EFFICIENCY OF BINAURAL CUES IN A BILATERAL COCHLEAR IMPLANT LISTENER

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ABSTRACT

Monaural Cochlear Implantation is a widely accepted and effective way to enable deaf people to achieve excellent speech understanding in quiet. Recently, it has been started to implant bilaterally to provide patients with the advantages of binaural information. We have conducted a series of basic experiments to study the availability of binaural cues to a bilateral CI-user of interaurally unsynchronized Cochlear Implant (CI) processors. The measurements included just-noticeable-difference (JND) for interaural level and time difference (ILD and ITD), lateralization by means of ILD and ITD, and speech-recognition in noise under different interaural amplitude or phase relationships of speech and noise. In the latter experiment we studied the efficiency of binaural masking level differences. The results indicate that the bilateral CI-user tested in this study was highly sensitive to ILD, comparable to normal hearing listeners, but less sensitive and consistent to ITD. We observed a small but significant degree of binaural unmasking of speech in noise when signal and masker had different amplitude or phase relationships at the two ears.

INTRODUCTION

Normal hearing subjects (NHs) utilize interaural differences in level and time to improve speech understanding in noise and to localize sound sources with high accuracy (Blauert, 1999). Unilateral cochlear implantation, although it opens deaf people the “world of hearing”, cannot provide the advantages of binaural hearing. Since a few years, it has been started to implant bilaterally in the hope that the implantees will be able to gain access to binaural information. Recent studies on 10 bilaterally implanted postlingually deafened subjects by Gantz et al. (2002) observed superior speech perception in noise and quiet in some individuals and a benefit in a basic directional hearing situation (left-right discrimination) when using both CIs as compared to the better one alone. Another recent study by Van et al., (2002) found large improvements in sound-direction identification and important advantages for speech perception in noise. A common finding was that CI-listeners seem to benefit more from acoustical advantages like using the ear with the better S/N-ratio (head-shadow effect) than from binaural processing per se (often referred to as binaural squelch). The basics for binaural squelch may be found in the so-called binaural masking level differences (BMLDs). In normal hearing listeners, BMLD-conditions, for which signal and masker have different amplitude and phase relationships at the two ears, lead to improved signal detection and speech recognition in noise (Hawkins and Stevens, 1950). Since BMLDs involve processing of ILD and ITD information, the sensitivity to these cues in binaural CI-listeners appears to be important. Studies measuring JND for ILD and ITD indicate a high sensitivity to ILD but inconsistent results regarding ITD (van Hoesel and Clark, 1997; van Hoesel et al., 1993; Lawson et al., 2000; Long et al., 1998).

In this study we conducted different experiments to explore the efficiency of ILD and ITD cues in binaural processing through a pair of binaurally uncoordinated state-of-the-art cochlear implant systems (Combi40+/Tempo+, Med-El Corp.). The specific goals were (a) to study the sensitivity to ILD and ITD and their salience in lateralization and (b) to determine the efficiency of interaural amplitude and phase differences in speech recognition in noise. Feeding the stimuli into the auxiliary inputs of the processors enabled us to control and study the specific effects of ILD and ITD, which is not possible when presenting the stimuli via loudspeakers.

In the first experiment, JNDs for ILD and ITD were obtained for various broadband signals differing in their temporal envelope characteristics. The specific question was: What role does the test-stimulus itself play in the transmission of ILD and ITD? In the second experiment, the salience of ILD and ITD in lateralization was measured applying a cross-modality matching procedure. The specific question was: If bilateral CI-listeners are able to discriminate relevant ILDs and ITDs, do they integrate them at higher auditory stages and perceive lateral in-head positions as known for normal hearing? In the third experiment, speech recognition in noise was tested under various BMLD-conditions.

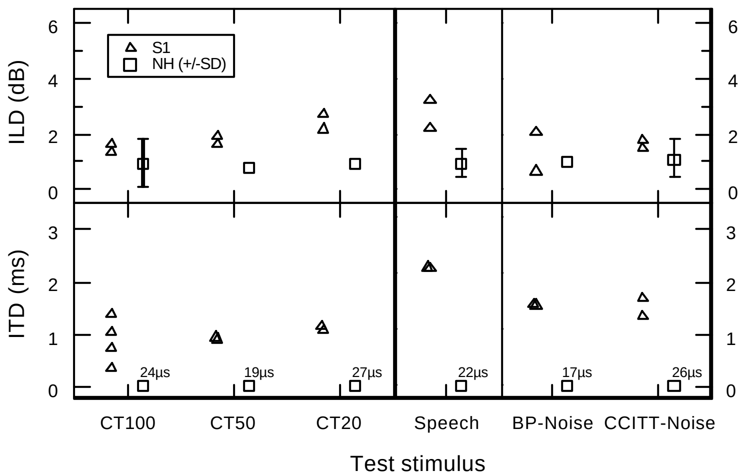

FIG. 1. JNDs for ILD (upper part) and ITD (lower part). Results for the CI-listener and the NHs are denoted with triangles and squares, respectively. The error bars in the upper part for NHs give the standard deviations. In some cases, the standard deviations are smaller than the symbol height.

SUBJECTS, EQUIPMENT, PROCESSOR FITTING AND LOUDNESS BALANCING

One female bilaterally implanted postlingually deafened subject completed all experiments reported in this paper. Due to the quick intervention (ENT-department Vienna) following a bacterial meningitis, the duration of deafness was only 1.5 months on the right ear and 5.5 month on the left ear (from onset of deafness until activation of the speech processor). Full 30mm insertion depth of the stimulation electrodes of the 12-channel COMBI40+, Med-El Corp. (Zierhofer et al. 1995), operating in monopolar configuration, was achieved on both sides. The subject achieved complete open-set speech understanding in quiet without lip-reading and is able to use the telephone without auxiliary equipment. At the time of testing she had a binaural CI-hearing-experience of 3y 5mo. During testing, she used her TEMPO+ BTE speech processors. These were programmed with the CIS-strategy applying standard fitting parameters as she was used to from her clinical fitting (logarithmic filterbank; compression constant: 1024; pulserate/electrode: 1515 pps; pulse duration: 26.7 µs/phase). Solely the electrical dynamic range was extra fitted for the purpose of the experiments, as described below. Three normal hearing listeners served as control subjects in experiment I, one of them in experiment II and two of them in experiment III. Their etiology was free of any hearing disorders and their audiometric thresholds in the relevant frequency range were below 10 dB HL.

The experimental stimuli were generated digitally and output at 96 kHz and 24 bit via an external DAC. This was connected to a headphone amplifier and a pair of attenuators. When testing the CI-listener, the outputs of the attenuators were connected to the auxiliary inputs of the speech processors. The automatic gain control was deactivated. In testing the normal-hearing subjects, the stimuli were presented via a circumaural headphone connected to the attenuators. The experiments were controlled by custom-made software routines within the STX[1]-system. The NH-subjects were tested in a double-walled sound-attenuating chamber.

All tests described here were performed using an experimental bilateral processor fitting. The aim of this fitting was to achieve interaurally symmetrical growth-of-loudness impressions, when a signal with increasing level is fed into the auxiliary inputs of the processors. First, the electrical dynamic at each electrode was determined. Then, loudness matching of the MCL-levels across the electrodes at either ear was performed. Finally, binaural loudness balancing was achieved by first loudness matching one interaural electrode pair in the middle of the array (by attenuating the louder one) and than adjusting the remaining electrodes on the modified side accordingly.

Each of the stimuli tested in experiments I and II was loudness balanced by means of an interaural loudness comparison task using a computer controlled procedure. Each balanced value was defined as the reference ILD-condition (0 dB) for that stimulus.

EXPERIMENT I: JND FOR ILD AND ITD

Stimuli and procedure

Three types of signals were used as stimuli: a) Clicktrains of 40 µs phase duration and repetition rates of 20, 50 and 100 Hz. b) a disyllabic German word with an onset-plosive and c) a bandpass-filtered random noise (150-1700 Hz) and a CCITT-noise (Rec. G.227). These were selected to test how the temporal envelope characteristics of these signals influence the transmission of ILDs and, in particular, ITDs. Clicktrains were expected to perform best due to their steep temporal envelope shifts at regular time intervals. In addition, an improvement in performance with increasing repetition rate was assumed. Noise stimuli, on the other hand, were expected to perform lowest, because their fast temporal envelope fluctuations might not be transmitted by the envelope extraction algorithm and the pulsatile electrode stimulation. The speech signal was expected to perform in between the first two signal types.

The sensitivity for ILD and ITD was measured by an adaptive two-interval two-alternative-forced-choice (2AFC) procedure with the 1up/3down rule, which converges at the 79.4 % point on the psychometric function. The subjects had to indicate if they heard the second of two successively presented stimuli to the left or the right of the first stimulus. To achieve a constant overall level, the ILDs were split between the two ears. To avoid monaural loudness comparison, the stimuli were randomly roved in overall level (± 4 dB). The threshold was defined as the mean of the last 8 of 12 reversals. At least two JND-measurements were performed for each stimulus.

Results

The upper part of Fig. 1 shows the ILD-JNDs of the CI-listener (triangles) and the means of three normal hearing observers (squares) with standard deviations for each of the signals ordered from left to right according to their expected performance for ITDs. The averaged JNDs of the CI-listener range from 1.4 to 2.7 dB. This is only slightly above the range of JNDs of the normal hearing subjects (0.8 – 1.1 dB). The ILD-JNDs of neither the CI-subject nor the NHs show a systematic dependency on the test stimuli.

The lower part of Fig. 1 presents the results for ITD. In contrast to the ILD-JNDs, we found a large difference in the ITD-JNDs between the CI-listener (mean values between 835 and 1935 µs) and the NHs (mean values between 17 and 34 µs). Furthermore, the CI-listener exhibited a high degree of test-retest variability. For the CI-listener, the order of performance for the different stimuli agrees in part with the expectations: clicktrains achieved lower JNDs (384-1400 µs) than the speech signal (2268-2296 µs) and the noise stimuli (1354-1705 µs), both differences being significant ($p<0.0001$). Increasing the repetition rate of the pulsetrains (20/50/100 Hz) tended to result in higher sensitivity, although this was not significant. However, in contrast to expectation, the speech stimulus did not perform better than the noise stimuli.

[1] STX is a windows-based software system for acoustics, speech and signal processing, developed at the Acoustics Research Institute of the Austrian Academy of Sciences.

EXPERIMENT II: LATERALIZATION BASED ON ILD AND ITD

Stimulus and Procedure

We selected the 100 Hz clicktrain as stimulus for the lateralization test because it yielded the lowest JND for ITD and a sufficient ILD-JND.

Measurement of perceived lateralization associated with ILDs and ITDs was performed by means of a cross-modality matching procedure. The subjects placed a slider on a horizontal lateralization axis to the position of the perceived intracranial position of the test stimulus. The axis ranged from the left to the right border of the computer screen and had no markers except at the midpoint. Each trial consisted of three stimulus presentations. The subjects could repeat stimulus presentation. Each stimulus block consisted of randomized presentations of 8 repetitions of 21 interaural conditions, resulting in a total of 168 trials per block. The ILD-conditions were linearly distributed in the range of $\pm$ 10 dB, the ITDs in the range of $\pm$ 1042 µs. To familiarize the subjects with the range of conditions, each block started with the test stimulus moving from far left to far right, corresponding to the range of ILDs or ITDs used in this block. The subjects were requested to make use of the entire lateralization scale.

Results

Fig. 2 gives a collection of the results for all tested conditions. The lateralization judgements (arbitrary units, +/- 100 corresponding to far left and right, respectively) are plotted as a function of ILDs (in dB) or ITDs (in µs). For all conditions, linear regression lines provide a good fit to the lateralization judgements ($p < 0.0001$). The slopes of all distributions differ significantly from that of a horizontal distribution ($p < 0.0001$, one-tailed *t* test). This indicates that all subjects (including the CI-listener) lateralized systematically upon ILDs as well as ITDs.

Regarding ILDs, the slope of the CI-subject's distribution and the variance of the judgements is similar to that of the NH. Concerning ITDs, the slope of the CI-subject (0.045 lat.unit/µs) is significantly shallower ($p < 0.0001$) than that of the NH (0.0704 lat.unit/µs). However, following Sayers (1964), some subjects might have normalized their lateralization judgements so that between-subject comparisons of the slopes should be interpreted with caution. In accordance with the ITD-JND for the CI-listener, the lateralizations in the range $\pm$ 400 µs yielded more variance. Outside this range, however, lateralization was systematic and differed significantly from the midline-condition, when the ITD was larger than 833 µs to the left side ($p < 0.001$) or 313 µs to the right side ($p < 0.003$).

EXPERIMENT III: SPEECH RECOGNITION IN NOISE: BINAURAL MASKING LEVEL DIFFERENCES

Stimuli and Procedure

Speech reception in noise was tested using the adaptive *Oldenburg Sentence Test* (Wagener et al., 1999). This determines the speech reception threshold (SRT), defined as the point of 50% speech recognition performance on the psychometric function, by adaptively varying the speech level against a constant speech-simulating noise (CCITT) at a comfortable level. Each sentence contains 5 elements: *name verb numeral adjective object* with random combination from an inventory of 50 words. This results in more or less meaningful sentences, avoiding context effects. The speech level at 50 % intelligibility was calculated over the last 20 out of a total of 30 presentations. Each measurement was repeated once.

The following interaural signal conditions were tested: S_LN_L, S_RN_R, S_0N_0, S_0N_p, S_pN_0, S_LN_0 and S_RN_0, where S symbolizes the speech and N the noise signal. The suffixes denote the relative amplitude or phase at the two ears (L=left ear only, R=right ear only, 0=diotic and π=phase inversion).

Results

Fig. 3 shows the SRTs for the different interaural conditions. The results for the CI-listener and two NHs are indicated by black and white bars, respectively. Regarding the two monaural conditions S_LN_L and S_RN_R, which can be viewed as *reference conditions*, the SRTs for the CI-listener are, on average, 6.4 dB lower than for the NHs.

To test the advantage of presenting signal and noise to both ears as compared to the better ear alone (*binaural summation*), we compared the conditions S_LN_L or S_RN_R with S_0N_0. The NHs showed nearly no binaural summation (0.2 dB), whereas the CI-listener yielded a slightly larger improvement (0.5 dB). However, since this effect is lower than the measurement error of 1 dB (Wagener et al., 1999), the number of measurements is to small to indicate significance.

The difference between the conditions S_0N_0 and S_0N_p, or S_pN_0 corresponds to the BMLD condition with different interaural phase relationships of signal and masker. While NHs exhibit a large effect (8.9 dB), the CI-subject show an advantage of 2.1 dB. The differences between the conditions S_LN_L and S_LN_0 as well as between S_RN_R and S_RN_0 correspond to the classical BMLDs with different interaural amplitude relationships of signal and masker. NHs yield a large effect of 6.5 dB (mean for both ears) and the CI-subject shows a small but reliable advantage of 1.2 dB (mean for both ears). The BMLDs for amplitude and phase differences are indicators for the benefit resulting from spatial separation of speaker and noise, excluding the head shadow effect. This is referred to as the *binaural squelch* effect, as obtained when testing with loudspeakers (e. g. Gantz et al., 2002 or Schön, et al., 2001) or by applying head-related transfer functions to simulate spatial separation of speech and noise (Lawson et al., 2001). Our results for binaural summation are in line with those of Gantz et al. (2002), and Lawson et al. (2001), showing either a small or no effect. Concerning binaural squelch, Gantz et al. (2002) reported effects between 10 and 18 % in three subjects and no effect in the remaining seven subjects tested. Lawson et al. (2001) reported on an improvement of about 4 % and Schön et al. on a gain of 10.7 %. The improvement in SRT of 2.1 dB found in our CI-listener roughly corresponds to 10-20 % gain in speech recognition in noise.

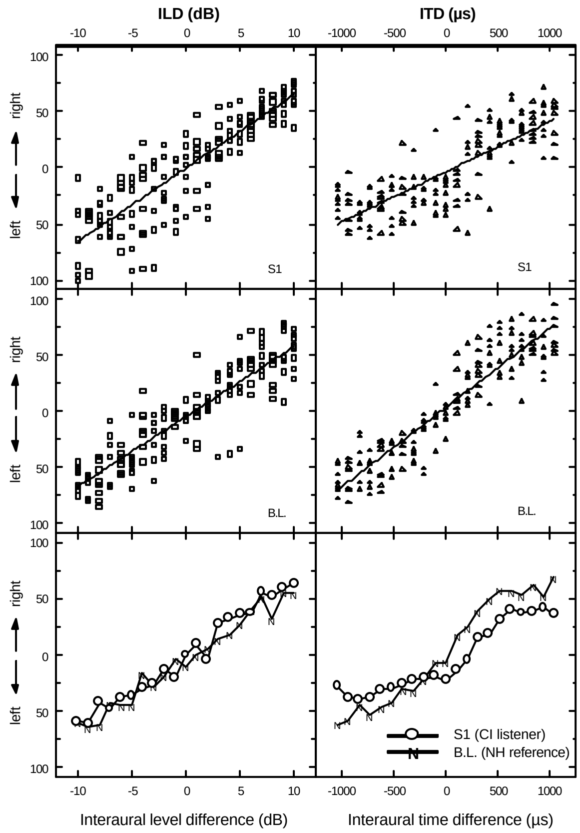

FIG. 1. Lateralization judgements based on ILD (left) and ITD (right). The top and middle panels give the results for the CI-listener and the NH, respectively, with linear regression lines. The lower plots compare the means of the judgements at each condition.

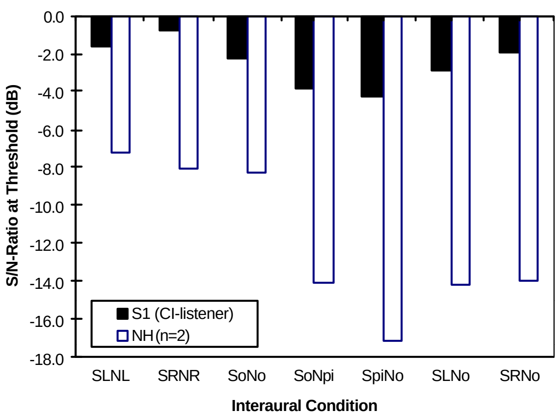

FIG. 3. Speech reception thresholds (SRTs) for various BMLDs (see text).

DISCUSSION

Experiment I demonstrated that a pair of state-of-the-art CI-systems used by the tested CI-listener enabled her to achieve ILD-JNDs comparable to normal hearing subjects. This ability is an important basis in different aspects of binaural processing. It is noteworthy that the obtained JNDs appear to represent the limit of sensation rather than the limits of amplitude resolution of the CI-system. Regarding ITD, the JNDs were considerably higher and the reproducibility was weaker than in normal hearing subjects. The observed JNDs are in agreement with recent measurements by Van et al. (2002). While the weak reproducibility might be due to the uncoordinated stimulation at the two ears, it appears unlikely that synchronization of the processors alone would completely restore "normal" JNDs. Rather, various other factors may limit performance. One of them might be the pulsatile stimulation, as applied in CIS-processors. This can be regarded as transformation from temporal fine-structure delays into temporal envelope delays. Following this argument, the minimum current step of the implant-system and the amplitude resolution of the CI-listener could be limiting factors. The lower ITD-JNDs for clicktrains than for random noises or a disyllabic word indicates that signals with stochastic temporal envelopes are not well suited as carriers of ITD. This might have implications for the choice of stimuli in localizations tests.

The results of Experiment II showed that ILDs lead to similar lateralizations along the aural axis as in normal hearing. The results for lateralization upon ITDs agreed with the JND-measurements in that there was a broad range of about 300 – 800 µs within which more or less consistent JND were obtained. Beyond this range, however, the lateralizations were as consistent as in normal hearing. This may indicate that the transmission of the ITD information was a limiting factor rather than auditory processing at higher auditory stages.

In Experiment III, the BMLD-conditions involving differences in interaural phase relationship between speech and noise surprisingly resulted in a higher improvement (2.1 dB) than those involving differences in interaural amplitude relationship (1.2 dB). The relatively small value of the latter effect indicates that a high sensitivity to ILD, as obtained from the ILD-JND, does not necessarily condition efficient usage of this information in hearing in noise.

In summary, the results of the reported experiments underline the potential of bilateral cochlear implantation. It can be assumed that the encouraging postoperative outcome of our subject is related with the patients history, in particular the short duration of - binaural - deafness.

ACKNOWLEDGEMENTS

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