Pitch discrimination for different musical instruments with cochlear implant simulations

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Introduction

Cochlear implants (CI) are electric hearing prostheses which compensate the function of the inner hair cells of deaf patients. Therefore an electrode array is implanted into the cochlea which stimulates the intact hearing nerve by electrical pulses. The neural processing of these stimuli elicits a hearing impression. Therewith many postlingually deafened CI subjects are able to receive high speech perception scores. Also difficult environments (telephone, car) are managed well by many CI subjects. Following, the interest in non-linguistic hearing situations (environment noise, music) increases. Up to now the focus of CI research laid on the optimization of speech coding strategies (Loizou, 1999). The evaluation of these algorithms normally took place with speech tests. With the introduction of new implant- and speech processor generations several new possibilities of electrical stimulation appear. In the literature there are only a few hints how coding strategies optimized for music can work.

The performance of speech coding strategies is usually evaluated by speech tests established in the audiology. Studies for music perception of CI subjects investigate the processing of pitch, timbre and rhythm. The majority of these studies conclude that the music perception of CI subjects is distinctly worse than of normal hearing subjects (McDermott, 2005). All of these studies detect large differences between the individual CI subjects.

One difficulty in the CI research is the impossibility to detect how a CI sounds. One approach for approximation is interrogating the CI subjects with either questionnaires or psychoacoustic methods. Another approach which is increasingly discussed in the literature is to simulate the signal processing in the CI and present the processed stimuli to normal hearing subjects (Kong et al. 2004, Wei et al. 2007). Advantages of this approach are e.g. the excellent possibility to investigate influences of CI parameters and the better availability of subjects. One drawback is that only the technical part of the CI can be simulated without a final validation if the CI subject hears the stimuli in that way.

In this study the pitch discrimination abilities were examined as difference limen in a psychophysical experiment with a simulated CI coding strategy. Therefore the seven musical instruments piano, clarinet, trumpet, violin, celesta, harpsichord and guitar which represent different instrumental families and additional pure tones were chosen. To investigate the influence of the absolute pitch the experiment was performed in two octaves. To obtain explanatory approaches for the influence of the instrument onto the difference limen spectrograms and stimulograms of the musical stimuli were calculated.

This study follows an earlier study with a similar paradigm (Haumann et al. 2007), where stimuli of the four instruments piano, clarinet, trumpet and violin were presented to CI subjects in the lower of the two octaves.

Materials and Methods

In this study 20 normal hearing subjects (11 m, 9 w) in the age of 21-58 years participated. All subjects took voluntarily part in the study. The local ethics commission approved the study. For the simulations a sine wave vocoder representing the MED-EL CIS+ coding strategy was used. Its function is shown in Figure 1.

The pitch difference limen were determined in an experiment with an adaptive 3-AFC algorithm implemented in MATLAB[1]. The stimuli consisted of a twice played randomized reference tone and a higher target tone which should be identified by the subjects. The frequency range covered C4 (262 Hz) to A5 (880 Hz), and the reference tones lay between C4 (262 Hz) and E4 (659 Hz) in the lower octave and A4 (440 Hz) and C#4 (554 Hz) in the higher octave respectively. The value range for the interval covered 1 to 17 semitones. The paradigm and the frequency range are illustrated in Figure 2.

[1] AFC - A psychophysical-measurement package for MathWorks MATLAB, developed by Stephan D. Ewert, Universität Oldenburg and Centre for Applied Hearing Research, e-mail: stephan.ewert@uni-oldenburg.de, URL: http://www.oersted.dtu.dk/personal/se/afc.

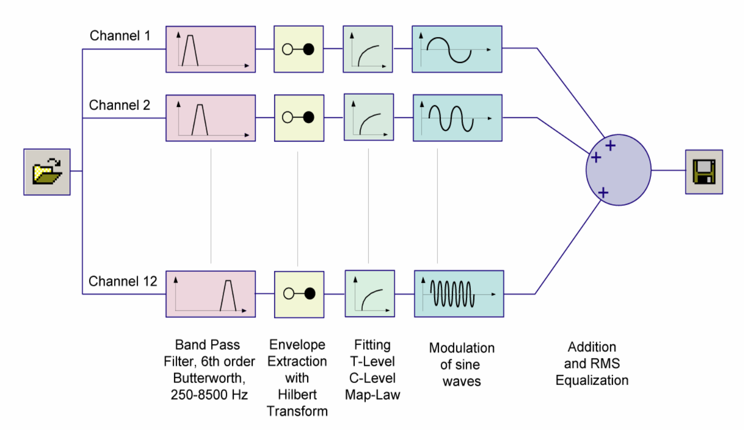

Figure 1: Function of the vocoder representing the MED-EL CIS+ coding strategy. First the wav file was bandpass filtered into 12 bands. Then the envelopes were extracted for each band by Hilbert transforms. With a nonlinear maplaw the acoustic stimuli were converted to their electrical representation and scaled for each channel with typical fitting parameters between the threshold level and the maximum comfortable level. Then sine waves with the centre frequency of each channel were modulated with the signal. Last the signals of all channels were added, loudness equalized by scaling them to the same rms value and saved as wav file

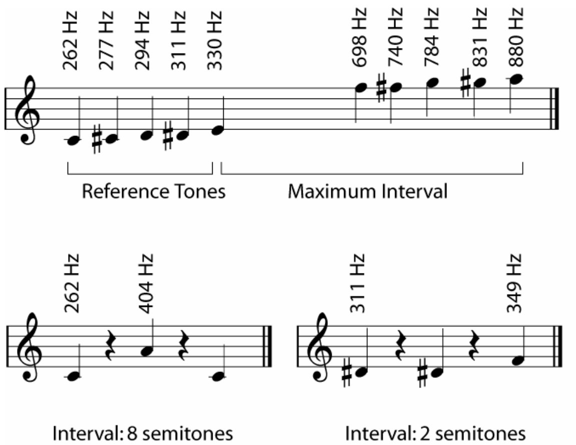

Figure 2: The stimuli consisted of a twice played randomized reference tone and a higher target tone. The bottom note patterns show examples for stimuli presentations with an 8 respectively 2 semitones covering interval between reference and target tone

The notes were recorded with a professional MIDI-Synthesizer and saved as wav file. The stimuli were processed with a simulator of the MED-EL C40+ system and presented in free field in a quiet clinic room. The subjects obtained a direct feedback. The investigated instruments piano, clarinet, trumpet, violin, celesta, harpsichord, guitar and pure tones were presented in random order.

To analyse the musical stimuli the spectrograms and stimulograms were calculated with MATLAB programs. The spectrogram shows the frequencies contained in the signal against the time. The magnitudes of the frequencies are colour-coded. For every regarded signal part the Fast Fourier transform was calculated. In the stimulograms the temporal characteristics of the stimulation magnitude are represented colour-coded for each channel of the CI. The generation of the stimulograms for MED-EL C40+ systems is described in Mühler et al. 2004.

Results

The results which are presented in Figure 3 show a high interindividual variability. Altogether the difference limen of the normal hearing subjects with processed stimuli are clear above the limen with unprocessed stimuli investigated in an earlier experiment (Haumann et al. 2007), where the limen were at one semitone which was the limit of the experiment. Averaged over the octaves the mean of the determined difference limen was for pure tones (1.5 semitones) significant lower than for piano (2.9 semitones), guitar (2.5 semitones), harpsichord and trumpet (both 2.2 semitones). The limen of the other instruments were 1.9 semitones (violin) and 1.7 semitones (celesta and clarinet). The limen determined in the lower octave (2.4 semitones) were significant higher than the limen of the upper octave (1.7 semitones). The significance was tested with an ANOVA on a significance level of 0.05.

One explanatory approach for the significant higher difference limen for piano, harpsichord, guitar and trumpet can be obtained by the time-frequency analysis of the acoustic stimuli (spectrograms) and their electric counterparts (stimulograms). Figure 4 shows exemplarily the spectrograms and stimulograms of a tone used in the experiment. The CI transmits the spectra of the acoustic signals very diffuse. After the attack the tones of piano and harpsichord fade, whereas the other instruments produce a nearly constant tone. Sine waves and celesta have got no or nearly no harmonics, so the tones of these instruments are only marginal distorted by the CI bandpass filter.

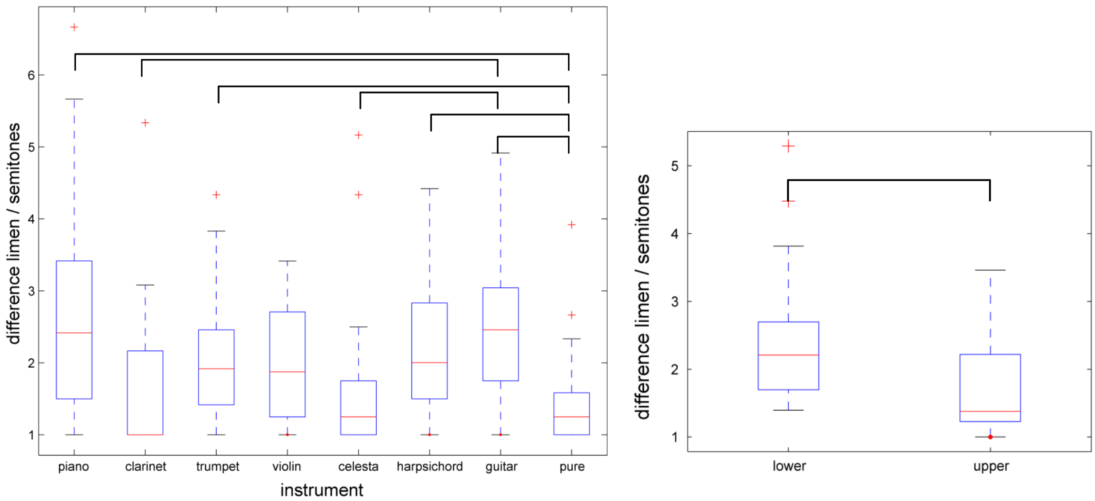

Figure 3: *Above the results are presented as boxplots, on the left the results of the experiment averaged for both octaves, on the right the results averaged for all instruments. Rightwards the instruments respectively the octaves are assigned and upwards the difference limen in semitones. The median is represented by a horizontal line, the upper and the lower quartile as upper respectively lower box limit. The minima and maxima are displayed as lines and outliers as cruxes outside the box. Significant differences between the instruments are marked with brackets.*

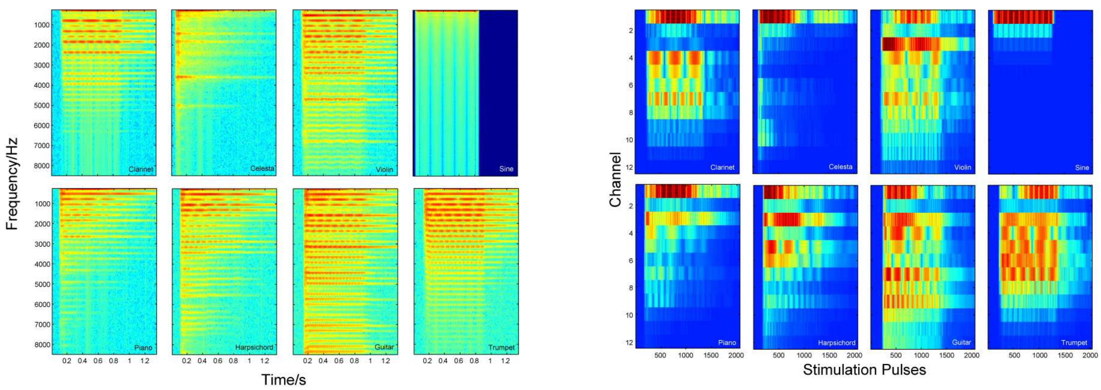

Figure 4: *The spectrograms (left) and the according stimulograms (right) of a tone which was used in the experiment (C4, 262 Hz) are shown for the seven instruments piano, clarinet, trumpet, violin, celesta, harpsichord, guitar and for sine waves. The stimulograms represent the temporal structure of the stimulation magnitude for each channel of the CI colour-coded. The applied coding strategy is the MED-EL CIS+. The frequency axes of the spectrograms are scaled linearly, the frequency axes of the stimulograms logarithmically. The harmonics of a tone have got frequencies which are integer multiples of the fundamental frequency. The bandpass filtering in the CI distorts these relationships.*

Discussion and Conclusion

In our study the pitch discrimination limen with simulations of a CI coding strategy were determined. Altogether the pitch perception with CI simulations is clearly poorer than with normal hearing, although a large interindividual variability was detected. These results are consistent to data in the literature (Gfeller et al. 2002, Leal et al. 2003, Schultz and Kerber 1994). With simulations of CI coding strategies the pitch of the plucked instruments piano, harpsichord and guitar can be discriminated worse than the pitch of other instruments. The pitch of pure tones can be discriminated best.

In an earlier experiment (Haumann et al. 2007) a part of the presented experiment was performed with CI subjects. There the detected limen were higher than the limen of the normal hearing subjects with processed stimuli, but the profile was very similar. Also the CI subjects could discriminate piano tones clearly worse than violin, trumpet and clarinet tones (in this order). The other instruments were not tested. So the results suggest that the simulation of the CI coding strategy and the presentation to normal hearing subjects is an adequate tool for CI research.

In our study the subjects could discriminate the notes in the lower octave worse than in the higher octave. This effect needs to be further investigated.

The time-frequency analysis of the acoustic stimuli can yield initial explanatory approaches for the differences between the musical instruments. In our experiment the instruments which produce a constant tone and which are only marginal distorted by the CI bandpass filter can be discriminated best. So the time-frequency analysis of the electrical stimuli (Mühler et al. 2004) can yield useful hints for understanding the transformation of the musical sounds in the signal coding algorithms of the CI speech processors.

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