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Minimum Audible Angle, Just Noticeable Interaural Differences and Speech Intelligibility with Bilateral Cochlear Implants Using Clinical Speech Processors

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Key Words
Cochlear implantation · Bilateral · Speech intelligibility · Sound localization · Minimum audible angle · Binaural hearing · Interaural intensity discrimination · Interaural time discrimination

Abstract
Sound localization and speech intelligibility were assessed in 5 patients implanted bilaterally with Medel C40+ or Medel C40 cochlear implant (CI) systems. The minimum audible angle (MAA) around the head in the horizontal plane was assessed in patients with bilateral CI using white noise bursts of 1000 ms duration presented from a loudspeaker mounted on a rotating boom and compared with the MAA of age-matched normal hearing controls. Spatial discrimination was found to be good in front and in the back of the head with near-normal MAA values (patients: 3–8°, controls: 1–4°). In contrast, poor performance on the sides was found (patients: 30 to over 45°, controls 7–10°). Bilateral CI significantly improved spatial discrimination in front for all patients, when compared with the use of either CI alone. Just noticeable differences (JNDs) in interaural intensity and time were assessed using white noise bursts (1000 ms duration; 50 ms linear ramp). In addition, interaural time JNDs were assessed using click trains (800 ms duration, 40 μs clicks, 50 Hz) and noise bursts in which either only the envelope or only the fine structure was shifted in time. In comparison with normal hearing controls, patients with bilateral CI showed near-normal interaural intensity JNDs but substantially poorer interaural time JNDs depending on the type of stimulus. In contrast to envelope onset/offset cues, interaural fine structure time differences were not perceived by the patients using CI systems employing the continuous interleaved sampling strategy without synchronization between their pulse stimulation times. Speech intelligibility in quiet and CCITT noise from the side (±90°) was assessed using the German HSM sentence test and was significantly better when using bilateral CI in comparison with either unilateral CI, mainly due to a head shadow effect. These favorable results are in agreement with the patients' subjective experiences assessed with a questionnaire and support the use of bilateral CI.

Introduction

Cochlear implantation (CI) has become a successful treatment of profound hearing loss and deafness. Already with one implant, high-level language skills can be achieved [Helms et al., 1997; Tomblin et al., 2000]. However, difficulties in speech perception in noise persist. In normal-hearing listeners, hearing with two ears is known

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to provide several advantages including improved speech perception and improved sound localization. The same advantages were found for users of bilateral hearing aids, when compared with the use of a single hearing aid only, and bilateral hearing aid fitting is widely accepted [Byrne, 1981; Byrne et al., 1992].

In the last decade, an increasing number of patients worldwide have received bilateral CI. First reports have shown improved speech understanding in noise with bilateral CI when compared with unilateral CI [Au et al., 2003; Tyler et al., 2002a, 2003; van Hoesel and Tyler, 2003; Gantz et al., 2002; Mawman et al., 2000; Müller et al., 2002; Schön et al., 2002; Vermeire et al., 2003; van Hoesel et al., 2002]. In a few studies, even an improvement of speech intelligibility in quiet has been found [Müller et al., 2002; Vermeire et al., 2003]. Three different mechanisms are believed to explain the improved speech intelligibility with bilateral CI: head shadow effect, binaural squelch and binaural summation.

The head shadow effect is a monaural effect, which, in principle, does not require any central processing by the brain, except choosing the ear with the better signal-to-noise ratio (SNR). It exploits the fact that with bilateral CI and at least one noise source that is spatially set apart from a target speaker, the ear with the more favorable SNR due to the acoustic head shadow can be used. In all studies, using noise coming from the side, a benefit of bilateral CI due to the head shadow effect has been found [Au et al., 2003; Gantz et al., 2002; Mawman et al., 2000; Müller et al., 2002; Tyler et al., 2002a, 2003; van Hoesel et al., 2002; van Hoesel and Tyler, 2003; Vermeire et al., 2003].

Binaural squelch describes an improvement in speech intelligibility in noise due to the addition of a second acoustic input at the contralateral ear with a poorer SNR than in the first ear. Central processing of interaural time and intensity differences between the two ears is mandatory to take advantage of the binaural squelch effect. Most patients with bilateral CI have some access to such interaural intensity and time cues (especially for low rate cues) but not all of these patients seem to be able to exploit this information [van Hoesel et al., 1993; van Hoesel and Clark, 1995, 1997; van Hoesel et al., 2002; Wilson et al., 2003; van Hoesel and Tyler, 2003]. Generally, the squelch effect has been found only in some bilateral CI users [Tyler et al., 2002a, 2003; Gantz et al., 2002; van Hoesel and Tyler, 2003; Müller et al., 2002; van Hoesel et al., 2002].

The binaural summation effect refers to the advantage of binaural hearing when identical signals (diotic effect) or linearly altered versions of the same signal arrive at the two ears. The binaural summation effect has been found by one group in bilateral CI users for speech intelligibility in quiet [Müller et al., 2002].

Substantial advantages in sound localization skills have been found in patients using bilateral CI in comparison with unilateral CI using various test protocols [Gantz et al., 2002; Tyler et al., 2002a, 2003; Lawson et al., 1998; Mawman et al., 2000; van Hoesel and Tyler, 2003; van Hoesel et al., 2002]. However, to date the lower limit of spatial discrimination in bilateral CI users, which would enable a comparison with normally hearing subjects has not been directly measured.

To fill this gap, we assessed the minimum audible angle (MAA) in bilateral CI users and normal hearing subjects by using a method first described by Mills in 1958 [Mills, 1958] and used by other researchers [Häusler et al., 1983]. The MAA describes the relative precision of auditory localization.

By comparing the MAAs with thresholds of interaural time and intensity discrimination, we aimed to deduce the way in which these parameters influence spatial discrimination. Regarding interaural time discrimination, we differentiated between envelope onset/offset and fine-structure effects of the test signals in order to experimentally confirm the effect of the continuous interleaved sampling (CIS) strategy's property to discard fine timing information. Although from the design of this strategy it can be expected that no fine structure information will be transmitted, to our knowledge this has been shown experimentally in 2 patients only [van Hoesel, 2004].

In order to add our own experiences to the relatively limited speech intelligibility results of bilateral CI users thus far reported in the literature and to compare the auditory skills of the tested subjects with patients at other centers, speech intelligibility tests in noise and in quiet using standard test protocols were also performed.

Materials and Methods

Bilateral CI Users

Two teenaged girls (T1 and T2) with prelingual deafness and 3 male adults (A3, A4 and A5) with postlingually acquired deafness were included in the study and gave informed consent. Table 1 shows a synopsis of the pertinent patient-related data. Prior to the first implantation, all patients had used hearing aids bilaterally. All but one patient were implanted bilaterally with MED-EL COMBI 40+ implants and used two Tempo+ speech processors with standard omnidirectional microphones [Kompis et al., 2002]. One patient (A3) used a MED-EL COMBI 40 implant in his left ear and a COMBI 40+ in his right ear. The filterbank of all Tempo+ devices used in this study was set to the frequency range of 250–7000 Hz. To determine the envelope, a Hillbert transformation instead of a low-pass filter approach is used. No data are given by the manufacturer regarding the transmitted modulation frequency range.

A two-step procedure using two separate surgeries with an interval ranging from 1 to 4 years was employed. Coincidentally, the left ear was implanted first in all patients. A classical approach including mastoidectomy and posterior tympanotomy was performed in 8 out of 10 ears and a pericanal approach without mastoidectomy [Häusler, 2002] in 2 ears (right ears of A4 and A5) with a deep electrode insertion (>30 mm) in each case. There were no complications related to the surgical procedures. The number of active channels ranged from 8 to 12 at the time of clinical testing.

Controls

Five age-matched (±2 years) normal-hearing persons (C1–C5) without a history of prior ear disease or ear operations participated voluntarily to serve as controls for the localization experiments. An ENT physician performed a routine examination and pure-tone audiometry revealing age-related normal findings in all of them.

Implant Fitting

Throughout the experiments, the speech processor fittings were identical to those used by the subjects in everyday life. In accordance with other studies [Müller et al., 2002; Tyler et al., 2002b], no attempt was made to optimize the fitting using channel-wise pitch or loudness matching techniques. For free-field measurements, the patients were allowed to adjust the volume controls to a comfortable level and to balance the loudness between the two sides prior to testing. For tests requiring direct audio input, the signals were similarly adjusted to comfortable levels.

Speech Intelligibility Measurements

Speech intelligibility in noise and quiet was assessed using the German HSM test [Hochmair-Desoyer et al., 1997] with prerecorded sentences from a CD for the conditions unilateral left CI only, unilateral right CI only and the bilateral CI condition. For each of the 9 possible conditions, a list of 20 sentences containing 106 words each was used. Three loudspeakers were positioned at a distance of 1 m in front and on each side of the patients head at 0°, 90° and –90° azimuth. Speech was presented from the front speaker. In the test conditions with noise, CCITT noise was presented either from the left or right side. Speech was presented at 70 dB SPL according to the test instructions, and the noise level was varied to achieve the desired SNR. Based on preliminary experiments, SNRs of 15 dB in subjects T1 and T2 (teenagers) and 5 dB in subjects A3 – A5 (adults) were chosen in order to avoid ceiling and floor effects. Levels were measured using a calibrated handheld sound level meter (type 116, Norsonic AS, Tranby, Norway) at a position corresponding to the center of the subject's head in absentia.

Spatial Discrimination (MAA Measurement)

The MAA is the smallest reliably discriminated change in angular displacement of a sound source [Mills, 1958]. A two-alternative-forced-choice, experimenter-controlled, adaptive procedure described by Häusler et al. [1983] was used. In this free-field experiment, the stimulus was presented with the source in the reference position and again with the source angularly displaced in the horizontal plane; the subject was then asked to orally indicate, in which of two directions the source was displaced. In the frontal and dorsal hemi fields the possible answers were 'left' or 'right' (left-right distinction) and on the sides 'forwards' or 'backwards' (front-back distinction). If the patient did not hear any displacement of the sound source, he was asked to guess; 'no change' was not a possible answer. No feedback was given to the subjects. The subject was blindfolded and the head leaned on a neck holder in order to minimize head movements. The stimulus signals (white noise bursts; table 2) were generated on a personal computer using custom-made software and presented through a loudspeaker mounted on a rotating boom at a distance of 1m from the subject's head (fig. 1). The increments used are listed in table 3, the performance criterion of convergence of the adaptive procedure was 8 out of 10 correct answers at a given reference position. The sound level was set to 65 dB SPL, measured at the center of the subject's head in absentia. Fixed rather than randomized presentation levels were used in order to enhance comparability with earlier studies [Häusler et al., 1983]. The measurements were performed in an anechoic chamber with a loudspeaker mounted on a boom that allowed the experimenter to set the position of the speaker manually. Angles were limited to ±45°. In this way, no unwanted sounds from the experimenter or from the rotating boom occurred during the measurement, therefore, no masking noise was necessary.

Table 1. Overview of subjects included in the study

Subject	Age at test, years	Age at implantation, years		Implant type (active channels)		Etiology
		l	r	l	r	
T1	14	11	12	C40+ (9)	C40+ (9)	congenital
T2	14	8	12	C40+ (9)	C40+ (12)	congenital
A3	51	45	49	C40 (8)	C40+ (9)	progressive
A4	50	47	49	C40+ (12)	C40+ (10)	progressive
A5	53	51	52	C40+ (12)	C40+ (12)	progressive

Table 2. Overview of stimulus parameters

	White noise bursts	Click trains
Frequency spectrum, kHz	0.25–10	0.25–10
Rise and fall time, ms	50	0
Duration of one signal, ms	1000	0.04
Number of signals per train	2	40
Interval between signals within train, ms	1000	20
Interval between reference and test train, ms	2000	1000

Table 3. Overview of selectable increments in localization tests

Test	Test range		Test subrange 1			Test subrange 2		
	lower limit	upper limit	lower limit	upper limit	increment size	lower limit	upper limit	increment size
MAA, degrees	1	45	1	20	1	20	45	5
Intensity JND, dB	1	10	1	10	1			
Time JND, μs	10	1000	10	100	10	100	1000	50
Fine structure time JND, μs	10	16000	10	100	10	125	16000	factor 2
Envelope time JND, μs	10	16000	10	100	10	125	16000	factor 2

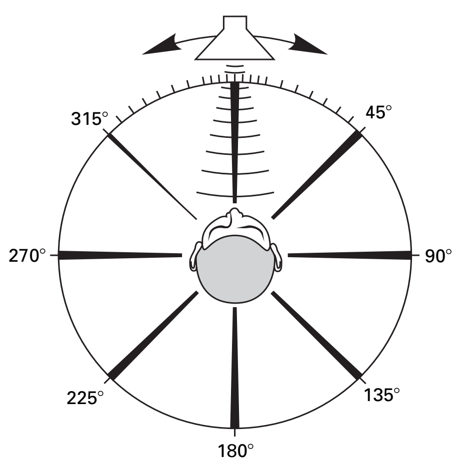

Fig. 1. Reference positions around the head in the horizontal plane for MAA measurements. In teenagers (T1, T2), the MAA was assessed in the reference positions at 0°, 90°, 180° and 270° azimuth. In adults (A3–A5), the MAA was assessed additionally at 45°, 135°, 225° and 315°.

The procedure was found to be quite tiring, especially for the teenagers, and in order to provide a good performance by all patients throughout the measurements and to keep testing time within reasonable limits, a different protocol was chosen for teenagers and adults. In the bilateral condition, the MAA was assessed in the horizontal plane at 4 reference positions around the head (every 90°) in the teenagers (T1, T2, C1, C2) and at 8 reference positions around the head (every 45°) in the adults (A3–A5, C3–C5) (fig. 1). For the reference position at 0° azimuth, the MAA was also assessed for each unilateral implant and compared with the bilateral listening situation for CI users and for the controls.

Interaural Discrimination Tests by Means of Just Noticeable Difference Measurements

The just noticeable differences (JNDs) for interaural intensity, time, fine structure and envelope shifts were assessed using a two-alternative-forced-choice, experimenter-controlled, adaptive procedure as described by Häusler et al. [1983]. Figure 2 illustrates the sequence of stimulus presentations for the white-noise bursts. Additionally, click trains were used as stimuli. All stimuli, as described in table 2, were sent directly from a personal computer to the audio input of the implant system. In all conditions, a diotic reference stimulus was presented first, followed by a test stimulus with an interaural difference in either intensity, time, fine structure time or envelope time, depending on the test. For intensity JND measurements, the levels at the audio input are reported. These are translated into intracochlear electrical levels according to the individual maps of the speech processors.

An interaural intensity difference generates a sound image displaced toward the ear with the greater intensity stimulus; an interaural difference in time, fine structure or envelope generates a sound image displaced to the ear receiving the leading signal. The task of the subject was to compare the test sound image with the reference sound image and indicate in which direction the test image was displaced (with a response alternative of 'right' or 'left'). For all of these tests, the amplitude or interval time of the second stimulus was increased or decreased in either the left ear or the right ear, both choices made randomly. The selectable increments in relation to the test are shown in table 3, the performance criterion of convergence of the adaptive procedure was 8 out of 10 correct answers. For the measurements of interaural fine structure time and envelope time differences, logarithmic increments were used in order to cover a wide test range ('factor 2' in table 2) and to keep testing time within reasonable limits.

Questionnaire

A questionnaire was used for a limited assessment of the subjective experiences with bilateral CI. The questions refer to the actual state and are listed in figure 7. The patients were asked to respond on a visual analogue scale.

Statistics

The most pertinent question is whether speech recognition scores and MAA's are better with two CIs than with either one of the implants. For each experiment, a nonparametric analysis of variance [Wald test; Brunner and Langer, 1999] was used to evaluate global differences between conditions. One-tailed Wilcoxon matched-pairs signed rank tests were then used for comparisons between individual conditions. All calculations were performed in collaboration with the Department of Mathematical Statistics of the University of Berne.

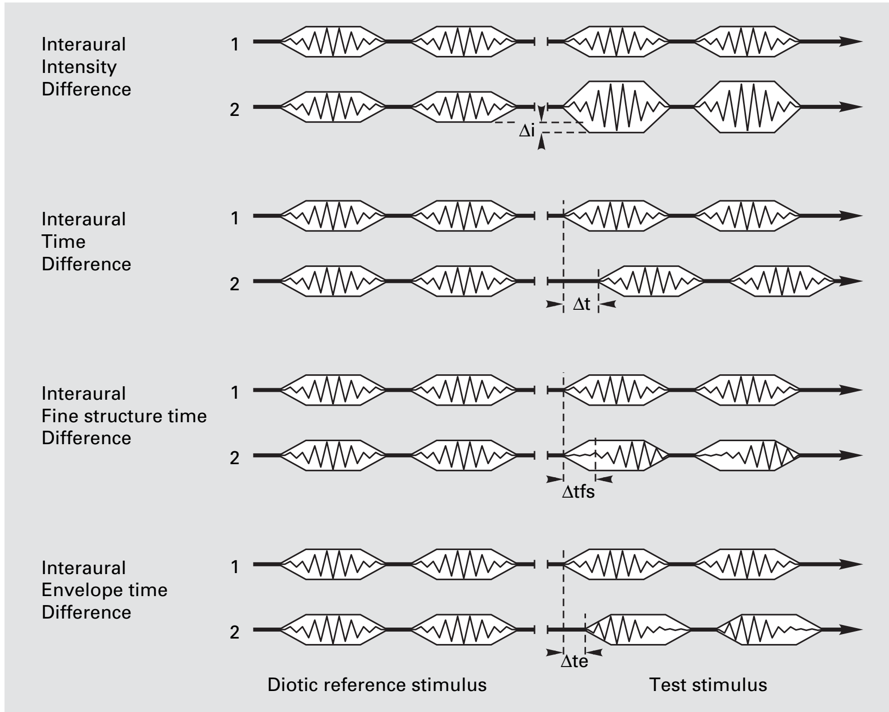

Fig. 2. Schematic representation of the stimuli used in the JND measurements. A diotic reference stimulus was presented first to both ears (channel 1 and 2), followed by the test stimulus with an interaural intensity, time, fine structure time, or envelope time difference.

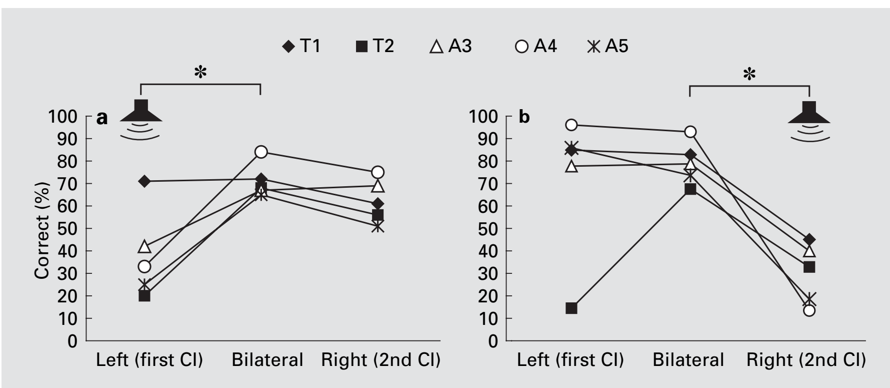

Fig. 3. Speech intelligibility assessed with HSM sentences in noise from the left side (**a**) and noise from the right side (**b**). Speech was always presented from the front (see text for a detailed description of the test conditions). First CI and second CI refer to the order of implantation; * $p < 0.05$, statistically significant (Wilcoxon matched pairs test).

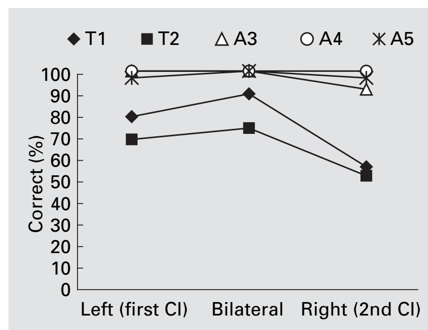

Fig. 4. Speech intelligibility assessed with HSM sentences in quiet. Speech was always presented from the front (see text for a detailed description of the test conditions). First CI and second CI refer to the order of implantation.

Results

Speech Intelligibility

Figures 3 and 4 show the results of the speech intelligibility tests. The nonparametric Wald test reveals that each of the two main factors (number and side of CI, presence and side of noise) as well as the interaction between these factors are all highly significant ($p < 0.007$).

Figure 3a displays the scores for speech intelligibility tests in noise arriving from the left side. The percentage of correctly understood words was significantly higher ($p = 0.03$) using bilateral CI in comparison with the use of the left CI alone (ipsilateral to the noise source). An average increase of 33% ($\pm$20.5 SD, range 1–51%), consistent with the head shadow effect, was observed. In all but one patient, higher scores were achieved with bilat-

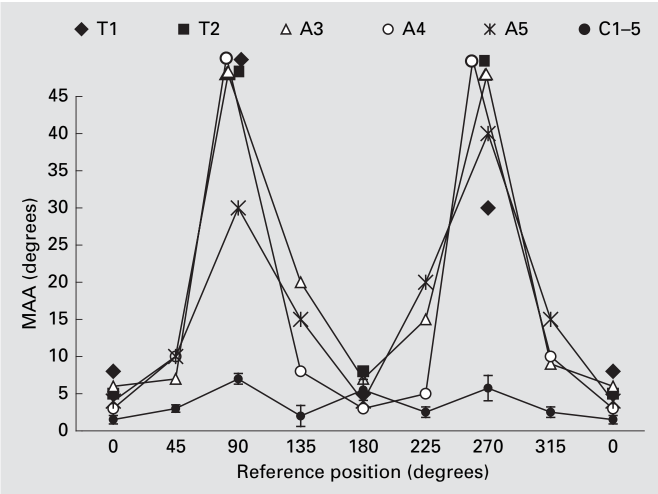

Fig. 5. Individual MAA values for patients (T1, T2, A3–5) with bilateral CI and average MAA values with standard deviation for normal hearing controls (C1–5) are shown as a function of different reference positions in the horizontal plane. The MAA was assessed for 4 reference points (every 90°) in teenagers and in 8 reference points (every 45°) in adults. MAA values above 45° were not measured (data points above frame).

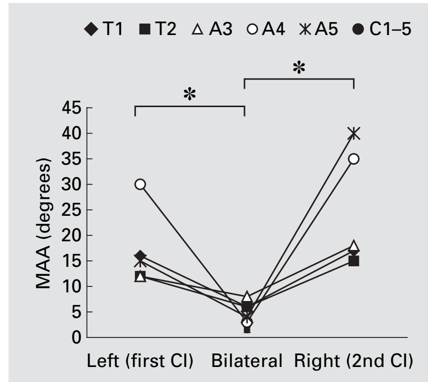

Fig. 6. Individual MAA in the horizontal plane for the reference position in front (0°) as shown for bilateral CI and either CI alone. First CI and second CI refer to the order of implantation * $p < 0.05$, statistically significant (Wilcoxon matched pairs test).

eral CI than with the right CI (contralateral to the noise source; squelch effect) alone. However, the differences were not quite statistically significant ($p = 0.06$).

In the opposite test situation with noise arriving from the right side (fig. 3b), the percentage of correctly understood words was significantly higher ($p = 0.03$) with bilateral CI than with the right CI (ipsilateral to the noise source) alone. An average increase of 56.2% (±20.8 SD, range 34–78%), consistent with the head shadow effect, was found. No significant difference between bilateral CI and the left CI (contralateral to the noise source; squelch effect) alone was observed ($p = 0.4$).

The head shadow effect can be assessed and differentiated from side asymmetries by comparing the data in figures 3a vs. b. It was calculated by comparing the speech recognition scores for ipsi- and contralateral noise for each implant. The head shadow effect was found to be 32.6% on average and was highly significant ($p = 0.002$).

Speech intelligibility results in quiet are shown in figure 4. The teenagers (T1 and T2) recognized sentences slightly better with bilateral CI (90% and 75% correct, respectively) compared with the first implant on the left side alone (80% and 70% correct, respectively). The scores when using only the 2nd implant on the right side alone were lower (58% and 54% correct). Although a tendency in favor of bilateral CI use was found, due to ceiling effects in adults (A3–A5) no significant differences were observed in this test setting.

MAA Measurements

Figure 5 illustrates the individual MAA results for all patients and the average values for the controls as a function of the reference positions. In the reference position in front at 0° and in the back at 180°, the MAA ranged from 4 to 8° in patients and from 1 to 4° in controls. In the frontal and dorsal quadrants (reference positions at 45°, 135°, 225°, and 315°) the MAA ranged from 5 to 20° in adult patients and from 2 to 4° in adult controls. On the sides in the reference positions at 90 and 270° azimuth, the MAA ranged from 30 to >45° (i.e. not measurable) in patients and from 3 to 8° in controls.

When comparing spatial discrimination in the front and in the back, only small differences were found. The joint average MAA for the frontal quadrants (reference positions at 45 and 315°) was 9.0 versus 10.6° for the dorsal quadrants (reference positions at 135 and 225°). The difference was not statistically significant ($p > 0.8$). Average MAAs for the reference positions at 0 and 180° were even identical (5.4°).

Figure 6 illustrates the comparison of the MAA measurements with bilateral and either unilateral CI in the frontal median reference position at 0° azimuth. The

Table 4. Results of interaural discrimination tests in patients (T1, T2, A3–5) and controls (C1–5)

Subject	Intensity JND, dB	Time JND, µs white noise bursts	Time JND, µs click trains	Fine structure time JND, µs	Envelope time JND, µs
T1	1	700	80	>16000	2000
T2	1	>1000	>1000	>16000	>16000
A3	2	800	100	>16000	>16000
A4	1	600	100	>16000	250
A5	1	900	200	>16000	4000
C1	1	20	10	20	100
C2	1	10	30	30	1000
C3	1	20	30	30	4000
C4	1	30	20	30	2000
C5	1	20	30	30	500

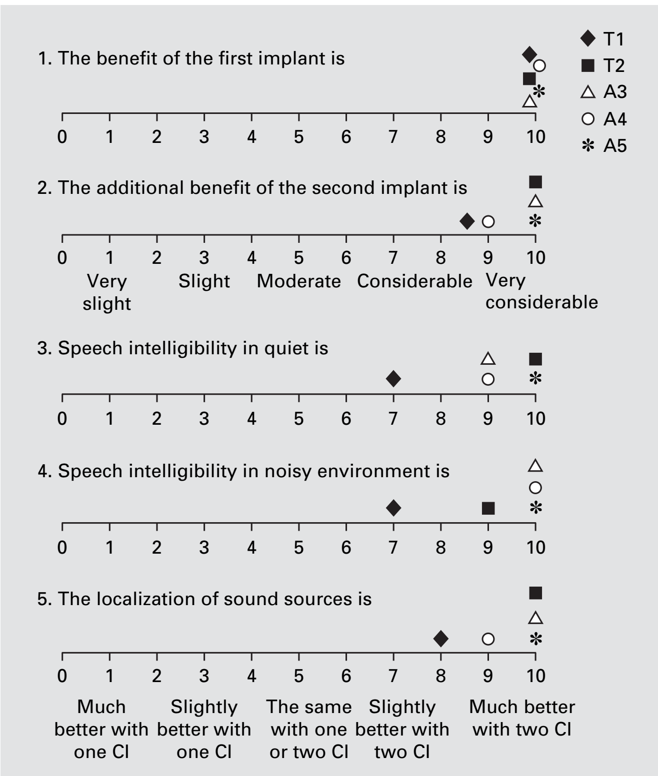

Fig. 7. Self assessment using visual analog scales. Note that questions 1 and 2 share a common assessment scale, which is different from that of questions 3–5.

MAA ranged between 3 and 8° for the bilateral CI condition, and was significantly ($p = 0.03$) lower than for either CI alone (range for the left CI alone: 12–30°, range for the right CI alone: 15–35°). The MAA in normal hearing controls (tested only bilaterally) ranged from 1 to 2°.

Interaural Discrimination Tests

Table 4 shows a synopsis of all measured JNDs.

Interaural Intensity JND

Interaural intensity discrimination did not differ significantly in patients (average 1.2 dB) and controls (average 1 dB).

Interaural Time JND

The interaural time JND was strongly influenced by the type of the stimulus in patients but not in controls. Using white noise bursts, the interaural time JND in patients ranged from 600 to above 1000 µs. Using click trains, the time JNDs improved to values below 200 µs except for one patient. The controls showed time JNDs ranging from 10 to 30 µs independent of the type of stimulus.

Interaural Fine Structure Time JND

None of the bilateral implant users were able to discriminate interaural fine structure time differences up to the upper test limit of 16 ms, in contrast to the controls with JNDs of 20 and 30 µs.

Interaural Envelope Time JND

The results were widely scattered in patients and controls ranging from 100 to over 16 ms in patients and from 100 to 4 ms in controls. The difference between patients and controls was not statistically significant.

Questionnaire

The most pertinent questions and the corresponding answers are shown in figure 7. All patients reported considerable advantages using bilateral CI.

Discussion

Of the three speech intelligibility benefits available to normal hearing listeners through the use of two ears, head shadow, squelch and the summation effect, only one, the head shadow effect could be found in each of the 5 tested patients and for each of the two CIs (fig. 3). These results agree with previous reports on bilaterally implanted patients with respect to speech intelligibility in noise [Au et al., 2003; Tyler et al., 2002a, 2003; van Hoesel and Tyler, 2003; Gantz et al., 2002; Müller et al., 2002; van Hoesel et al., 2002, 2003].

The binaural squelch effect, defined as the *additional* benefit of a second CI with a *lower* SNR compared to the first CI alone, can be found in 6 out of 10 individual measurements (fig. 3). However, the difference between the scores of the bilateral CI condition and the condition with the CI contralateral to the noise source alone is not statistically significant. These results are in agreement with previous reports [van Hoesel and Tyler, 2003; Tyler et al., 2002a, 2003; Gantz et al., 2002]. The highest percentage of patients with a measurable squelch effect was found by Müller et al. [2002] who reported a significant squelch effect for a group of 9 patients in a total of 16 out of 18 individual measurements or 89 % of all measurements. They used a similar test setting and the same implant systems (MED-EL COMBI 40 or 40+) as in the present work.

The main challenge for the speech intelligibility tests in quiet was the choice of test material, which would be suitable for all of our patients. Because of the substantial differences in speech understanding between young teenagers and adults in the group, ceiling effects could not be completely avoided. As a consequence, although a summation effect (advantage of bilateral CI vs. unilateral CI for speech presented from the front) was found in both teenagers and partially in adults (fig. 4), the differences are not statistically significant. For a different patient group, Müller et al. [2002] found a significant summation effect in quiet in the aforementioned group of 9 patients.

Another possible limitation related to the test procedure consists of the listening experience with bilateral and unilateral CI. It is possible that listeners who are accustomed to bilateral CI would need extended training time to reveal optimum performance with only one implant. It may be speculated that the observed differences between bilateral and unilateral stimulation in figures 3, 4 and 6 would be smaller if the subjects were accustomed to listening unilaterally rather than bilaterally prior to the experiments. Nevertheless, the favorable objective results with bilateral CI are in agreement with other reports [Gantz et al., 2002; Lawson et al., 1998; Müller et al., 2002; Schleich et al., 2004; Schön et al., 2002; Tyler et al., 2002a; van Hoesel et al., 2002; van Hoesel and Tyler, 2003; van Hoesel, 2004; Vermeire et al., 2003] and also agree with the subjective assessment of the patients with bilateral CI.

Throughout all speech intelligibility tests, we found a decreased performance of the later implanted ear on the right side in comparison with the first implanted ear on the left side for the same test situations (cf. fig. 3a vs. b; fig. 4). Although the differences were not statistically significant, these findings might indicate a deprivation effect of the later implanted ear. The deprivation effect has been defined as a systematic decrease over time in auditory performance associated with the reduced availability of acoustic information [Arlinger et al., 1996], and the term has been predominantly used for patients with symmetrical hearing losses and monaural hearing aid fitting [Arlinger, 2003; Hurley, 1999]. A shorter time for auditory acclimatization is another hypothesis to explain the decreased performance of the later implanted ear. Auditory acclimatization has been defined as a systematic change in auditory performance with time, linked to a change in the acoustic information available to the listener. It involves an improvement in performance that cannot be attributed purely to task, procedural or training effects [Arlinger et al., 1996]. Such effects can be ruled out for the time of our experiments but not necessarily for the time prior to testing. In principle, training effects or listening experience might be responsible for the first-to-second CI difference, even after 1.5 or more years of bilateral CI use. However, after this time, speech recognition scores in adults usually do not continue to increase significantly [Tyler and Summerfield, 1996]. Furthermore, early cochlear implantation of the second ear would still be expected to result in improved speech recognition when compared to a long waiting period. Longitudinal studies could help to clarify whether it is possible for the second implanted side to acclimatize and 'catch up' completely with the first side and how long such a process would take.

To our knowledge, this is the first report to directly measure the lower limit of spatial discrimination in the horizontal plane by means of MAA measurements in patients with bilateral CI (fig. 5). The best MAA values (3–8°) in the present study were found for the reference positions at 0° and 180° (front and back of the head; fig. 1). These values are only slightly higher than those measured in the normal hearing controls C1–C5 (MAA 1–4°) and the MAA values of normal hearing listeners as reported in the literature using the same protocol [Häusler et al., 1983; Mills, 1958]. Using a different setting including an array of eight fixed loudspeakers, van Hoesel and Tyler [2003] found a comparable localization performance in the frontal horizontal plane in 5 subjects with bilateral CI with calculated localization errors of 4–11°. Using research processors preserving fine timing information, the calculated localization errors improved to 2.5–11°. Even if we consider a possible overestimation of the localization abilities in our subjects by a factor of 1.4 due to a different interpretation of the MAA measurement protocol as suggested by Hartmann and Rakerd [1989], the localization abilities found in the present study remain comparable to those found by van Hoesel and Tyler [2003].

For the reference positions at 90° and 270° (right and left side; fig. 1), MAA values were much higher in patients than in controls (MAA 30 to >45°, i.e. not measurable; controls: 7–10°). A possible reason for this finding is the microphone position of the CI above the auricle. In this way, auriclular cues, which enable front-back distinction on the side of the head in normal-hearing listeners [Moore, 2003] cannot be used. This is similar to the findings in subjects with behind-the-ear hearing aids with microphones also above the auricle [Häusler et al., 1983]. Although the intensity JNDs of subjects with bilateral CI were in the same range as those of the normal hearing controls, subtle differences in interaural intensity discrimination not detected in our experiments might contribute to the poorer localization performance on the sides, where interaural intensity difference cues are smaller than in the front or back. It might also be that the restricted frequency information from the implant system is not sufficient to provide enough spectral cues needed for front-back distinction.

It is conceivable that spatial discrimination on the sides could be improved either by intrameatal placing of the microphone [Häusler et al., 1983] or by directional microphone systems [Kompis, 2003].

Bilateral CI significantly improved spatial discrimination in front in comparison with either unilateral CI alone (fig. 6). Improved sound localization using bilateral CI in comparison with unilateral CI has been shown previously, although different protocols with fixed loudspeaker positions have been used, and the lower limit of spatial discrimination were not measured directly [Gantz et al., 2002; Mawman et al., 2000; Tyler et al., 2002b; van Hoesel et al., 2002, 2003; van Hoesel and Tyler, 2003; van Hoesel, 2004]. In the present study, stimuli levels were fixed rather than randomized, allowing spatial discrimination due to the head shadow for all 5 patients for each CI alone. It can be hypothesized that the difference in MAA values between unilateral and bilateral CI would be even greater using randomized levels.

As shown in figure 6, monaural spatial discrimination tended to be better using the first implanted ear on the left side alone in comparison with the second implanted ear on the right side alone. Although the difference was not statistically significant, it was found in 4 out of 5 subjects. Again, this finding might be another subtle effect of auditory deprivation, although the term 'deprivation effect' has been mainly used in the context of decreased speech intelligibility performance with the later aided ear and not in the context of sound localization [Arlinger et al., 1996]. In principle, the deprivation effect in its simplest form would predict that the effect should be proportional to the delay of implantation. However, it is known that there is a substantial interindividual variation [Tyler and Summerfield, 1996]. In our data, subject A5 had the shortest delay but a large effect.

Results of the JND measurements (table 4) revealed that for broadband noise, patients with bilateral CI have an interaural intensity discrimination comparable to normal hearing controls (C1–C5) [Häusler et al., 1983]. In contrast, CI users performed poorer than controls in JND measurements involving temporal cues. In agreement with the recent literature, we found that the type of stimulus greatly influences JND results involving temporal cues for CI users [van Hoesel and Tyler, 2003; van Hoesel, 2004; van Hoesel et al., 2002]. While there was no difference in time JNDs between noise bursts and click trains for controls, CI users performed significantly better with click trains. In contrast to the controls, none of the CI users was able to detect interaural fine structure time differences. There was a significant difference between CI users and controls found in the present study: while normal hearing subjects are better at perceiving fine structure time differences than envelope time shifts, for CI users the contrary holds true. For the envelope time differences, the performance of CI users and controls is similar. This finding confirms that the CIS strategy does not propagate fine structure information to the user, while envelope information is preserved [Wilson et al., 1991]. This is probably a major limitation for bilateral hearing with current clinical CI systems. While this may be irrelevant for monaural CI users, it can be speculated that other coding strategies preserving fine structure information might be advantageous for bilateral CI users. Three out of 5 bilateral CI users showed better localization abilities with research processors preserving fine timing information compared to the use of clinical processors of the Nucleus CI-24M implant systems [van Hoesel and Tyler, 2003]. Another possibility to improve the binaural sensitivity might be to optimize matching of electrode pairs according to their position in the two inner ears [Long et al., 2003].

Results from table 4 imply that sound localization in the horizontal plane, as measured by assessing MAAs, is mainly based on intensity cues and less on temporal cues. This has already been suggested by van Hoesel and Tyler [2003]. Although patients with bilateral CI could discriminate interaural time differences, the time JNDs were too poor to contribute significantly to spatial discrimination. This is particularly true for white noise bursts, for which time JNDs were found to be even larger than for click trains (table 4).

The generally favorable test results using bilateral CI were confirmed by all of the tested patients in the subjective evaluation (fig. 7). For all patients, the benefit from the first CI was very substantial, and the additional benefit from the second CI was only slightly smaller. For all three aspects considered (speech intelligibility in quiet, in noise and sound localization), the performance was estimated to be substantially better using bilateral CI. Our findings agree with subjective experiences of bilaterally implanted patients in other centers [Gantz et al., 2002; Mawman et al., 2000; Müller et al., 2002; Schön et al., 2002; Tyler et al., 2002a; Vermeire et al., 2003].

Conclusions

All patients had a substantial additional benefit – both objectively and subjectively – from the second CI. In our group of subjects, bilateral CI improves speech intelligibility in noise because of the head shadow effect. Binaural squelch and summation effects can be observed in some patients. Bilateral cochlear implantation significantly improves spatial discrimination in the horizontal plane in front (left-right distinction) to near-normal MAA values, whereas spatial discrimination on the side of the head (front-back distinction) remains poor. Bilateral CI enables at least partial binaural hearing with near-normal interaural intensity discrimination and variable interaural time discrimination. For the CI systems using the CIS speech coding strategy considered in this study, these abilities depend strongly on the type of the acoustic stimulus, as fine structure cues are not accessible to patients. These findings suggest that further developments such as ear-canal or directional microphones (already available for some CI systems) or new coding strategies might further increase the benefit of bilateral CI. Even after 1.5 years or more of bilateral CI use, the performance with the later implanted ear is inferior to the performance of the first implanted ear, suggesting auditory deprivation or insufficient auditory acclimatization. However, a training effect cannot be ruled out even after this time period. In either case, these findings are in favor of an early implantation of the second ear.

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