength is nearly reduced in CI as compared to NH children.

Extraction of the acoustic-phonetic features which are relevant for linguistic categorization (cf. 9.2.2.2) is only rarely delayed in CI children; rather, it is nearly systematically less accurate in CI relative to NH children. Additionally, the patterns of brain area activation and of hemisphere involvement during extraction of the acoustic-phonetic features which are relevant for linguistic categorization are frequently different in CI relative to NH children as well as the response strength is systematically reduced in CI as compared to NH children.

Extraction and representation of the the auditory regularities (e.g., the acoustic-phonetic features) which are meaningful in linguistic terms in the auditory cortex, and, more generally, with respect to how vowel neural representations have been successfully developed in terms of distintive feature specification (cf. 9.2.3.2) does not appear challenged either for the time interval required, or for the accuracy, or the size of neuronal activation. However, the patterns of brain area activation are systematically different and the patterns of hemisphere involvment are often different in CI as compared to NH children. Additionally, the response strength is often reduced in CI relative to NH children.

Taken together, these findings suggest that, despite the the initial period of auditory deprivation as well as despite the differences in the peripheal input (e.g., natural hearing in NH children vs. electric hearing in CI children), and in spite the fact that detection and processing of single vowels are likely to be delayed or challenged, the brain of CI children is processing pairs of vowel phonemes in a very similar fashion to NH children [cf. Näätänen et al. 2012]. Nevertheless, because of the initial auditory deprivation period experienced by CI children as well as because of the differences in the peripheral input, brain area activation are often different and brain area involvement are often reduced during the processing of vowel pairs in CI children.We would like to interpret the above-mentioned results as indicating that the impairment exhibited by CI children during cortical vowel processing concerns the auditory level, not the cognitive level. In fact, when evoked by speech sounds, the P1 and the N1 responses indicate detection of speech sounds and extraction of the acoustic-phonetic features which are relevant for the speech sound categorization. It is only the MMN response that is assumed to be a correlate of the representation of the vowel acoustic-phonetic features which are meaningful in linguistic terms (e.g., the formant values, especially F1 and F2) in the auditory cortex during processing of different-vowel pairs. During auditory processing of vowel pairs, perception of the repetitive vowel (e.g., $/u/_{std}$) activates the neural trace of the corresponsing vowel in the auditory cortex; perception of the rare vowel (e.g., $/i/_{dev}$) subsequently activates the neural trace of the corresponding vowel. We would like to observe that, for each vowel phoneme, a single neural trace is assumed to be stored, irrespective of whether the vowel occurs as a standard or as a deviant. The vowel neural traces, whose formation in the child auditory cortex can only be driven by speech input, delivered either naturally (as in the case of NH individuals) or electrically (as in the case of CI users), are assemblies of cortical cells forming the memory traces for learned cognitive representations relative to speech sounds (in this case, vowels). The vowel neural traces consist of information about the vowel phonological representation in terms of appropriately specified (e.g., as [+] or [-]) distinctive features (e.g., [+HIGH]). The MMN response is elicited when the phonological representation of the deviant vowel, which is part of the vowel neural trace, is compared against the phonological representation of the standard vowel and a the specification of a couple of distinctive features (e.g., [BACK, ROUNDED]) does not match between the deviant (e.g., /i/$_{\text{dev}}$ is assumed to be specified as [-BACK, -ROUNDED]) and the standard (e.g., /u/$_{\text{std}}$ is assumed to be specified as [+BACK, +ROUNDED]). The recognition of a mismatch in the distinctive feature specification of two vowels elicits the MMN response. The MMN can be regarded as a memory trace indicator, i.e. as an index of the fact that the memory traces representing the auditory regularities characterizing both the standard and the deviant as well as the auditory irregularities differentiating them have been formed in the short-term (or sensory or echoic) auditory memory, and as signaling the intact auditory memory capacities in CI users.

As already pointed out in 2.5.1, auditory P1 and N1 are obligatory (or exogenous) responses of the ERPs, since their elicitation is predominantly dependent on the acoustic/physic characteristics of the external auditory stimulus and on the integrity of the central auditory system. Auditory MMN (cf. 2.5.2) is a discriminative (or endogenous) response of the ERPs, since its elicitation requires the subjects to have the ability to discriminate between acoustic-phonetic changes in the stimulus sequences, rather than being simply triggered by physical differences between two auditory stimuli [cf. Purdy et al. 2001, 2005; Mazza & Turatto 2005: 9; Pulvermueller & Shtyrov 2006; Wunderlich & Cone-Wesson 2006; Martin et al. 2008]. Thus, MMN is considered as a cognitive response which correlates with higher-order perceptual processes underlying stimulus discrimination, whereas P1 and N1 are auditory responses, i.e. they are more “low-level” as compared to MMN (Pulvermueller & Shtyrov 2006).

Building on the different processes indexed by the P1 and N1 responses on the one hand as compared to the MMN response on the other hand, as well as building on the results achieved in the present study, we would like to conclude that the impairment exhibited by CI children concerns the auditory level, i.e. the detection and the processing of single vowels, not the cognitive level, i.e. the processing of vowel pairs. As already spelled out in 9.3.1, from the systematic presence of MMN in all the CI children monitored for all the pairs tested, we would like to infer that, despite the initial auditory deprivation period, but thanks to regular CI use and adequate auditory training, the CI children examined succeed in developing the neural traces of the Salento Italian vowels with correct specification of the relevant distinctive features. In other words, these children are supposed to compensate for the often reduced accuracy in detection of single vowels as well as in extraction of the vowel acoustic-phonetic features which are relevant for linguistic categorization (and for subsequent representation) by developing a perceptual strategy allowing them to rely on the reduced cues of sound properties and on other cues (e.g., visual cues, cf. 9.3.5) to optimally process speech sounds [cf. Sandmann et al. 2009].

To recapitulate, the Italian CI children studied turn out to present an auditory-cognitive gap. They are partially impaired at the auditory level, by typically presenting a reduced accuracy in detection and processing of single vowels and by only rarely needing a prolonged interval required to accomplish these processes. However, at the cognitive level, they are able to succesfully develop the neural traces of Salento Italian vowels with correct specification of the relevant distinctive features. To the best of our knowledge, this result is new not only for the literature on speech sound processing of Italian CI users at the cortical level, but also for the literature on cortical speech sound processing in pediatric CI users in general.

CHAPTER 10

Conclusion, clinical implications, limitations of the study, and future perspectives

10.1 Introduction

This chapter closes the dissertation. The main findings of the study are first recapitulated (cf. 10.2), followed by the limitation of the study (cf. 10.3). The factors explaining the great variation in the language outcomes characterizing the CI users are then addressed (cf. 10.4), together with the clinical implications of the present study (cf. 10.5). Finally, future research perspectives are mentioned (cf. 10.6).

10.2 Main findings of the present study

The evolution of CI devices during the last 20 years has led to considerable success in the functional rehabilitation of deafness [cf. Moller 2006]. Modern multichannel CI devices allow congenitally-deafened children to understand spoken speech [e.g., Sharma et al. 2002abc, 2005; Beynon et al. 2002; Singh et al. 2004; Henkin et al. 2008; Munivrana & Mildner 2013; Ortmann et al. 2013], environmental sounds, and even in some cases to listen to musics [e.g., Vecchiato et al. 2011; Torppa et al. 2012].

The present research investigates the processing of single vowels (/u, i, ɛ, ɔ, a/) as well as of vowel pairs at the behavioral (e.g., conscious) and at the neurophysiological (e.g., automatic) levels in a group of deaf children implanted during the sensitive period for central auditory maturation (range of age at surgery: 2.1 – 4.4 years) and who had been using their CI for at least 2.4 years (range of duration of CI stimulation: 2.4 – 8.1 years). The main findings achieved throughout the present research are detailed in (i) – (xi).

i) The detection of single vowels (e.g., /u/, /i/, /ɛ/, /ɔ/, and /a/), which was investigated only at the neurophysiological level, is never delayed, but it is frequent less precise in CI as compared to NH children.

ii) The processing of single vowels (e.g., /u/, /i/, /ɛ/, /ɔ/, and /a/) was investigated at the behavioral and neurophysiological level: correct processing of single vowels is not less frequent in CI relative to NH children at the behavioral level; however, it is often less accurate, and only rarely delayed, in CI relative to NH children at the neurophysiological level.

iii) The processing of same-vowel pairs (e.g, /u/-/u/, /i/-/i/, /ɛ/-/ɛ/, /ɔ/-/ɔ/, and /a/-/a/) was investigated only behaviorally: /u/-/u/, /i/-/i/, and /ɔ/-/ɔ/ are discriminated with comparable frequency and accuracy by CI and NH children, whereas /ɛ/-/ɛ/ and /a/-/a/ are discriminated with lower frequency and lower accuracy by CI children as compared to NH children, thus resulting more difficult to discriminate for CI children.

iv) The processing of different-vowel pairs (e.g., /u/-/i/, /i/-/u/, /ɛ/-/i/, /i/-/ɛ/, /a/-/ɔ/, and /ɔ/-/a/) was investigated both behaviorally and neurophysiologically. At the behavioral level, /u/-/i/, /ɛ/-/i/ ed /a/-/ɔ/ are discriminated with comparable accuracy and frequency by CI and NH children, whereas /i/-/u/, /i/-/ɛ/ and /ɔ/-/a/ are discriminated with lower frequency and lower accuracy by CI children, thus appearing more difficult to discriminate. At the neurophysiological level, the six vowel pairs are processed during a similar time interval as well as with comparable accuracy and size of neuronal activation by CI as compared to NH children.

v) The pairs /u/-/i/, /ɛ/-/i/, and /a/-/ɔ/ are easier-to-process for the CI children, in that they are processed with higher frequency and accuracy at the behavioral level as well as faster or with higher accuracy at the neurophysiological level.

vi) The brain areas involved in the processing of single vowels as well as of vowel pairs are those fronto-central and/or fronto-temporal, both in CI and in NH children. However, the fronto-central areas are more frequently activated in CI children, whereas the fronto-temporal brain areas are more frequently activated in NH children

vii) The response strength at the cortical level, as indexed by the degree of brain area activation, is systematically reduced in CI relative to NH children.

viii) During the processing of single vowels as well as of vowel pairs, both hemispheres tend to be equally committed in CI chidlren, whereas the left hemisphere often appears more committed than the right one in NH children, although not systematically.

ix) The vowel quality (e.g., /u/, /i/, /ɛ/, /ɔ/, and /a/), the Euclidean distance (e.g. smaller vs. larger), and direction of change in the distintive feature specification (e.g., from [+] to [-] or from [-] to [+]) turn out to play no role either on the processing of single vowels or on the processing of vowel pairs, both at the behavioral and at the neurophysiological level.

x) The age at surgery (range: 2.1 – 4.4 years) is categorically irrelevant for behavioral vowel processing. At the cortical level, earlier vs. later age at surgery is largely irrelevant for vowel processing. Nevertheless, detection and processing of single vowels is likely to be faster as well as processing of vowel pairs can be more accurate in those deaf children receiving their unilateral CI before 3.5 years.

xi) The duration of CI stimulation (range: 2.4 – 8.1 years) is categorically irrelevant for behavioral vowel processing as well. At the cortical level, longer vs. shorter duration of CI stimulation is largely irrelevant for vowel processing. Nevertheless, detection and processing of single vowels may be faster as well as processing of vowel pairs may be faster and/or more accurate in deaf children benefiting from a duration of CI stimulation of at least 5.8 years.

Taken together, the main findings detailed in (i) – (xi) lead us to infer the following three points detailed in (xii) – (xv):

xii) A main difference exists between the behavioral and the neurophysiological levels of processing in CI children: the processing of vowel pairs is partially impaired for frequency and accuracy only at the behavioral level, whereas the processing of single vowels is partially impaired, mostly for accuracy, and rarely for the time interval required, only at the neurophysiological level.

xiii) At the neurophysiological level, CI children are impaired at the auditory, not at the cognitive, level. In fact, in spite of typically being less accurate in detection and processing of single vowels, both of which are auditory processes, CI children are not impaired in the processing of vowel pairs, which is a cognitive process.

xiv) Age at surgery and duration of CI stimulation are irrelevant for behavioral vowel processing, whereas they constrain cortical vowel processing, although not systematically: deaf children implanted before 3.5 years and/or who had been using their CI for at least 5.8 years are likely process single vowels as well as vowel pairs faster and more accurately.

xv) The visual cues which have been learned by the CI children during the linguistic rehabilitation appear to be of crucial importance during the processing of vowel pairs presented auditorily, in that the visual cues appear to be recalled during vowel processing in order to compensate for the often degraded electrical signal delivered by the CI devices. In particular, those vowel pairs where the first vowel is pronounced with rounded lips (e.g., /u/-/i/) or with a lowered jaw (e.g., /ɛ/-/i/) are auditorily processed faster or more accurately at the cortical level as well as with higher accuracy and frequency at the behavioral level as compared to the other vowel pairs

10.3 Limitations of the present study

In a large percentage of children fitted with unilateral CI during the optimal age range, a remarkable degree of language communication via the auditory domain is restored [cf. Näätänen et al. 2012]. This is the case of the Italian CI children examined here, who were implanted early in their life (range of age at surgery: 2.1 – 4.4 yrs) and who were experienced CI users (range of duration of CI use: 2.4 – 8.1 yrs). In deaf children implanted during the sensitive period for central auditory pathways' maturation, CI use may effectively promote auditory pathways' maturation for the processing of single vowels and of vowel pairs at the behavioral and at the neurophysiological levels, despite the initial auditory deprivation. Fulfilling these prerequisites, the CI children examined in the present study can be regarded as 'successfully-implanted children' or as 'good performers' from the point of view of their abilities in the processing of single vowels and of vowel pairs, both behaviorally and neurophysiologically.

Nevertheless, as recognized in clinics, and as scientific studies have shown, there is a considerable amount of variation in the language outcomes and in perception of speech sounds in children using CI devices, both at the unilateral and at the bilateral levels [e.g., Geers et al. 2003; Schauwers 2006; Pisoni et al. 2011]. Even successfully-implanted children with good performance of processing of isolated speech sounds as well as of pairs of speech sounds, as the ones examined here, often present delays and deviances in their mastery of (at least) some communication aspects. CI children were found to have poorer (or partially impaired) abilities than NH children in receptive and expressive language [cf., among others, Pisoni 2000; Uchanski & Geers 2003; Nicholas & Geers 2004; Backhshaee et al. 2007; Gérard et al. 2010; Niparko et al. 2010; Huttunen & Rider 2012; Schwartz et al. 2013; Löfkvist 2014], in voice quality [e.g., Horga & Liker 2006], in verbal fluency [e.g., Wechsler-Kashi et al. in press; Kenneth et al. 2013], in vocabulary [e.g, Osberger et al. 1986; Boothroyd et al. 1991], in grammar [cf., Power & Quigley 1973; Geers & Mog 1994, among many others], in pragmatics [cf. Kretschemer & Kretschemer 1994], in pronunciation of vowels and consonants [cf., among many others, Serry & Blamey 1999; Harnsberger et al. 2001; Ertmer et al. 2007; Liker et al. 2007; Lofviqst et al. 2010; Neumeyer et al. 2010; Baudonck et al. 2011], in perception of prosody and speech [e.g., O' Halpin 2010], in perception of speech in background noise [e.g., Asp et al. 2012; Caldwell & Nittrouer 2012], in auditory working memory [e.g., Pisoni et al. 2011], and so on. Even though substantial advances in traditional hearing aid technology as well as in teaching methodologies for CI children have taken over the past decades, these avances have led to functional rehabilitation of deafness (cf. Moller 2006), but they have not translated into crucial improvements in the overall language or academic attainment levels of deaf children using CI devices [cf. McConkey Robbins 2006: 154]. It is well known that the reading and writing abilities are strongly based on the mastery of language. For this reason, delays in language resulting from SNHL typically interfere with the child's development of literary skills, thus severely limiting the options for secondary school and job placement for CI users [cf. Holt et al. 1997].

Language is a complex entity made up of different modules, such as phonetics, phonology, morphology, syntax, semantics, pragmatics, vocabulary. As observed by McConkey Robbins [2006: 154], most research studies on CI users have investigated only one module, or at least two modules, at time. Depending on the module(s) investigated, CI users may compare more or less favorably to their age peers with normal hearing. However, the results achieved by each study are to be interpreted only with respect to the module(s) investigated and they do not provide us with the complete picture concerning language development in pediatric or adult CI users. For this reason, the results concerning processing of single vowels and of vowel pairs at the behavioral and at the neurophysiological levels by the Italian CI children presented and discussed throughout the present study have to be interpret with caution, since they provide researchers with a partial picture concerning the degree of the receptive language effectively achieved by the CI children monitored. In this respect, it always has to be kept in mind that, even the best CI users, however, do not hear normally, since the signal they receive through the stimulation provided by the CI device is degraded, at least to a certain extent.

Nevertheless, it is worth observing that good abilities in processing of isolated vowels and of vowel pairs at the behavioral and cortical level represent a crucial prerequisite for an adequate receptive and expressive language in pediatric CI users.

Another limitation of the present research is the difficulty in obtaining pediatric CI users to enroll in the study. It has to be pointed out that we decided to select pediatric CI users without additional cognitive problems, thus 'purely deaf children'. However, most pediatric CI users who were part of the ENT operative unit at the Lecce hospital had additional cognitive problems beside SNHL and, therefore, they could not be regarded as suitable pediatric CI users for the current study.

10.4 Factors explaining the great variation in language outcomes characterizing CI users

Partial restoration of the hearing sensation through CI stimulation usually results in a lowered (but with increased variability) F0 and intensity, a change in voice quality to a less breathy voice, a more normal breathing patterns [cf. Oester 1987, 1998; Lane et al. 1997, 1998] as well as a transformation of the vowel spaces which become less reduced, less compressed, and less fronted both in perception [cf. Smith 1975; Harnsberger et al. 2001] and in production [cf. Lane et al. 2001; Ménard et al. 2007; Schenk et al. 2003; Neumayer et al. 2010; Horga & Liker 2006; Liker et al. 2007; Löfqvist et al. 2010].

Although CI devices partially restore the hearing sensation in congenitally deaf children affected by SNHL, these children show a very wide range of speech perception, comprehension, and production skills. Not only can successful CI users easily hold a face-to-fact conversation, but they also manage to communicate on the telephone, a difficult task because there are no visual cues available to CI users as well as because the acoustic signal itself tends to be highly degraded. Unsuccessful CI users, on the other hand, are unable to communicate on the telephone; rather they encounter many difficulties in communicating even in face-to-face conversations and they can barely perform above chance on speech perception task relying on auditory cues alone [cf. Dorman et al. 1993; Gstoettner et al. 1997; Harnsberger et al. 2001]

Successful CI implantation and good linguistic performance concerning speech perception, comprehension, and production in CI users are constrained by a variety of factors and by their interplay. The most-frequently mentioned factors are the following eight: i) the age at implantation; ii) the duration of CI stimulation, iii) the presence vs. absence of additional handicaps; iv) the etiology of deafness; v) the residual hearing; vi) the neural plasticity; vii) the parental support; and viii) the educational environment [cf. McConkey Robins 2006: 160], among many others]. To these factors, one has to add the so-called ‘x-factors’, i.e. those characteristics which are unique to each child [cf. Head 1983], such as temperament, tolerance, frustration, personality, and internal motivations. In the present study, we were able to control the children selected for age at surgery, duration of CI stimulation, absence of additional handicaps, parental support, and educational environment, but not for the other above-mentioned factors which are also likely to play a role in successful CI implantation and good linguistic performance.

10.5 Clinical implications

The findings of the present study are very useful for the CI manufacturers as well as for the speech therapists taking care of CI children.

First, the manufacturers of CI devices are invited to rely on the findings of the present research to implement more fine-grained speech processors which are able to better capture the acoustic-phonetic features of speech sounds and to better convey them along the auditory pathways in order for them to be adequately interpreted in the auditory cortices. Second, the speech therapists should take advantage of the results of the present study in order to customize the rehabilitation strategy to each pediatric CI user for achieving better language outcomes.

10.6 Future research perspectives

The present study casts a bit of light on the cortical processing of speech sounds by Italian pediatric CI users. It is important that future research further investigates the waveform, the morphology, the parameters, the scalp distribution, the response strength, and the eventual hemispheric lateralization of the ERP responses to better understand the processing of speech sounds at the cortical level in Italian pediatric CI users.

However, future research should investigate not only the processing of native vowels, but also that of native consonants in Italian pediatric CI users. Furthermore, future research on the cortical processing of speech sounds should compare the performance of deaf Italian children with unilateral CI devices to those achieved by deaf Italian children with bilateral CI devices. Finally, since Italian children learn English as a second language at school, it would be interesting to investigate detection, categorization, and discrimination of English vowels and consonants to cast light on the cortical processing of non-native speech sound in Italian CI children.

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