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ORIGINAL ARTICLE

Speech perception results in children implanted with Clarion® devices: Hi-Resolution™ and Standard Resolution modes

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Abstract

Conclusions. Formal testing showed that HiRes users seem to make significant use of acoustic information. Furthermore, from observations reported by experienced care-givers, for example, family, teachers and speech therapists, these children learn a lot from their surrounding environment. Incidental learning, which takes place when acquiring skills or knowledge through naturally occurring events, is a key become available to these deaf paediatric cochlear implant recipients. *Objective*. To compare speech perception skills in children with a Clarion® cochlear implant using different speech coding strategies, such as continuous interleaved sampling (CIS), simultaneous analogue stimulation (SAS) and Hi-Resolution (HiRes)™. *Material and methods*. The study population comprised 40 children, 17 implanted with a Clarion Hi-Focus 1.2 and 23 with a Clarion CII. All children were pre-lingually deaf and differed in terms of age and cause of deafness. All children had undergone a trial (minimum 6 months) with hearing aids before implantation. Children implanted with a Clarion 1.2 were either CIS or SAS users [Standard Resolution mode (SRM) group]; children implanted with a Clarion CII were Hi-Resolution users [Hi-Resolution mode (HRM) group]. Findings were assessed according to Erber's hierarchical model (detection, discrimination, identification, recognition and comprehension), making use of a battery of speech perception tests calibrated to the age of the child. Further information concerning use of the implant in everyday situations was obtained by means of the Meaningful Auditory Integration Scale (MAIS) questionnaire, which was administered to the parents. Tests were carried out prior to each fitting session, at switch-on and then at 3, 6, 9 and 12 months. Findings at pre-implantation and at 12 months follow-up were collected for both the SRM and HRM groups. Speech perception results were analysed for the SRM and HRM groups, independent of age at implantation, for five subgroups of children according to the paediatric test battery in use and for two subgroups of children, one $<$ and one $>$5 years of age. *Results*. Clarion-implanted children using the Hi-Resolution strategy can develop better speech perception skills at 12 months post-implantation compared to children fitted with the SAS or CIS strategy. SAS or CIS users implanted before the age of 5 years tend to achieve better results at 1 year follow-up than children implanted later. In contrast, in Hi-Resolution users, a trend towards better results for recognition and comprehension tasks was observed in children implanted after 5 years of age.

Keywords: *Children, cochlear implant, continuous interleaved sampling, family, Hi-Resolution, Meaningful Auditory Integration Scale, simultaneous analogue stimulation, speech coding strategies, speech perception*

Introduction

The cochlear implant has had positive effects on the achievements of young profoundly deaf children; however, results vary considerably in relation to subjective and implantation variables [1,2]. The primary measure of benefit from cochlear implantation is the ability to perceive speech and it has been shown in many studies [3,4] that a wide range of speech perception abilities can be achieved by implanted children. O'Donoghue et al. [5], in a study of 40 implanted children, found that young age at intervention, as well as oral communication mode, were the most important known determinants of the development of speech perception in children. In another study [6] it was revealed that, concerning measures of speech perception and intelligibility at 3, 4 and 5 years after implantation, children using oral communication outperformed those using sign communication.

Numerous characteristics may affect the performance of a child with a cochlear implant. There is general consensus that the earlier in life implantation

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is performed, the better the development of speech perception [7]. Geers et al. [8] investigated factors contributing to auditory, speech, language and reading outcomes after 4–6 years of cochlear implant use in children with pre-lingual deafness. Characteristics of the child (age, onset of deafness, age at implantation, non-verbal IQ) and the family (size, level of education of the parents) accounted for 18% of the variance in outcome, implant characteristics (number of active electrodes, duration of strategy in use, dynamic range and loudness growth) for 24% and educational factors (primarily communication mode) for 12%. The evolution of speech perception in implanted children depends on subjective and audiological characteristics. The main subjective characteristics are good non-verbal intelligence, family characteristics and communication mode. The main audiological characteristics are age at implantation, use of hearing aids, length of acoustic deprivation and the speech coding strategy in use. The technological evolution of cochlear implants has led to the development of new speech coding strategies and, therefore, to greater flexibility in fitting implants to patients. Many studies performed in adults [9] and children [10,11] have attempted to focus on both intra- and inter-individual speech perception differences resulting from different strategies in use with the same implant or with different types of implant. Oral language acquisition depends, to a large extent, on what the deaf child can actually hear. Therefore, improved speech processing strategies can probably provide better language enhancement.

The aim of this study was to evaluate the effect of the Hi-Resolution™ (HiRes) mode, a new coding strategy, on speech perception skills. As improvement depends on the quality of the auditory input, assessment of speech perception was viewed as the most direct way to evaluate the benefit derived from these strategies, independently of other related variables. In this investigation, the speech perception skills of children implanted with Clarion® devices were examined at 12 months follow-up. This would appear to be the first report on the results obtained with the HiRes mode in children.

Material and methods

Implant variables

The study population comprised children implanted with a Clarion® (Advanced Bionics, Sylmar, CA) device. Since the introduction of the Clarion® device, the implantable electronic components (i.e. receiver, stimulating electrodes) and speech processor have been modified, over time, to meet the needs of patients. Modification of the electrode carrier has led to the introduction of various stimulating strategies, as detailed below.

The continuous interleaved sampling (CIS) strategy is a digital non-simultaneous strategy that can be applied on all Clarion® devices. It was the main strategy used in both adult and paediatric populations until 2001. It is characterized by a series of interleaved digital pulses with a 75-μs pulse width (pw) which rapidly stimulate consecutive electrodes in the array. The CIS strategy covers the frequency band 350–6800 Hz. With Clarion® 1.2 and Clarion® Hi-Focus a maximum of 8 channels are available, and the filter bands for each channel are spaced on a logarithmic basis between 350 and 5500 Hz. Each channel has an update rate of 833 pulses/s (pps) [12].

The simultaneous analogue stimulation (SAS) strategy was introduced with the Clarion® Hi-Focus and is characterized by analogue processing of the signal. The frequency range is 250–6800 Hz and a maximum of eight channels are available. Each of the filter outputs is compressed to fit into the available electric dynamic range, favouring temporal information at the expense of spectral information. In fact, the update rate is ≈13 000 pps. Further, simultaneous stimulation may induce some field interactions [12].

The HiRes strategy was first introduced into clinical trials in 2001, when we became involved in the paediatric pilot study. HiRes is a digital stimulation strategy which uses interleaved pulses, presented one channel at a time. The pw can be widely varied, starting from 11 μs, and a maximum of 16 channels are available. At a pw level of 11 μs, in sequence mode, the stimulation rate is 2900 pps channel. This faster stimulation of the nerve is thought to induce a more stochastic and, therefore natural, response of the nerve, which should broaden the electric dynamic range [13]. With the use of this fast digital stimulation it is possible to maintain good spectral information, as with the CIS strategy, whilst, at the same time, providing good temporal information.

Fitting procedures

The HiRes experiment fitting bench was provided in May 2002. All children were fitted according to the following variables: 12 active channels (2nd, 4th, 6th and 8th channels switched off); pw = 21 μs; pulse rate = 2017 Hz/channel. The fitting parameters were those used in the initial phase of the HiRes study in adults, which had been identified as the overall parameters preferred. Determination of M and T levels was done, regularly, at switch-on/switch-over (s.on/s.over) and at 1, 3, 6, 9 and 12 months, based on the direct response (older children) or the behavioural reaction to sounds (small children). Initially, fitting was performed on 13 children using the first experimental test bench (Bionic Ear Programming System; Advanced Bionics), where M and T levels were determined using a tone burst. It follows that, especially in very young children, determination of thresholds was done for three to four channels only (basal, medial and apical) to make maximum use of the child's limited attention span. Afterwards, nine children were fitted with the new Sound Wave™ software (version 1.0.671; Advanced Bionics), which is equipped with both a tone burst and a speech burst (test tone delivered to a group of four channels at a time), using the same variables described above in order to reduce bias in the study group.

Children using CIS and SAS strategy were fitted with SCLIN 2000 software (version 1.8; Advanced Bionics). Determination of M and T levels was done, regularly, at s.on and at 1, 3, 6, 9, 12, 18, 24 and 36 months, based on the direct response (older children) or the behavioural reaction to sounds (small children). Fitting variables for the CIS strategy were 75 μs pw, 8 active electrodes, monopolar coupling mode and mean frequency of stimulation 813 Hz/channel. Fitting variables for the SAS strategy were 7 electrodes, bipolar coupling mode and stimulation frequency 13 000 Hz/channel. M and T levels were determined using a tone burst. It follows that, especially in very young children, thresholds were determined on only three channels (basal, medial and apical) to make maximum use of the child's limited attention span.

Study groups

HiRes mode group. A total of 23 of the profoundly deaf children implanted with a Clarion CII at the ENT Department of the University "La Sapienza" between December 2001 and May 2003 were enrolled in the HiRes mode (HRM) group. Bilateral profound sensorineural hearing loss was confirmed with preoperative behavioural audiograms and/or frequency-specific auditory-evoked potentials. All children were pre-lingually deaf and differed considerably in terms of age (mean age at implantation 5.5 years; range 2–13 years) and cause of deafness (hereditary, $n=2$; connexin 26, $n=2$; bacterial meningitis, $n=2$; hypoxia at birth, $n=1$; cytomegalovirus infection, $n=2$; rubella, $n=1$; unknown, $n=13$). The mean period of acoustic deprivation was 18.9 months (SD 14.2 months). All children underwent a trial with hearing aids for a minimum of 6 months before implantation. The mean duration of hearing aid use was 46.6 months (SD 40.04 months). Thereafter, 11 children (47.8%) were implanted below the age of 5 years and 12 (52.2%) between the ages of 5.1 and 13 years. All children received the Clarion® CII implant, three being implanted bilaterally. A behind-the-ear speech processor was used in 8 children, while 14 received a body-worn speech processor (Platinum Series). All children had undergone oral rehabilitation. Two children (brothers) are bilingual: the parents are deaf and mute and Italian Sign Language is generally used at home. At the time of the study, all children had completed the 12-month follow-up period in HRM: 16 children were switched on in HRM and 7 (s.over group) were formerly using either CIS ($n=2$) or SAS ($n=5$). The mean duration of CIS or SAS use was 6.5 months.

Standard resolution mode group. A group of 17 profoundly deaf children implanted at the ENT Department of the University "La Sapienza" between October 1999 and November 2001 were included in the SRM group. Profound bilateral sensorineural hearing loss was confirmed with preoperative behavioural audiograms and/or frequency-specific auditory-evoked potentials. All children were pre-lingually deaf and differed in terms of age (mean age at implantation 5.1 years; range 2–11.5 years) and cause of deafness (connexin 26, $n=2$; bacterial meningitis, $n=1$; rubella, $n=2$; Waardenburg syndrome, $n=1$; cytomegalovirus infection, $n=2$; incomplete cochlear partition, $n=1$; unknown, $n=8$). The mean period of acoustic deprivation was 15.7 months (SD 6.9 months). All children underwent a trial with hearing aids for a minimum of 6 months before implantation. The mean duration of hearing aid use was 42.9 months (SD 44.7 months). 9 children (53%) were implanted below the age of 5 years and 8 between the ages of 5.1 and 13 years (47%). All children were implanted with the Clarion Hi-Focus® 1.2; 5 children were CIS users and 12 were SAS users and the mean duration of use was 38 months. All children at s.on were provided with a body-worn speech processor (S and Platinum Series). All children had undergone oral rehabilitation. Two children were bilingual: Slav and Philippine, respectively being the first languages used at home.

Paediatric test battery

The full paediatric test battery employed in the present investigation has been developed using the most commonly used test in Italy in order to adopt common criteria, and is based on assessment of the following:

- Speech perception, which, according to Erber's hierarchical model [14], can be classified as detection, discrimination, identification, recognition and comprehension.
- Language development, which includes: linguistic competence according to the categories of Dyar [15], where communicative competence is broken down into preverbal, transitional or functional; oral and written comprehension and production. Communicative competence considers mode (oral/aural, visual/gestural), style (passive, interesting or demanding) and extra verbal cues (when the child makes use of gaze, crying, smiling, pointing and referential gestures).
- Further information concerning use of the implant in everyday situations was obtained by administering the Meaningful Auditory Integration Scale (MAIS) [16] and Meaningful Use of Speech Scale (MUSS) [17] questionnaires to parents.

In the present report, only performance on speech perception tests and the results of the MAIS questionnaire are described.

This speech perception battery (Table I) consists of tests that were either developed by Italian audiological centres or are Italian adaptations of frequently used international English language tests. The use of acoustic feedback was assessed according to different age groups (I, 2–3.5 years; II, 3.6–5 years; III, 5.1–8 years; IV, 8.1–11 years; V, 11.1–14 years; VI, 14.1–18 years) and therefore all tests were carried out for each age group and for individual levels of listening skill. Both open- and closed-set conditions were used. In the closed-set condition, the therapist presented an item and the child had to point to an object or picture. In the open-set condition, depending on the test and the child's age, the child had to either repeat the item or use it to build up actions. The distribution of children in each age group was as follows: HRM group: I = 6 (3 bilaterally implanted), II = 5, III = 6, IV = 3, V = 3; SRM group: I = 6, II = 3, III = 3, IV = 3, V = 2.

The tests administered in each age group were as follows:

1. Listening Progress Profile (LIP) [18]. This involves detection and identification of environmental sounds, musical instruments and the five Ling sounds. Ling sounds were also used in our test battery to evaluate recognition in age group I [19].
2. Test Abilità Percettive [Perceptive Ability Test (TAP)]. This test involves detection of phonemes, identification of words and comprehension of sentences. Items are presented in randomized order. This test is used in children aged >4 years, and is an Italian adaptation of the Glendonald Auditory Screening Procedure (GASP) [20].
3. Test Identificazione Parole Infantili [Children's Word Identification Test (TIPI 1,2)]. This test, an Italian adaptation of the Northwestern University Children Perception of Speech (NU-CHIPS) [21] used in children >4 years, involves identification of phonetically balanced bisyllabic words.
4. Bi-Trochee-Polysyllabic (BTP) word test. This test involves the discrimination and identification of words for children aged 2–5 years old. Six figures or objects are presented according to the child's age, and the presentation is repeated three times [22].
5. Test Abilità Uditive Varese [Varese Auditory Skills Test (TAUV)] [23]. This is a non-standardized test, widely used in Italian cochlear implant centres, that explores all speech perception skills. From this battery of tests, we used one that evaluates identification of words in children >8 years, the test comprising 20 words varying in length and stress.
6. Protocollo Comune (Common Protocol) [24]. This is a test battery developed by different Italian audiological centres to evaluate all auditory skills in all age groups (from 1 year to adult). From this battery, we used only those tests aimed at evaluating discrimination identification, recognition and comprehension in children aged >5 years.
7. Speech audiometry. Phonetically balanced bisyllabic words, in closed- and open-set, were used in children aged >6 years [25].

As there are no standardized tests in the Italian language for the evaluation of recognition and comprehension in children belonging to age group I, at our Centre we developed two tests on an ad-hoc basis, in the process of standardization and publication. Recognition [Word Recognition through Indication (PIRP)] is evaluated by presenting six words belonging to the child's vocabulary, as gathered from parents and speech therapists, and six words from the BTP test. The words correspond to 12 objects; during evaluation, 6 other objects are present as distractors. The child is asked to repeat the word or to select, by pointing, the required word/object (modified open-set). Comprehension [Comprehension of Sentences through Action Responses

Table I. The paediatric test battery used.

Age group	Detection	Discrimination	Identification	Recognition	Comprehension
I	Free-field audiometry; LIP (Ling and environmental sounds)	LIP	LIP (Ling and environmental sounds); BTP (6 × 3 repetitions)	Ling sounds; word/objects[a] (12 items)	Sentences comprehension (with action responses) (10)
II	Audiometry; LIP	LIP; BTP (6 × 3 repetitions)	LIP (Ling and environmental sounds); BTP (6 × 3 repetitions); TAP (2nd subtest)	Bisyllabic words (10); TAP (1st subtest)	TAP (3rd subtest) (10)
III	Audiometry; TAP (1st subtest)	TAP (2nd subtest)	TAP (2nd subtest); TIPI 1/2; Speech audiometry (closed-set)	TAP (1st subtest); Bisyllabic words (10); Common Protocol: Sentences (10); Speech audiometry (open-set)	TAP (3rd subtest) (10)
IV	Audiometry; TAP (1st subtest)	Common Protocol: Intonation (10 sentences) Duration (10 words); TAUV (20 words)	TAUV (20 words); Common Protocol: Vowels (10) Consonants (20); Speech audiometry (closed-set)	TAP (1st subtest); Bisyllabic words (10); Common Protocol: Sentences (10); Speech audiometry (open-set)	TAP (3rd subtest) (10); Common Protocol: Questions (10)
V	Audiometry; TAP (1st subtest)	Common Protocol: Intonation (10 sentences) Duration (10 words); TAUV (20 words)	TAUV (20 words) Common Protocol: Vowels (10) Consonants (20); Speech audiometry (closed-set)	TAP (1st subtest); Bisyllabic words (10); Common Protocol: Sentences (10); Speech audiometry (open-set)	TAP (3rd subtest) (10); Common Protocol: Questions (10)
VI	Audiometry; TAP (1st subtest)	Common Protocol: Intonation (20 sentences) Duration (20 words); TAUV (20 words)	TAUV (20 words); Common Protocol: Vowels (10) Consonants (20); Speech audiometry (closed-set)	TAP (1st subtest); Bisyllabic words (10); Common Protocol: Sentences (10); Speech audiometry (open-set)	TAP (3rd subtest) (10); Common Protocol: Questions (10)

[a]Word recognition, pointing to objects.

(PACF)] is evaluated using the 12 previously described words/objects in addition to a further 12, which allow the child to build up actions; the child is asked to act upon 10 of the speech therapist's requests (to give, to point and to do) (modified open-set). The MAIS questionnaire was administered to parents to evaluate children's meaningful use of auditory skills in everyday living situations.

Tests were carried out prior to the main fitting sessions (at pre-implantation and at 1, 3, 6, 9, 12, 18, 24 and 36 months), even though some children also required intermediate sessions.

The results (mean ± SD) of the speech perception tests were analysed as follows. (i) Considering the two groups of children, HRM and SRM, independently of age at implant. Differences in test scores were also analysed using the unpaired t-test. $p \leq 0.05$ was considered statistically significant. (ii) Considering five subgroups of children, according to the paediatric test battery used (Table I). In this case the results represent a trend, and so no statistical analysis can be performed. (iii) Considering two subgroups of children: one <5 and one >5 years of age. Differences in test scores were also analysed using the unpaired t-test. $p \leq 0.05$ was considered statistically significant.

Results

Speech perception skills

HRM group. The number of control sessions needed to reach optimal regulation varied according to various factors, such as the age of the child and previous listening experience. Furthermore, we observed a quick adjustment to M levels in both the s.on and s.over groups. Using the experimental test bench, both children coming from other strategies and children at their first s.on were monitored at least four times in 3 months and often 1–2 weeks after s.on/s.over due to insufficient sensation of loudness.

With the Sound Wave software and the use of speech bursts, the number of fitting sessions was decreased. An insufficient sensation of loudness (verified during both free-field audiometry and detection tests for vowels and consonants) has often been found for basal channels. This result might be related either to anatomical factors (increased distance of the electrodes from the modiolus compared to more apical channels) or to the fact that young children, despite good hearing aid use, do not necessarily have experience with high-frequency stimuli.

The pre-implantation level for the group as a whole was as follows: detection, 52.15% (SD 42.6%); discrimination, 25.1% (SD 28.7%); identification, 20.1% (SD 24%); recognition, 3.1% (SD 7.3%); comprehension, 1% (SD 4.6%).

Independent of age, children in the s.over group needed time to adjust to a new listening experience (1 month on average), during which we noted a temporary decline in performance. Nevertheless, due to their previous listening experience, results were better than those for s.on children at the initial fitting of HiRes for all speech perception skills (mean difference between s.over and s.on children: detection, 37.8%; discrimination, 28%; identification, 10.9%; recognition, 10%; comprehension, 3.3%). After 12 months of HiRes use, we found no significant difference in performance between the 2 groups (mean difference between s.over and s.on children: detection, 1.5%; discrimination, 11.9%; identification, 2.9%; recognition, 2.8%; comprehension, 3.4%) (Figure 1). For this reason, the findings at 12 months for the s.over and s.on children will be discussed as a single group.

SRM group. The number of control sessions needed to reach optimal regulation was, on average, 2 within the first month, after which children underwent fittings at 3, 6, 9 and 12 months postoperatively and thereafter every year. Fitting sessions were, on average, longer for CIS users because both the threshold and the maximum comfortable level (MCL) were measured. In contrast, in SAS users we only determined the MCL.

The pre-implantation level for the group as a whole was as follows: detection, 41.9% (SD 34.1%); discrimination, 20.9% (SD 22.7%); identification, 14.9% (SD 20.8%); recognition, 2.7% (SD 6.1%); comprehension, 2.3% (SD 8.3%). No significant difference was observed between CIS and SAS users.

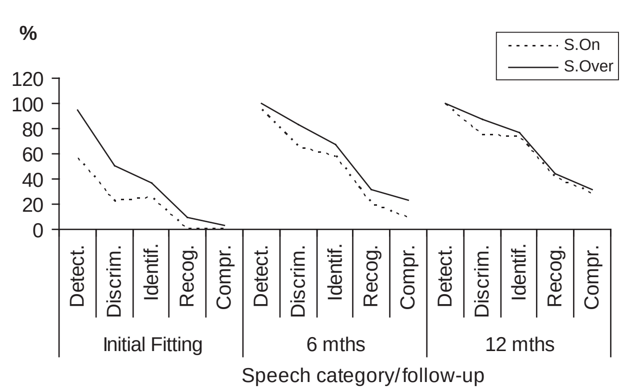

Figure 1. Results from the HRM group at initial fitting and at 6- and 12-month follow-up. Detect. = detection; Discrim. = discrimination; Identif. = identification; Recog. = recognition; Compr. = comprehension.

Results at 12-month follow-up were as follows: CIS users: detection, 96% (SD 4.6%); discrimination, 57.5% (SD 34%); identification, 52% (SD 34.3%); recognition, 20% (SD 11.5%); comprehension, 5% (SD 10%); SAS users: detection, 100% (SD 0%); discrimination, 61.7% (SD 27.5%); identification, 59.9% (SD 32.3%); recognition, 27.3% (SD 20.6%); comprehension, 5.4% (SD 12.1%). As no significant difference was found between the two groups, data were pooled for statistical analysis and comparison with the HRM group.

HRM vs SRM group

Detection. No significant differences were found between HRM and SRM users when data were analysed according to age group (Figure 2) (HRM SD: I = 6.7%, II = 0%, III = 0%, IV = 0%, V = 0%; SRM SD: I = 14.1%, II = 0%, III = 0%, IV = 0%, V = 0%). In the groups of children implanted before and after the age of 5 years, no substantial difference in performance was observed between SRM and HRM users (Figure 3) and the *t*-test was not significant. In HRM bilaterally implanted children the mean result was 100% (SD 0%). When the data were analysed as the mean values for all age groups (Figure 4), both HRM and SRM users achieved almost 100%, with greater variability in the SRM group (HRM SD 5.7%; SRM SD 10.4%); the *t*-test was not significant ($p = 0.42$).

Discrimination. The results varied widely between the different age groups (Figure 2). The SD was greater for SRM users (mean SD = 26.2%; I = 7.1%, II = 24.4%, III = 10.6%, IV = 35.3%, V = 10.4%) compared to HRM users (mean SD = 20.5%; I = 25.4%, II = 24.4%, III = 10.6%, IV = 35.3%, V = 10.4%). Performance was better in HRM users, both in the children implanted before (mean difference between HRM and SRM users 12.7%) and after the age of 5 years (mean difference between HRM and SRM users 24.2%) (Figure 3). The mean result for HRM bilaterally implanted children was 87% (SD 18.3%). When the data were analysed as mean values for all age groups (Figure 4) better performance was detected in HRM users (discrimination 80.8%) compared to SRM users (discrimination 60.6%) and the *t*-test was significant ($p = 0.04$).

Identification. There was greater variability of results according to age group for the SRM compared to the HRM users. Results were better in HRM children in all cases (Figure 2), with the exception of those belonging to age group V. Performance was better in HRM users, both in the children implanted before (mean difference between HRM and SRM users 15.5%; *t*-test not significant) and after (mean difference between HRM and SRM users 18.1%; *t*-test not significant) the age of 5 years (Figure 3). The mean result for HRM bilaterally implanted children was 83.3% (SD 24.7%). When the data were analysed as mean values for all age groups (Figure 4), HRM users showed better results (72.3%) than SRM users (57.8%), with a greater variability in SRM users [HRM SD 24.7%; SRM SD 29.1%; *t*-test not significant ($p = 0.09$)].

Recognition. Considerable variability was observed in the results according to age group in both HRM and SRM users (SRM SD: I = 24.3%, II = 17%,

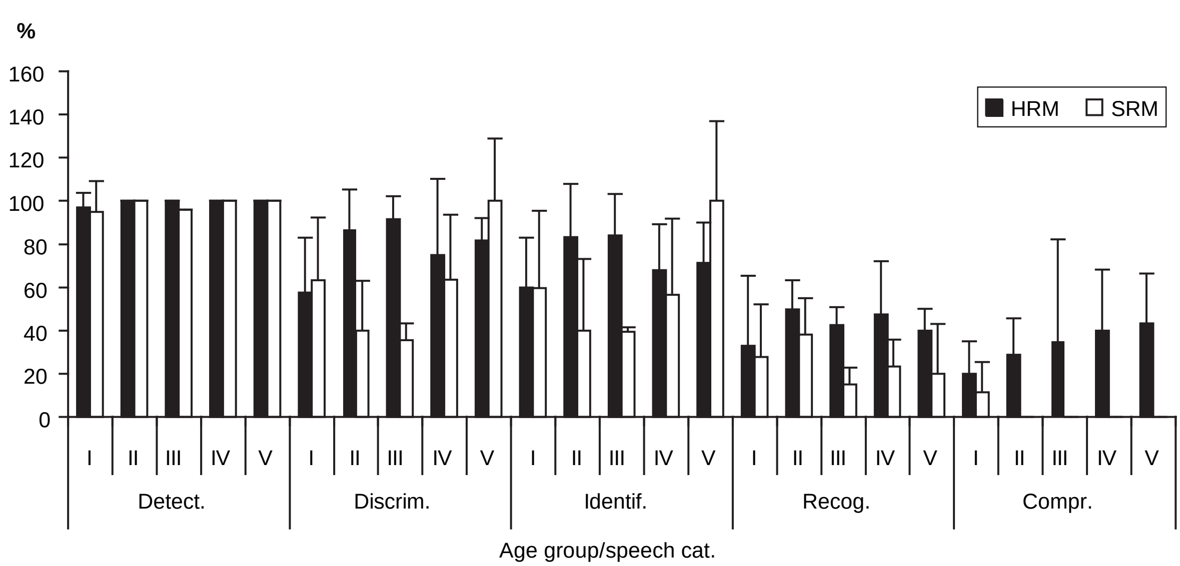

Figure 2. Results of speech perception skills for the HRM and SRM groups at 12-month follow-up. For abbreviations see Figure 1.

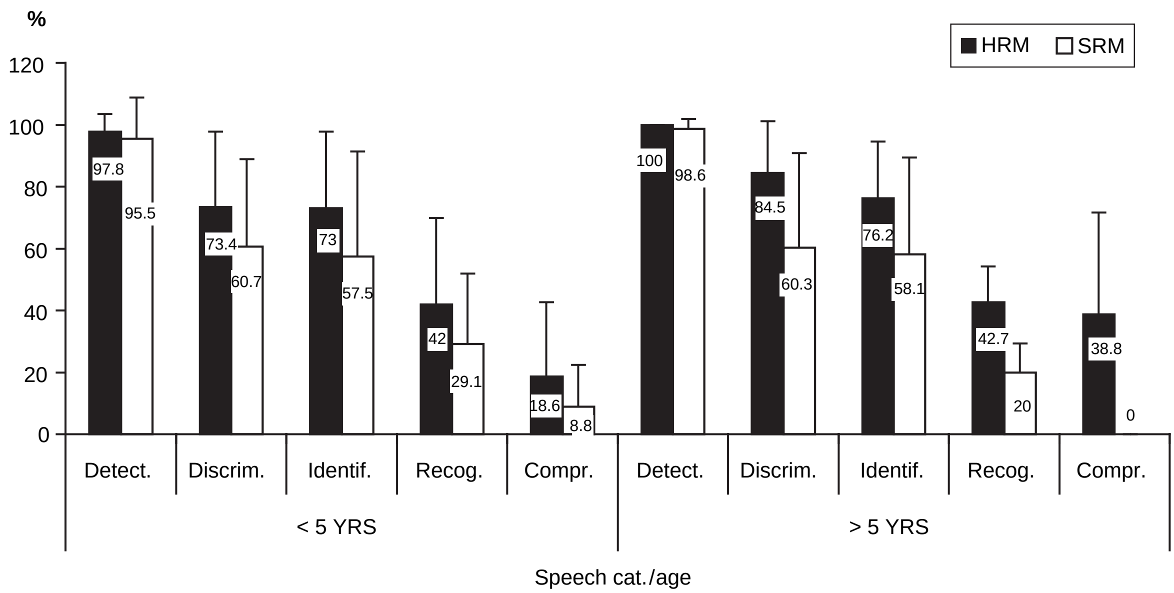

Figure 3. Mean results of speech perception skills in children implanted before and after the age of 5 years for the HRM and SRM groups at 12-month follow-up. For abbreviations see Figure 1.

III = 7.7%, IV = 12%, V = 23%; HRM SD: I = 32.3%, II = 13.5%, III = 8.3%, IV = 24.7%, V = 10%); however, the results were always better in HRM users (Figure 2). Performance was better in HRM users, both in the children implanted before (mean difference between HRM and SRM users 12.9%; *t*-test not significant) and after [mean difference between HRM and SRM users 22.7%; *t*-test significant ($p = 0.002$)] the age of 5 years (Figure 3). The mean result for HRM bilaterally implanted children was 49.7% (SD 13.5%). When the data were analysed as mean values for all age groups (Figure 3), values were higher for HRM users (42%; SD 27.8%) compared to SRM users (25.2%; SD 16.7%); the *t*-test was significant ($p = 0.01$).

Comprehension. Comprehension was achieved in a few children in both the HRM and SRM groups. In age group I, only 3/17 SRM users (20%, 30% and 30%, respectively; mean score 13.3%; SD 14.1%) and 3/23 HRM users (20%, 30% and 50%, respectively; mean score 16.7%; SD 15%) achieved comprehension. In the other age groups, HRM users achieved better results (II = 28.9%, SD = 16.7%; III = 47.3%, SD = 35%; IV = 40%, SD = 28.3%;

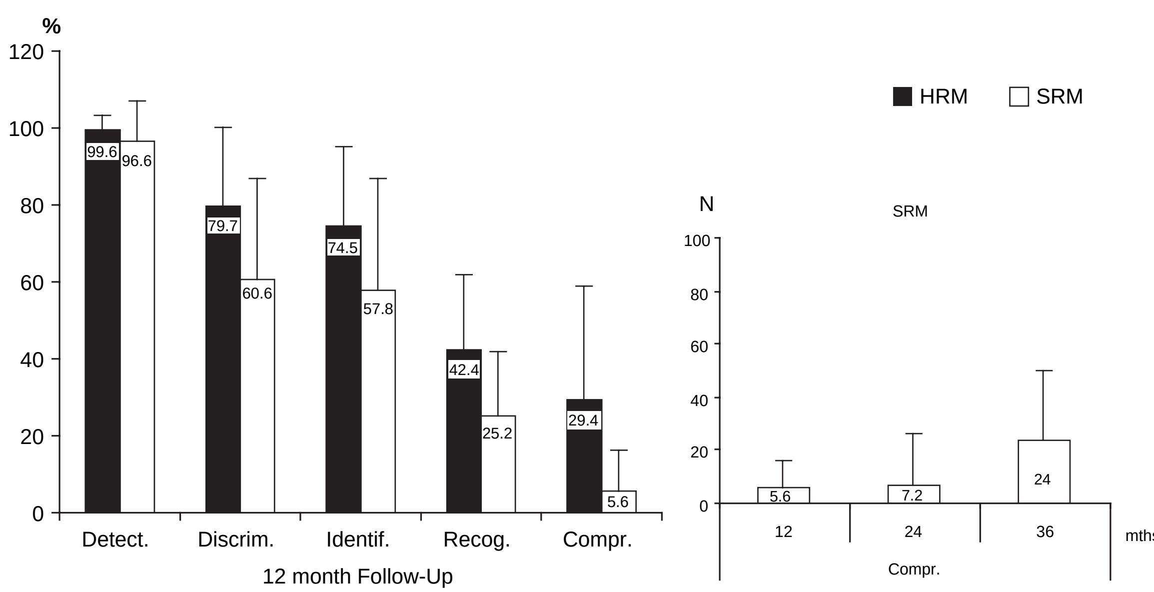

Figure 4. Mean results of speech perception skills for the HRM and SRM groups at 12-month follow-up. In the insert on the right: SRM results at 12, 24 and 36 month follow-up. For abbreviations see Figure 1.

V = 43.3%, SD = 23%) compared to SRM users (0% in all age groups) (Figure 2). Performance was better in HRM users, both in the children implanted before (mean difference between HRM and SRM users 9.8%; t-test not significant) and after the age of 5 years [mean difference between HRM and SRM users 38.8%; t-test significant ($p = 0.01$)] (Figure 3). Only one bilaterally implanted child achieved comprehension (50%). Mean values for all age groups were higher for HRM (29.4%; SD 29.5%) compared to SRM users (5.6%; SD 10.6%). Indeed, SRM users achieved comparable results only at 36 months (24%; SD 25.9%) (Figure 4, inset). The t-test was significant ($p = 0.007$).

MAIS questionnaire results. The results showed a trend towards better performance in HiRes users, being more evident in children in age groups II, III and IV (Figure 5). Performance was better in HRM users, both in children implanted before (HRM 85%, SD 13.5%; SRM 68.05%, SD 18.1%) and after the age of 5 years (HRM 83.5%, SD 11.1%; SRM 70.7%, SD 11.3%). The t-test was significant in both age groups (<5 years: $p = 0.05$; >5 years: $p = 0.03$). The mean results for HRM and SRM users were 85.2% and 69.2%, respectively, with SDs of 11.7% and 15.3%, respectively. The t-test was significant ($p = 0.003$).

Discussion

The analysis of speech development in children is a challenging task due to the numerous variables that can affect the results. For example, speech perception tasks may be too difficult for very young children to understand and often their vocabulary is insufficient to perform all the tests. In this study much effort has been made to develop and assess a battery of speech tests that are, first of all, age-appropriate and, at the same time, offer results comparable with those obtained at other international Centres. For age group I, which is the most difficult to assess, two tests were developed that take into account the child's vocabulary and ability to build up actions as a response to questions rather than answering them.

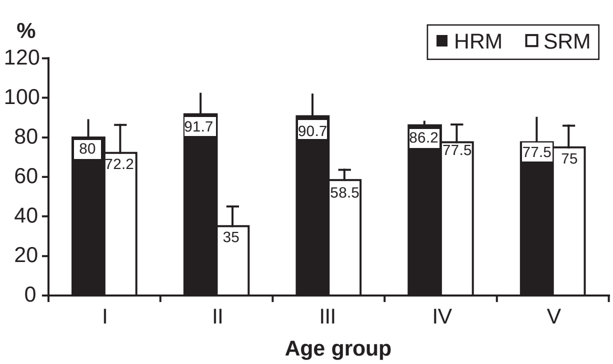

Figure 5. Mean results of administering the MAIS questionnaire to parents in the HRM and SRM groups.

The results of this study revealed that children implanted with a Clarion® device who used the HiRes strategy can develop better speech perception skills at 12 months post-implantation than those fitted with the SAS or CIS strategies.

The children in the HRM and SRM groups were not homogeneous concerning age at implantation and distribution between age groups. Nevertheless, mean age at implantation, the duration of pre-implantation acoustic deprivation, use of hearing aids and aided speech perception results did not differ significantly between HRM and SRM users. The average results of HRM users, in terms of all speech perception skills, were better in all the data analyses, and the t-test revealed statistically significant differences, especially in terms of recognition and comprehension. Indeed, in the HRM group, children who were directly switched on in the HiRes strategy showed a more rapid growth rate compared to those who had formerly used the SRM strategy. HRM users showed a trend towards faster improvement in listening skills compared to SRM users, especially for the more difficult tasks, such as comprehension. The difference in age distributions and the small numbers of children in each group do not allow any conclusions to be drawn in this respect. Nonetheless, the results of the MAIS questionnaire confirmed the trend shown by the battery of tests used for speech perception.

Differences in speech perception results may, therefore, be related to implant variables (i.e. the number and shape of electrodes) as well as to the speech coding strategy in use. Young et al. [11] compared closed- and open-set speech perception in two groups of children implanted before the age of 5 years, one with a Nucleus® device who used the spectral peak coding (SPEAK) strategy and the other with Clarion® devices who used the CIS strategy. At 12 months post-implantation, all speech perception scores were better for Clarion® users. Pasanisi et al. [10] reported a difference in speech perception benefits in children implanted with a Nucleus® CI24M device who used the advanced combination encoders (ACE) and SPEAK strategies, reaching the conclusion that the ACE strategy improves open-set speech recognition scores in children implanted both before and after the age of 6 years.

Analysis of data for word recognition and sentence comprehension in open set in children implanted before and after the age of 5 years gave more unexpected results. As already reported by others

[26–28], children implanted before the age of 5 years tend to achieve better results, at 1-year follow-up, than those implanted later. In contrast, children implanted after the age of 5 years using the HiRes mode show a trend towards better results for both recognition and comprehension. This result may depend on the fact that recognition and comprehension tend to mature at a later age [29]. In this respect the influence of maturing of speech perception skills on paediatric outcomes can be partly overcome by using speech perception tests known to be within the linguistic competence of the child [2]. It is also tempting to speculate that the HiRes mode can improve speech perception in children implanted after the age of 5 years, as differences between HRM and SRM users in this age group are statistically significant. All bilingual children (from the HRM and SRM groups) followed oral/aural rehabilitation and the results were comparable with those for the age group to which they belonged. Bilaterally implanted HRM users showed better results than the average group of HRM users implanted before the age of 5 years.

The study group would need to be larger and there would need to be fewer variables in order to corroborate findings showing improvement in the s.on and s.over groups for all listening skills, within the limits and characteristics of each individual. The group who switched to HRM from SRM stressed that time was needed to adjust to a new listening experience. Based on the results of formal testing, HRM users seem to make significant use of acoustic information. Furthermore, from observations reported by experienced carers, such as parents, teachers and speech therapists, these children learn a lot from the surrounding environment. This incidental learning, which takes place when skills or knowledge are acquired through naturally occurring events, is becoming a key which is available to these deaf paediatric cochlear implant users.

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