Audio Engineering Society

Convention Paper

Presented at the 118th Convention
2005 May 28–31 Barcelona, Spain

Fundamental Frequency Coding in NofM Strategies for Cochlear Implants

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ABSTRACT

Current speech processing strategies for cochlear implants are based on decomposing the audio signals into multiple frequency bands, each one associated with one electrode. However, these bands are relatively wide to accurately encode tonal components of audio signals. To improve the encoding of tonal components and performance in cochlear implants, a new signal processing strategy has been developed. The technique is based on the principle of a so-called NofM strategy. These strategies stimulate fewer channels (N) per cycle than active electrodes (M) (NofM; $N < M$). However, the new strategy incorporates a fundamental frequency estimator which is used to emphasize the periodic structure of tonal components. The new technique was acutely tested on cochlear implant recipients.

1. INTRODUCTION

Cochlear implants are accepted as the most effective means of improving the auditory receptive abilities of people with profound hearing loss. Current cochlear implants consist of a microphone, a speech processor, a transmitter, a receiver and an electrode array which is positioned inside the cochlea. The speech processor is responsible for decomposing the input audio signal into different frequency bands and delivering the most appropriate stimulation pattern to the electrodes.

Studies from different authors [1], [2] have revealed that there are two basic cues for pitch perception in cochlear implant subjects [3]. The first cue, known as temporal pitch, is related to the rate of stimulation in one channel. This cue is also related to the *volley theory* for frequency perception [4], [5] in a normal auditory system. The volley theory suggests that the auditory nerve fibers fire at rates proportional to the period of the input signal. At low frequencies, nerve fibers are "phase locked" with the fundamental frequency of the stimulus. The second cue, known as place pitch, is related to the location of excitation along the cochlea. Excitations located toward the base of the basilar membrane are perceived as high frequencies while excitations located toward the apex of the basilar membrane are perceived as low frequencies. Therefore, signal processing strategies in cochlear implants may extract and encode temporal and/or spectral cues in the audio signals.

The *temporal pitch* mechanism was used to encode the fundamental frequency F0 in strategies like F0/F1/F2 or MPEAK [5]. The F0 was coded by proportionally modulating the pulse rate of the implant during voiced sounds. This mechanism was also used in more recent strategies [6] in order to improve speech perception in tonal languages. The perception of the fundamental frequency is useful for recognizing speakers [7], [8], for speech instruction to the hearing impaired [9] and for melody recognition [10].

The *place pitch* mechanism was also used by F0/F1/F2 and the MPEAK strategies, where spectral information of the formants F1, F2 from speech signal was used to select stimulation electrodes. However, the place mechanism was better exploited by the actual commercial signal processing strategies like CIS [11] (Continuous Interleaved Sampling) or ACE [12] (Advanced Combinational Encoder). These strategies divide speech signals into several bands and derive envelope information from each band to the electrodes. Electrodes near the base of the cochlea are representing high-frequency information, whereas those near to the apex are presenting low-frequency information. Perception of the fundamental frequency with these strategies is related to the temporal fluctuations in the envelopes of each spectral band [13]. However, these bands are relatively wide to accurately encode tonal components of audio signals. Comparisons between ACE like strategies and the MPEAK strategy showed significant advantages for the ACE strategy on word, consonant, and vowel recognition [14].

Therefore, in order to improve F0 perception in actual speech processing strategies for cochlear implants, a new signal processing strategy has been designed. The new strategy is based on the structure of the ACE strategy. The ACE strategy is of the class of "NofM" strategies, which divide speech signals into M sub-bands and derive envelope information from each signal. N bands with the largest amplitude are then selected for stimulation (N out of M). The basic principle here is to increase time resolution by neglecting the less significant spectral components and to concentrate on the more important features. The "NofM" strategies showed significant improvement over CIS-like strategies where all the bands are selected for stimulation (N=M) [15], [16], [17].

The new strategy incorporates a fundamental frequency estimator in addition to the ACE extraction algorithm. If a fundamental frequency is found, the stimulation pattern resulting from the ACE extraction algorithm is modified in a way, such that each electrode is stimulated with a period approximating the pitch period as accurately as possible without modifying the pulse rate of the implant. Therefore, in the new strategy the N bands selected are not necessarily the N maxima as is the case in the ACE.

First experiments, consisting of speech intelligibility tests, were conducted using both the ACE and the new strategy, and the scores were compared in order to test whether the use of the new algorithm can indeed yield improved speech understanding for cochlear implant users.

The paper is organized as follows: In section 2, a review of the ACE strategy is presented. Furthermore, the new algorithm and its incorporation into an "NofM" strategy is described. Section 3 gives the results from the tests with patients and finally, in section 4, conclusions are presented.

2. METHODS

2.1. Review of the ACE Strategy

Speech processing strategies for cochlear implants can be classified into two groups: strategies based on feature extraction of the speech signals and strategies based on waveform representation. The ACE (Advanced Combinational Encoder)[12] strategy used with the Nucleus implant is an "NofM"-type strategy belonging to the second group. Figure 1 shows the basic block diagram of the strategy.

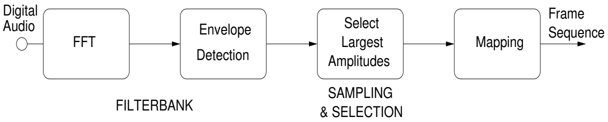


Fig. 1: ACE block diagram.

A digital signal sampled at 16 kHz is sent through a filterbank. The filterbank is implemented with an FFT (Fast Fourier Transform). The block update rate of the FFT is adapted to the rate of stimulation on a channel (i.e the total implant rate divided by the number of bands selected N). The FFT is performed on windowed input blocks of 128 samples (L=128) of the audio signal. The window is a 128-point Hann window [18]. Then, the uniformly-spaced FFT bins are combined by summing the powers to provide the required number of frequency bands M, and thus obtaining the envelope in each spectral band. The frequency bounds of the spectral bands are uniformly spaced below 1000 Hz, and logarithmically spaced above 1000 Hz. Each spectral band is allocated to one electrode and represents one channel.

Since only N out of M electrodes (N<M) are stimulated in each cycle, a subset of filterbank output samples with the largest amplitude is selected. If N is decreased, the spectral representation of the audio signal gets worse, but the channel stimulation rate can be increased giving a better temporal representation of the audio signal. On the other hand, if the channel stimulation rate is decreased, N can be increased giving a better spectral representation of the audio signal.

For each frame of the audio signal, N electrodes are stimulated sequentially and one cycle of stimulation is completed. Thus, the number of cycles per second determines the rate of stimulation on a single channel, also known as channel stimulation rate. The total stimulation rate is defined as the product of the channel stimulation rate and the number of bands selected N.

Finally, the last stage of the process maps the amplitudes to the corresponding electrodes and compresses the acoustic amplitudes into the subject's measured threshold and maximum comfortable loudness level for electrical stimulation. The electrodes are then stimulated sequentially. A more detailed description of the process by which the audio signal is converted into electrical stimuli is given in [19].

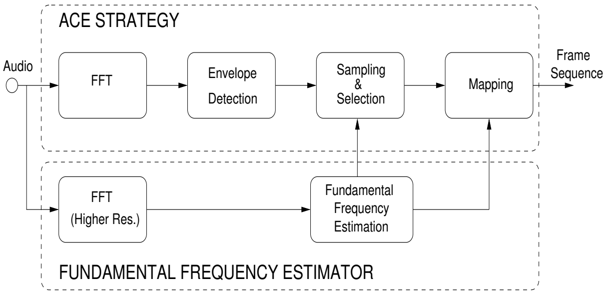


Fig. 2: Block diagram of an "NofM" strategy incorporating a fundamental frequency estimator to select the N bands..

2.2. Fundamental Frequency Coding in NofM Strategies for Cochlear Implants

Based on the general structure of the ACE (Figure 1) but incorporating a fundamental frequency estimator, a new approach has been designed in order to select the N ($N < M$) bands and to control the order in which the electrodes are stimulated in "NofM" strategies. The basic block diagram of the new strategy is presented in Figure 2.

The novel speech-processing strategy has two signal pathways, including the traditional envelope extraction method and an additional fundamental frequency estimator.

The envelope extraction method is exactly the same as in the ACE strategy if no fundamental frequency is estimated by the second pathway.

The second pathway extracts the fundamental frequency (F_0) by a specially designed algorithm (see section 2.2.1). F_0 is used either to select the bands in the sampling and selection block and for controlling the order of stimulation of the electrodes. In the following sections both the frequency estimator and the sampling and selection algorithm are explained.

2.2.1. Fundamental Frequency Estimator

The fundamental frequency estimator is based on the structure of the one used in [20] for the mod-

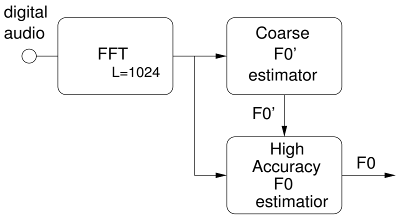


Fig. 3: Block diagram of the fundamental frequency estimator.

eling of harmonic components. The basic block diagram of the Fundamental Frequency estimator is presented in Figure 3. The fundamental frequency is searched in the range between 70 Hz (Usual minimum fundamental frequency for speech) and the channel stimulation rate of the implant (as explained in 2.2.2).

The algorithm is divided in three stages. First, the audio signal is converted to the frequency domain using a 1024-point FFT of a windowed signal (Hann window) in order to provide a better frequency resolution than the 128-point FFT used for extracting the envelopes. The block update rate of the FFT is adapted to the channel stimulation rate. The second stage makes a coarse estimation of the fundamental frequency F_0' based on searching the cepstrums's peak location on a coarse grid [21]. Finally, the third stage provides a further refinement estimation of the fundamental frequency by doing a new peak search of the 1024 FFT spectrum in the surrounding of F0' on a finer frequency grid.

Figure 4 shows an example of the extracted F_0 for the sentence "Sometimes it's necessary to do so" uttered by a female voice.

2.2.2. Sampling and Selection

In addition to the traditional maxima extraction algorithm used by the ACE strategy, the new sampling and selection block tries to emphasize the temporal structure of the audio signals. This emphasis is reached by stimulating the electrodes with a rate which coincides as accurately as possible with the fundamental frequency. In doing so, it is expected to imitate the *volley theory* explained in section 1.

The algorithm works as follows: if no fundamental frequency is found the sampling and selection block selects the N maxima as in the ACE strategy. However, if for a frame *i* a fundamental frequency is found, the N maxima are extracted and the inverse of the fundamental frequency or pitch period is approximated as a combination of the channel stimulation rate and the total stimulation rate:

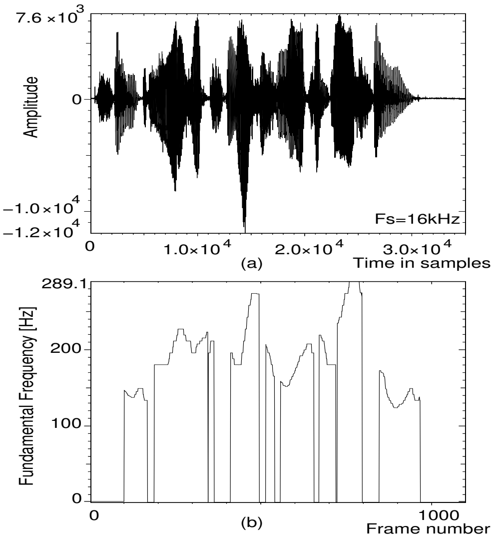


Fig. 4: a) Speech waveform of the sentence "Sometimes it's necessary to do so" uttered by a female voice sampled at Fs=16kHz. b) Corresponding fundamental frequency as a function of time extracted from the audio sample a) using the algorithm described in section 2.2.1

$$\frac{1}{F_0} = a\left(\frac{1}{channel\ rate}\right) + b\left(\frac{1}{total\ rate}\right) \qquad (1)$$

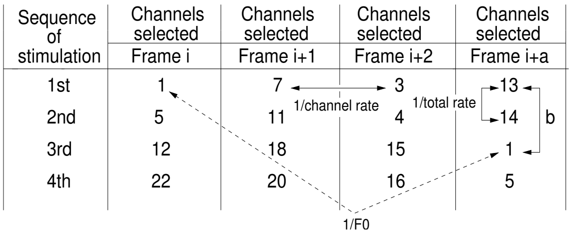
where:
a, *b* are integer numbers.

For the frame *i+1*, the sampling and selection block selects the N maxima without taking into account the bands previously selected for the frame *i*. In the next frame, *i+2*, the N maxima are selected without taking into account the bands already selected in frames *i* and *i+1*. This process is repeated until frame *i+a-1*. If there is no possibility of selecting different bands than the ones selected in the previous frames, the bands are selected randomly. For frame *i+a*, the N maxima are selected without restrictions. For high channel stimulation rates, the electrodes are stimulated at a rate of two times the fundamental frequency. In such a way, the values of *a* and *b* are reduced and less bands have to be selected randomly.

Furthermore, in the frame *i+a*, the parameter *b* of equation 1 is used to control the order of stimulation of the electrodes. The order of stimulation for the frames between *i* and *i+a-1* is from Apex-to-Base following a sequentially order. However, for the frame *i+a*, if some of the bands selected in this frame coincide with the bands selected in the frame *i*, then these bands are sent to the electrodes *b* positions later in the sequence of stimulation respect to the position that they had in the frame *i*. In doing so, the electrodes that are stimulated both in the frame *i* and *i+a* are stimulated with a rate that approximates the fundamental frequency.

The Apex-to-Base order of stimulation was chosen because it was considered more important to emphasize the temporal structure of the audio signals in the channels representing low frequency information than in those representing high frequency information. The implementation of the algorithm was then easier following the order Apex-to-Base.

Figure 5 illustrates with an example the procedure explained above, when N=4 maxima are selected per frame and the fundamental frequency is decomposed with a=3 and b=2.



Sequence of stimulation	Channels selected Frame i	Channels selected Frame i+1	Channels selected Frame i+2	Channels selected Frame i+a
1st	1	7	3	13
2nd	5	11	4	14
3rd	12	18	15	1
4th	22	20	16	5

Fig. 5: Example: Algorithm of selection, when four maxima are selected (N=4) and a fundamental frequency with a=3 and b=2 is estimated.

It should be noted that for a fundamental frequency larger than the channel stimulation rate, the value of *a* in equation 1 would be lower than 1. In these cases, the sampling and selection algorithm would work exactly the same as in the ACE strategy. For this reason, the maximum F0 that can be obtained from the fundamental frequency estimator is set to the channel stimulation rate.

2.3. Application to the ACE Strategy

The new strategy has been incorporated into a research ACE strategy made available by Cochlear Corporation as a MATLAB “toolbox”, termed NIC (Nucleus Implant Communicator). However, this ACE strategy does not incorporate the pre-emphasis and adaptive gain control filters used in the Nucleus implant [12]. The software permits the researcher to communicate with the Nucleus implant and to send any stimulus pattern to any of the 22 electrodes. The NIC communicates with the implant via the standard hardware used also for the fitting of patients during the clinical routine. A specially initialized clinical speech processor serves as a transmitter for the instructions from the personal computer (PC) to the patient’s implant meaning that the clinical processor itself does not perform any speech coding computations. The NIC, in conjunction with Matlab, processes the audio signals on a PC. An interface then provides the necessary functionality for a user application that takes signals, processed using the Matlab toolbox, and transmits them to the cochlear implant via the speech processor mentioned above.

2.3.1. Objective Analysis

The NIC software described above permits a comparison between the ACE strategy and the new strategy. For example, the audio signal presented in Figure 4a was processed with both strategies with a channel rate of 500 stimulations/second. The filterbank and the envelope detection algorithm were configured to decompose the audio signal into M=22 bands. The number of bands selected by the selection algorithm was set to N=8 for both the ACE and the new strategy. Figure 6 presents the bands selected by the ACE and the new strategy for frames 720, 721 and 722. As can be observed from figure 4b, the fundamental frequency for frame 720 was about 220 Hz. From equation 1, the inverse of the fundamental frequency can be expressed as combination of the channel stimulation rate (500 stimulations/second) and the total rate (4000 stimulations/second), which yield the values a=2 and b=2.

As can be observed from Figure 6, the bands se-

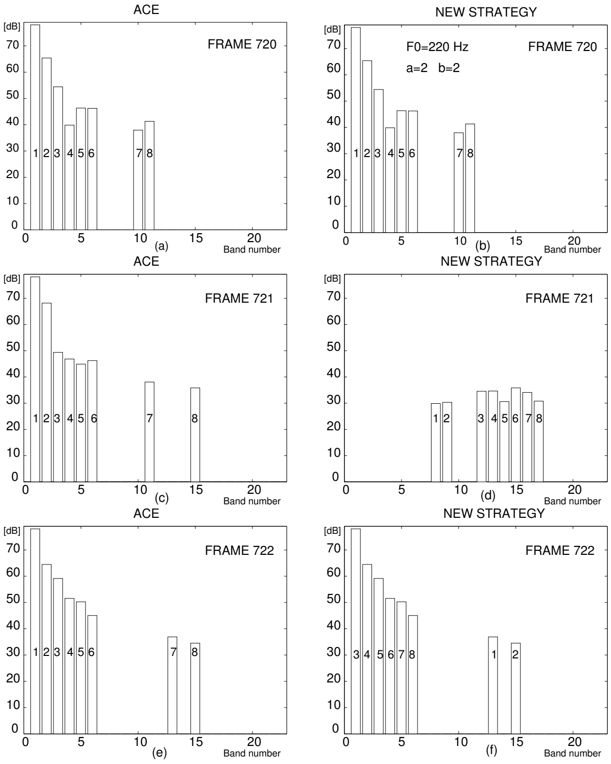


Fig. 6: a) c) e) Bands selected by the ACE strategy. b) d) f) Bands selected by the new strategy. The numbers inside the amplitude bars give the stimulation order in which each band is stimulated in each frame. The y axis is expressed with dB units and the x axis give the band number after the envelope detection

lected in frame 720 by both the ACE and the new strategy are exactly the same. However, because in frame 720 a fundamental frequency of 220 Hz was found (a=2, b=2), the bands selected in frame 721 by the new strategy are different from those selected in the ACE. For frame 722 the new strategy selects the N maxima without restrictions, for this reason the bands selected coincide exactly with the bands selected by the ACE strategy. However, because for the new strategy some of the bands selected in the frame 722 coincide with the bands selected in the frame 720, they are reordered using the parameter b of equation 1.

2.4. Intelligibility Tests

2.4.1. Study Design

The strategies programmed within the NIC environment were tested on patients using a Nucleus 24 implant manufactured by Cochlear Corporation. The total number of electrodes for this implant is 22. However, only 20 electrodes were used by all the test subjects as their everyday speech processor "ESPrit 3G" only supports 20 channels and the patients were used to that configuration.

The test material used was the HSM (Hochmair, Schulz, Moser) sentence test [22]. It consists of 30 lists, each with a total of 106 words in 20 three-to-eight word everyday sentences. Scoring is based on "words correct". All tests had to be conducted acutely as the described research environment does not permit any chronic use, i.e. take home experience. In generating the subject's program, the same psychophysical data measured in the R126 clinical fitting software were used in both the ACE and the new strategy. The signals were presented in quiet. The channel stimulation rate was adapted to the needs of each patient and the number of bands selected per frame N was set to 8 (Table 1). The stimulation order of the electrodes was set to Apex-to-Base for both the ACE and the new strategy because the new strategy has been only implemented using this stimulation order. The test subjects spent some minutes listening to the processed material, using both strategies, in order to become familiarized with them. At the same time, the volume was adjusted to suit the needs of the subjects by increasing the value of the comfort and threshold levels. This procedure was carried out on 3 patients over a period of several hours.

For the actual testing at least 2 lists of 20 were presented with both the ACE and the new strategy (Table 1). The order of the lists was randomized and the subjects had to repeat each sentence without knowing which strategy they were listening to (ACE or the new strategy).

After testing, some sample sentences were processed using both the ACE and the new strategy. The patients were asked which strategy sounded more comfortable and melodious.

Patient id	Number of lists tested for each condition	Number of electrodes selected	Channel stimulation rate
P1	2	8	500
P2	2	8	1000
P3	3	8	1000
P4	3	8	1000
P5	3	8	1000

Table 1: Test details for each patient

2.4.2. Subjects

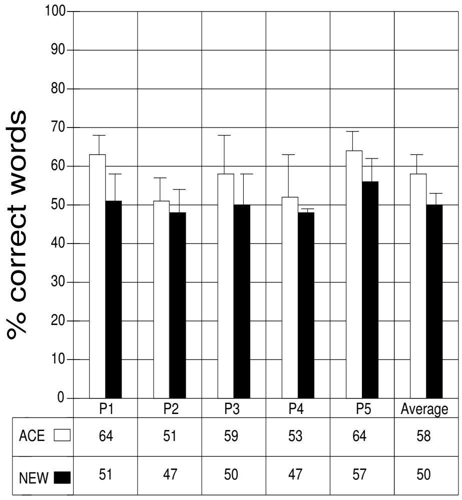
Three adult users of the Nucleus 22 cochlear implant participated in this study. The strategy used by all the patients in their daily life was ACE and all patients were at least able to understand speech in quiet. The relevant details for all subjects are presented in Table 1.

As both strategies were tested on the same hardware and are based on the same psychophysical parameters, a fair comparison could be made.

3. RESULTS

Figure 7 presents the averaged scores obtained by each subject for the different tests done.

All 3 patients obtained slightly better results using the ACE strategy. The mean scores for the HSM sentence test in quiet were 58 % using the ACE strategy and 49 % using the new strategy. However, due to the low number of tests done and the low number of subjects tested results are not statistically significant. It should be remarked that the strategy used by their clinical speech processors is ACE.



	P1	P2	P3	P4	P5	Average
ACE □	64	51	59	53	64	58
NEW ■	51	47	50	47	57	50

Fig. 7: Score by patient (average and standard deviation). Unless otherwise specified, scores were obtained in quiet conditions.

All subjects reported that the sound experienced using both strategies was understandable. Patient number 1 reported that he did not hear any difference between the two strategies. The other 2 patients reported that the sound experienced using the ACE strategy was easier to understand than with the new strategy, however they reported that the sound perceived from the ACE contained more low frequency components than the new strategy, and that for this reason the new strategy sounded more comfortable. Furthermore, these two patients reported that they could hear clear oscillations in the

Patient id	Age	Duration of Deafness in years	Cause of deafness	Implant experience (Nucleus 24) in years	Electrode type	Usual strategy
P1	63	12	otosclerosis	12	CI24R	ACE 8 of 20, 720 pps
P2	65	3	sudden hearing loss	2	CI24R	ACE 8 of 20 900 pps
P3	67	4	lupus	1	CI24R	ACE 8 of 20, 900 pps
P4	65	5	unknown	5	CI24R	ACE 8 of 20, 1200 pps
P5	64	2	sudden hearing loss	5	CI24R	ACE 8 of 20, 900 pps

Table 2: Patient demographics

test material presented with the new strategy, leading to a kind of melody perception.

4. CONCLUSION

The introduction of “NofM” approaches in the 1990s represented a significant improvement over conventional CIS-like strategies by stimulating less electrodes per frame but increasing the channel rate in each channel [15], [16], [17]. However, rate can not be the only factor contributing to better hearing with “NofM”-type strategies, as researchers have also seen advantages of “NofM”-type strategies over CIS-like speech coding using comparable stimulation rates [15], [16].

The overall stimulation rate and frequency resolution of most cochlear implant systems is still too low to resolve a given audio signal without utilizing intelligent selection or compression algorithms. Nevertheless, technical advances in this field have shown huge performance increases in patients in the recent past. However, the electrode-nerve interface that is intended to substitute the hair cells inside the cochlea is far from being as sophisticated as a fully functional cochlea. With today’s systems we are attempting to mimic thousands of nerve fibers using crude electrode arrays with 8 to 22 electrode contacts at most. Bearing these limitations in mind, it becomes apparent that the way those few electrodes are selected and stimulated plays a key role in helping cochlear implant subjects understand speech in difficult hearing situations.

The idea behind the new strategy is to stimulate the same electrodes with a rate similar to the fundamental frequency in tonal components. In doing so, the phase-locked mechanism of the auditory system was tried to be exploited improving in that way the limited resolution of the cochlear implant and the electrode-nerve interface.

One advantage of the new strategy is that the selection of bands is not merely a matter of selecting the largest amplitudes (as with the ACE); this means that smaller electrical currents are required, resulting in power savings. However, the fact that the electrodes are stimulated with lower amplitudes may be a reason why speech perception gets worse with the new strategy. For this reason, it could be possible that the emphasis of certain audio components, as transient components of lower amplitudes, could help to improve performance in speech perception as it is done in the Transient Emphasis Spectral Maxima (TESM) strategy [23].

First results from intelligibility tests with cochlear implant subjects showed that the use of a fundamental frequency estimator to select the N bands in ”NofM”-type strategies lead to worse speech intelligibility in comparison to the ACE strategy. However, it should be noted that all the subjects tested were used to the ACE strategy because it is the strategy used by their daily speech processors. The number of tests and patients tested in this study are not enough to obtain significant results. The mean scores for the HSM sentence test in quiet were 58 % using the ACE strategy and 49 % using the new strategy. However, two out of three patients reported that the sound experienced with the new strategy was more melodious than with the ACE strategy.

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