INTERSPEECH 2013

Processing of /i/ and /u/ in Italian cochlear-implant children: a behavioral and neurophysiologic study

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Abstract

Cochlear implants partially restore auditory sensation in individuals affected by severe to profound hearing loss. We investigated vowel detection, identification, and discrimination in a group of congenitally-deafened, unilaterally-implanted, Italian children and in a group of age-matched controls, by combining behavioral and neurophysiologic measures. Comparable vowel identification and discrimination performance emerged for cochlear-implant and normal-hearing children at the behavioral level. At the neurophysiologic level, on the other hand, cochlear-implant children appeared to lag behind their age-matched normal-hearing peers for vowel detection and identification, but not for vowel discrimination. Length of cochlear implant use significantly affected vowel processing at the neurophysiologic level, although not systematically.

Index Terms: vowel processing, behavioral measures, neurophysiologic measures, Italian cochlear-implants children.

1. Introduction

Acoustic and articulatory cues to vowels and consonants are present in the higher frequencies of the speech signal. Unilateral cochlear implants (CIs) partially restore auditory sensation in individuals affected by congenital, bilateral, and severe to profound hearing loss, who present poor thresholds in the high-frequency region and who would otherwise perceive no speech sounds [1]. With a CI, perception is fairly well restored especially in children receiving their CI during the sensitive period for central auditory pathway maturation (≤44months) [2]. If CI surgery happens outside the sensitive period, auditory deprivation induces partial to total reorganization of the auditory cortex and the dormant auditory areas are recruited by the visual modality [3]. Reorganized auditory pathways may explain why CI efficacy is low in many prelingually-deafened children [4-5].

Passively recorded Cortical Auditory Event Potentials (CAEPs) are brain responses automatically elicited by auditory sounds (typically speech). CAEPs provide information regarding the timing (through latency), accuracy or strength (through amplitude), and hemisphere involvement (through scalp topography) in speech sound processing [6-8]. CAEPs are useful in (pediatric) CI treatment, enabling clinicians to automatically assess some aspects of CI fitting and effectiveness and to objectively measure CI stimulation benefits [6, 9-10]. Early-implanted children [4-5, 10] detect, identify, and discriminate consonants better than late-implanted ones [11-13] in terms of accuracy/strength and processing time. Vowel processing, on the other hand, has been investigated only in late-implanted children, without exploring the possible influence of length of CI use [11, 13]. To our knowledge, vowel processing in Italian CI children has been investigated only behaviorally, without uncovering the possible role played by age at surgery and/or length of CI use [14-15]. When investigating speech sound processing in CI users, combining behavioral and neurophysiologic measures is of crucial importance [16], as CI users may show poor behavioral — but good neurophysiologic — speech sound discrimination [11], or the reverse pattern [13, 17].

In this study, for the first time we investigate high vowel detection, identification, and discrimination in Italian early-implanted children, by recurring to neurophysiologic and behavioral measures, aiming to assess to what extent age at surgery and length of CI use affect vowel processing.

2. Methods

2.1. Participants

Eight congenitally-deaf, unilaterally-implanted (7 left, 1 right) CI children (6 male, 2 female) and nine normal-hearing (NH) children (7 female, 2 male), all right-handed [18] and living in the province of Lecce (Salento, Southern Italy), participated in the study. The mean age at surgery was 33months (range= 24—53months). With one exception, the CI children are early-implanted children, since they received their CI before the 44th month of life. The CI children (mean age at testing= 109months, range= 81—129months; mean length of CI use at testing= 76months, range= 28—97months) were attending a clinical follow-up at Lecce Hospital. The NH children had a mean age of 92months at testing (range= 51—131months). All parents signed the informed consent in accordance with the declaration of Helsinki. The study was approved by the Ethical Committee of Lecce ASL.

As for the auditory performance [19] of the CI children examined, four children managed to use the telephone with known speakers, three children were able to understand conversations without lip reading, and one child could understand common phrases without lip reading. With respect

25 – 29 August 2013, Lyon, France

to speech intelligibility [20] of the CI children examined, the connected speech of four children was intelligible to all listeners, whereas that of the other four children appeared intelligible to listeners with a little experience with deaf persons' speech. Altogether, the eight CI children exhibit good auditory and speech intelligibility performance.

2.2. Linguistic stimuli

Salento Italian has five vowels (/i/, /ɛ/, /a/, /ɔ/, /u/) [21]. We focus on the high vowels /u/ and /i/. Both are produced with advanced tongue root, while differing by place of articulation (/u/ is back and /i/ is front), which is acoustically cued by F2 values [22]. The acoustic distance in the F1/F2 space between /u/ and /i/ is large (847Mel), which should enhance their discrimination, especially in CI children [13].

We used 10 repetitions of /i/ and /u/ realized in isolation by a male native speaker of Salento Italian in the CRIL soundproof room. The vowels produced were first recorded with *CSL 4500* (sampling rate= 44.1kHz) and a *Shure SM58-LCE* microphone and then segmented and analyzed acoustically with *Praat 5.3.42*. The total duration and the F1/F2 values in the vowel steady tract, 0.050s centered at the midpoint, of the elicited vowels are: i) mean duration: 300ms; ii) mean F1: 268Hz for /i/ and 308Hz for /u/; iii) mean F2: 2333Hz for /i/ and 665Hz for /u/. The elicited vowels were normalized for duration by resynthesis (100ms), for F0 (130Hz for /u/; 145Hz for /i/), intensity (70dB/SPL), and rise/fall times (5ms) with *Akustyk 1.9.3 for Praat,* to keep them as homogenous as possible [7] despite acoustic variation [23]. The normalized stimuli were categorized and rated as good vowel category representatives by five adult Italian native speakers before presenting them to children [24]. All children were confronted with two vowels in isolation (/i/, /u/) and three pairs (/i/-/i/, /u/-/u/, /u/-/i/).

2.3. Behavioral experiment

The behavioral experiment was carried out with *Praat 5.3.42* in the soundproof room at Lecce Hospital. First, we wanted to ascertain whether CI children were able to identify the stimuli (2.2) as exemplars of the intended phonetic categories. To this end, children listened to 20 vowels (/i/, /u/) through a loudspeaker placed in front of them, and they had to identify the stimuli by clicking with a computer mouse on panels labeled as "I" or "U" on a computer monitor. Our second goal was to assess whether CI children could discriminate the sequential presentation of two exemplars of the same phonetic category from the presentation of exemplars of two different phonetic categories, which is a crucial prerequisite for participation in the neurophysiologic experiment (2.4). For this, children had to discriminate 30 vowel pairs (/i/-/i/, /u/-/u/, /u/-/i/) by clicking with a computer mouse on panels labeled as "SAME" or "DIFFERENT" on a computer monitor.

2.4. Neurophysiologic experiment

Vowel-elicited P1, N1, and MMN are of interest in this study. In the CAEP waves, P1 and N1 indicate that vowels have been detected and identified, while MMN indexes that vowels have been recognized as native phonemes and phonetically discriminated with respect to their acoustic and articulatory characteristics (2.2). P1 indexes vowel detection and its latency is a biomarker for central auditory pathway maturation [4-5, 10]. N1 encodes early extraction of vowel-specific acoustic features and vowel representation in the auditory cortex [25-28]. Mismatch Negativity (MMN) indicates phonetic change detection based on the previous sound context and it is sensitive to long-term representations of phonemes in the auditory cortex [27-28]. N1 and MMN are modulated by the vowel-specific acoustic features. Actual identification and discrimination of speech sounds takes place when phonemes are recognized and their long-term memory representations, stored in the auditory cortex, are activated [27-28].

An oddball paradigm with 680 standard ($/u/_{std}$) and 120 deviant ($/i/_{dev}$) stimuli (ISI=700—900ms) was implemented. At least five standards separated two deviants. Nine standards preceded the first deviant. The EEG was passively recorded while children were watching a silent movie on a TV screen. *BrainVision Recorder 1.20* and *Acticap System* (also *BrainAmp* and *BrainVision Analyzer 2.0,* BrainProducts, Gilching, Germany) with 32 active Ag/AgCl channels (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, $FP1_{VEOG}$, $FP2_{VEOG}$, $FT9_{HEOG}$, $FT10_{HEO2}$, FCz_{Ref}, and AFz_{Gnd}) were used to record the EEG signal. This was 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.

To reduce/eliminate the CI artifacts, we performed an Independent Component Analysis (ICA) [29-31] implemented on EEGLAB [32] and running in MATLAB. The ICA was conducted for each CI user, decomposing the EEG data into 16 components. Only components clearly showing CI related artifacts were removed. All EEG data were imported into *BrainVision Analyzer 2.0*. Individually, the initial nine standards and the 120 standards following the deviants were excluded from the analysis. The CAEP epochs (a 750ms time window including a 100ms pre-stimulus baseline) were digitally filtered by a 0.3−40Hz bandpass filter and re-referenced to Pz, which is an appropriate reference when analyzing the EEG recorded with a low-density system in CI children [33]. Artifact rejection criteria were set as follows: i) voltage step= 75µV/ms; ii) difference= 150µV/200ms; iii) amplitude= ±100µV; and iv) lowest activity= 0.5µV/50ms [34]. Artifact-free segments were separately averaged for $/u/_{std}$ and $/i/_{dev}$ for each participant. Grand Averages were generated over all CI and NH children. P1 and N1 were identified on the waves elicited by $/u/_{std}$ and $/i/_{dev}$; MMN was detected on the subtraction wave ($/i/_{dev}$ minus $/u/_{std}$). The time window used was of 40−130ms (for P1), 110−270ms (for N1), and 150−300ms (for MMN). CAEP latencies (ms) and amplitudes (µV) were measured on fronto-central channels (F3-F4, FC1-FC2, FC5-FC6, C3-C4), with a time window of 30ms (for P1), 40ms (for N1), and 50ms (for MMN) surrounding the peak, depending on the CAEP response duration [35].

2.5. Statistical analysis

Descriptive and inferential statistical analysis was computed with *IBM SPSS Statistics 20*. The *T-test for independent samples* was computed as follows: i) on the percentages of behavioral performance to assess whether accuracy is comparable in CI vs. NH children; ii) on CAEP parameters to ascertain whether they are comparable in both groups; and iii) on MMN parameters to investigate whether MMN is left-lateralized in CI and NH children. The relationships between age at surgery or length of CI use and CAEP parameters or behavioral percentages in CI children were studied by using *Pearson correlation coefficient analysis*.

3. Results

3.1. Behavioral results

NH children correctly identify and discriminate high vowels in 100 percent of the cases. The behavioral performance of CI children is presented in Table 1.

Table 1. *Behavioral performance (percentages to target stimuli) in CI children.*

Stimuli	Mean	SD	Min	Max	Range	Mode
/i/	92	18	50	100	50	100
/u/	96	5	90	100	10	100
/i/-/i/	98	5	90	100	10	100
/u/-/u/	100	0	100	100	0	100
/u/-/i/	99	3	90	100	10	100

Comparable behavioral performance emerge for CI and NH children in vowel identification ($t(7)=1.37$, $p=.213$ for /i/; $t(7)=2.05$, $p=.080$ for /u/) and discrimination ($t(7)=1.53$, $p=.170$ for /i/-/i/; $t(7)=1.00$, $p=.351$ for /u/-/i/). Two points are worth mentioning. First, CI children always correctly discriminate /u/-/u/. Second, the statistical value for identification of /u/ in CI children approaches statistical significance.

3.2. Neurophysiologic results

Neurophysiologic P1 and N1 were identified in all CI and NH children. MMN was identified in all CI children, even in those who performed worst in the behavioral task, and in seven NH children. Thus, two NH children were excluded from the analysis. For /u/$_{std}$, 547 artifact-free trials were individually averaged for CI (SD=7) and NH (SD=4) children. For /i/$_{dev}$, 119 trials were individually averaged for CI and NH children (SD=1). Artifact-free trials are nearly the same in CI and NH children because ICA allows selective removal of CI artifacts contaminating the EEG trials [29-31] .

For P1, comparable peak latencies emerge for CI and NH children ($t(118)=-.20$, $p=.841$ for /u/$_{std}$; $t(118)=.52$, $p=.604$ for /i/$_{dev}$), but lower peak amplitudes are found in CI children ($t(88)=5.42$, $p<.001$ for /u/$_{std}$; $t(100)=4.32$, $p<.001$ for /i/$_{dev}$), see Figure 1 and Table 2.

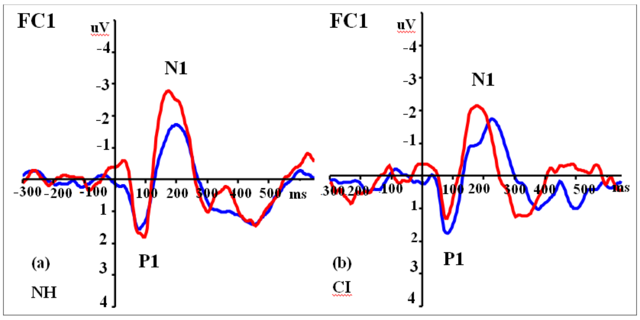

Figure 1: *Grand Average of /u*$_{std}$ *(blue) and /i*$_{dev}$ *(red).*

Table 2. *Mean (±SD) peak latencies and amplitudes of P1.*

P1	Latency (ms)		Amplitude (μV)	
V	NH	CI	NH	CI
/u/$_{std}$	84 ±13	85 ±13	1.06 ±0.6	0.54 ±0.4
/i/$_{dev}$	85 ±21	85 ±17	1.36 ±0.8	0.77 ±0.6

Amplitude of P1 evoked by /u/$_{std}$ tends to be larger in children benefitting from longer CI use ($r=.296$, $p=.018$), see Figure 2.

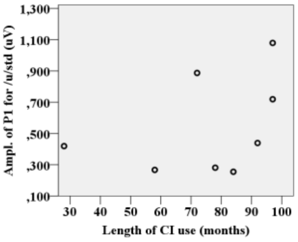

Figure 2: *P1 amplitude for /u/*$_{std}$ *and CI use.*

For N1, longer peak latencies ($t(118)=3.26$, $p=.001$ for /u/$_{std}$) and smaller peak amplitudes ($t(95)=4.49$, $p<.001$ for /u/$_{std}$; $t(118)=4.65$, $p<.001$ for /i/$_{dev}$) are generally found in CI compared to NH children (Table 3 and Figure 1). Surprisingly, the latency of N1 evoked by /i/$_{dev}$ appears significantly shorter in CI compared to NH children ($t(118)= 2.343$, $p=.021$).

Table 3. *Mean (±SD) peak latencies and amplitudes of N1.*

N1	Latency (ms)		Amplitude (μV)	
V	NH	CI	NH	CI
/u/$_{std}$	185 ±32	205 ±35	-1.56 ±0.9	-0.92 ±0.6
/i/$_{dev}$	191 ±34	177 ±29	-2.40 ±1.4	-1.37 ±1.0

Even though the amplitude of N1 evoked by /u/$_{std}$ tends to be larger in children with longer CI use ($r=.380$, $p=.002$; Figure 3a), late-implanted children may sometimes present a larger N1 amplitude compared to early-implanted ones ($r=-.252$, $p=.045$, Figure 3b).

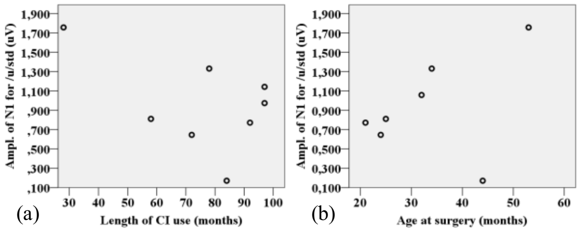

Figure 3: *N1 amplitude for /u/*$_{std}$ *and (a) length of CI use or (b) age at surgery.*

For MMN, comparable latencies ($t(118)=.727$, $p=.469$) and amplitudes ($t(118)=.345$, $p=-731$) are found in CI and NH children (Figure 4 and Table 4).

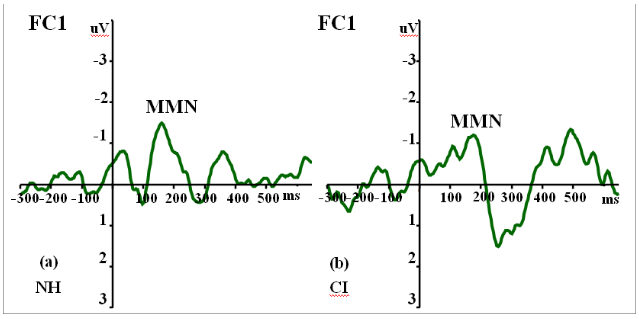

Figure 4: *Grand Average of the difference wave (/i/*$_{dev}$*– /u/*$_{std}$*).*

Table 4. *Mean (±SD) peak latencies and amplitudes of MMN.*

MMN	Latency (ms)		Amplitude (µV)	
V_1-V_2	NH	CI	NH	CI
$/u/_{std}$ - $/i/_{dev}$	199±38	194±30	-1.00±0.7	-0.95±0.8

Children with longer CI use sometimes discriminate high vowels with a higher accuracy (*r*=.300, *p*=.016; Figure 5a) and a shorter processing time (*r*=-.255, *p*=.042; Figure 5b).

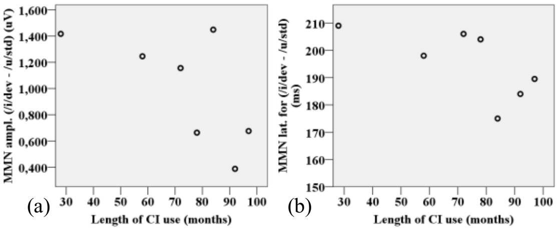

Figure 5: *CI use* and *(a) MMN amplitude or (b) latency.*

MMN presents a shorter latency (*t*(50)=2.130, *p*=.038) and a larger amplitude (*t*(54)=2.311, *p*=.025) in the left hemisphere in NH children (Table 5), but not in CI children (*t*(62)=1.257, *p*=.213 for latency; *t*(62)=-.833, *p*=.408 for amplitude).

Table 5. *Scalp distribution of MMN (mean values).*

MMN	Left hemisphere		Right hemisphere	
	NH	CI	NH	CI
Lat. (ms)	188	199	210	189
Ampl. (µV)	-1.22	-1.04	-0.78	-0.87

4. Discussion

Given the intrinsic perceptive salience of high vowels, these are easily processed by early-implanted children, both behaviorally (3.1) and neurophysiologically (3.2) [13]. At the behavioral level, CI children present vowel identification and discrimination performance comparable to NH children.

A more fine-grained picture for CI children emerge when we look at CAEP data. With respect to vowel detection, early-implanted children do not need additional time to detect /u/ and /i/ compared to NH children, as indicated by P1 latencies. However, early-implanted children systematically rely on a lower strength as compared to NH children, as shown by the smaller P1 amplitudes and as found in previous studies [11, 13]. Children benefitting from longer CI use usually detect /u/ and /i/ more precisely compared to the other CI children. As for vowel identification, early-implanted children are in some cases ($/u/_{std}$) slower than NH children, as indicated by the prolonged N1 latencies. The shorter latency of N1 evoked by $/i/_{dev}$ in CI compared to NH children, instead, does not imply a faster vowel identification by CI children, since electrical stimulation may reach the auditory cortex of CI users faster than natural stimulation reaches the auditory cortex of NH users [35]. Vowel identification is less strong in CI compared to NH children, as can be inferred from the smaller N1 amplitudes. Few CAEP studies have found N1 in successfully-implanted children [11 vs.12, 37-38]. The N1 presence in all the CI children analyzed here indicates maturation of superficial cortical layers as well as efficient intra- and inter-hemispheric communication [37-38]. Interestingly, children with longer CI use sometimes identify high vowels more precisely compared to the other CI children. However, late-implanted children may present even higher N1 amplitudes as compared to early-implanted ones. For what concerns discrimination of the phonetic contrast $/u/_{std}$–$/i/_{dev}$, early-implanted children turn out to be neither slower nor less accurate than NH children, as proved by MMN latencies and amplitudes. MMN evoked by isolated speech sounds is not systematically left-lateralized in normal, right-handed individuals [7-8, 27]. MMN appears left-lateralized in the NH children but not in the CI children examined here. The absent lateralization of the MMN is not new in CI users [12, 35-38] and cannot be interpreted with CI location here (2.1). Rather, it may suggest that, although CI stimulation allows deaf children to detect and identify /i/ and /u/, the maturation of the auditory cognitive processes related to high vowels processing is not complete so far. Interestingly, children with longer CI use may discriminate native high vowels differing by place of articulation with a higher accuracy, as indexed by larger MMN amplitudes, and a shorter processing time, as indicated by shorter MMN latencies.

We conclude that CI stimulation allowed auditory pathway maturation and detection, categorization, and discrimination of high vowels differing by place of articulation in early successfully-implanted children. The formation of long-term memory representations of phonemes in the child's auditory cortex can only be driven by speech input [39]. Nevertheless, it appears that, despite auditory deprivation, regular CI use and linguistic training allow early-implanted children to develop long-term memory representations for high vowels, indicating that CI children have learned /i/ and /u/. The lower strength exhibited by CI users in high vowel detection and identification at the neurophysiological level may be attributed to many factors. In general, the auditory sensation experienced by children with unilateral CIs is close to the one experienced by children with a mild hearing loss. Specifically, the acoustically/phonetically relevant information extracted from speech and delivered by CIs is less precise in terms of acoustic cues (i.e. the F2 values, which cue place of articulation), spectral shape, pitch, and loudness by comparison with the finer transduction taking place in the human ear, thus leading to incomplete perception of the stimulus features in CI users [40-42] and to compressed vowel spaces in production [43-44]. Furthermore, during initial auditory deprivation, some of the dormant auditory areas may have been re-assigned to the vision modality [3-5]. The incoming auditory stimuli may then be processed by a subset of the areas initially allocated to auditory processing, which could further lower the processing accuracy (i.e. smaller CAEP amplitudes) in CI children.

5. Conclusion

Given the intrinsic perceptive salience of high vowels, these are easily processed by CI children. At the behavioral level, CI children are not less accurate than NH children in vowel identification and discrimination. At the neurophysiologic level, CI children are not slower than NH children in vowel detection. CI children are also neither slower nor less accurate than NH children in vowel discrimination. However, CI children are slower in vowel identification and less accurate in vowel detection and identification compared to NH children. Length of CI use influences neurophysiologic vowel processing performance, whereas age at surgery only minimally affects this parameter.

6. References

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