Localization ability with bimodal hearing aids and bilateral cochlear implants

Bernhard U. Seeber[a)]
AG Technische Akustik, MMK, Technische Universität München, Arcisstr. 21, D-80333 München, Germany

Uwe Baumann
Department of Experimental Audiology, University of Munich, D-81377 München, Germany

Hugo Fastl
AG Technische Akustik, MMK, Technische Universität München, Arcisstr. 21, D-80333 München, Germany

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After successful cochlear implantation in one ear, some patients continue to use a hearing aid at the contralateral ear. They report an improved reception of speech, especially in noise, as well as a better perception of music when the hearing aid and cochlear implant are used in this bimodal combination. Some individuals in this bimodal patient group also report the impression of an improved localization ability. Similar experiences are reported by the group of bilateral cochlear implantees. In this study, a survey of 11 bimodally and 4 bilaterally equipped cochlear implant users was carried out to assess localization ability. Individuals in the bimodal implant group were all provided with the same type of hearing aid in the opposite ear, and subjects in the bilateral implant group used cochlear implants of the same manufacturer on each ear. Subjects adjusted the spot of a computer-controlled laser-pointer to the perceived direction of sound incidence in the frontal horizontal plane by rotating a trackball. Two subjects of the bimodal group who had substantial residual hearing showed localization ability in the bimodal configuration, whereas using each single device only the subject with better residual hearing was able to discriminate the side of sound origin. Five other subjects with more pronounced hearing loss displayed an ability for side discrimination through the use of bimodal aids, while four of them were already able to discriminate the side with a single device. Of the bilateral cochlear implant group one subject showed localization accuracy close to that of normal hearing subjects. This subject was also able to discriminate the side of sound origin using the first implanted device alone. The other three bilaterally equipped subjects showed limited localization ability using both devices. Among them one subject demonstrated a side-discrimination ability using only the first implanted device. [DOI: 10.1121/1.1776192]

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I. INTRODUCTION

The localization of sounds is a basic attribute of binaural hearing. It enables us to draw attention to sound sources–to look at a certain speaker in conversations, or to react to dangers coming from behind. Hearing impaired persons often suffer from a restriction in these abilities. A restoration of hearing abilities should therefore focus not only on monaural and binaural speech reception but also on localization. Sound localization in the horizontal plane is essentially a binaural process and is based on the evaluation of frequency-dependent interaural time and level differences (Middlebrooks and Green, 1991). Along with the evaluation of these cues, interaural time differences (ITDs) derived from the temporal envelope at each ear serve as an additional cue (Grantham, 1995; Henning, 1974). Normal hearing subjects are able to localize wide-band noise stimuli in the frontal horizontal plane very precisely. At more lateral positions the localization error increases. Blauert (1997) states an underestimation of the lateral position of about 10° for the lateral direction 90° and a shift of 1° to the right for the frontal direction.

Some users of cochlear implants (CIs) continue to use a hearing aid (HA) on the non-implanted side after successful cochlear implantation. They report improved speech perception especially in noise, as well as better perception of music when both devices are used together. Some individuals in this bimodal patient group also report improved localization ability. Similar experiences are reported by the group of bilateral cochlear implantees. These subjective experiences suggest that binaural information is transmitted with bimodal combination of CI and HA as well as with bilateral CIs. The purpose of the present study is to assess the impact of the bimodal and bilateral usage on auditory localization. To avoid quantization of the listeners' response scale (Durlach *et al.*, 1981; Hartmann *et al.*, 1998), that would be introduced by the fixed spacing of speakers used in identification methods, a continuous laser pointing technique with high accuracy and resolution is used (Seeber, 2002). Subjects adjust a laser spot projected onto a curtain covering several loudspeakers to the direction of perceived sound incidence.

[a)]Present address: Auditory Perception Lab, University of California at Berkeley, 3210 Tolman Hall #1650, Berkeley, CA 94720-1650. Electronic mail: bernhard_seeber@gmx.de

The computer-controlled laser spot moves smoothly according to the turning of a trackball, which makes this method fast and intuitive. In contrast to previous studies using identification methods, this new method conveys a continuous distribution of perceived angles. This allows for a direct analysis for the parameters of the localization process: error, bias, and variance.

A coarse localization ability has been demonstrated by some users of unilateral cochlear implants. Gray and Baguley (1993) found with three subjects a 43% correct identification of the quadrant of sound origin in a room if head movements were allowed. The subjects of Luntz *et al.* (2002) identified a 1 kHz sinusoid from five frontal, horizontal speakers with a 45° spacing at 27.5% correct, and through training an improvement to 66.5% accuracy could be achieved.

The use of bimodal aids (one CI and one HA) allows the use of binaural cues. Specifically, Dooley *et al.* (1993) reported the utilization of binaural cues of the CI and HA for speech reception when both devices were controlled by a binaural processor. Improved identification of the side of sound origin using bimodal aids was shown by Tyler *et al.* (2002b). Localization studies or identification studies employing more than two speakers with bimodal aids are currently not reported to our knowledge.

The use of binaural cochlear implants has led to several reports of advantages relative to the monolateral case. A binaural advantage for speech reception was demonstrated by, e.g., van Hoesel *et al.* (2002), van Hoesel and Tyler (2003), Lawson *et al.* (1998, 2000), and Müller *et al.* (2002). Additionally, Tyler *et al.* (2002a, b) showed a good side discrimination ability for speakers at ±45°. Van Hoesel *et al.* (2002) demonstrated, for one subject, a good identification ability of 11 speakers with relative errors of about 9° and rms errors of 15–16°. Recently, van Hoesel and Tyler (2003) showed average rms errors of about 10° for source identification with eight speakers. Most of their subjects identified the two frontal speakers with higher accuracy than speakers located on the side. Using monaural aids, most subjects were able to discriminate the side.

Superior localization ability for sources in the horizontal plane requires inputs from both ears. When using an HA and CI in combination, different stimulation schemes complicate an integrated evaluation of bilateral information. Different compression methods and setups in both devices will affect interaural level cues. Different processing times between the CI and HA will lead to an offset in interaural temporal cues. The pulsatile strategy of the CI will not transmit changes in envelope before the next pulse, which creates an additional temporal uncertainty. Thus, it is interesting to see whether a localization ability with a bimodal arrangement can be achieved based on modified interaural cues.

II. METHODS

A. Cochlear implants and hearing aids

The Combi 40+ implant (Med-El, Innsbruck) consists of an intracochlear array of 12 active electrodes spaced 2.4 mm apart, and the CI24M implant (Cochlear, Melbourne) supports 22 active electrodes with 0.75 mm distance. Both implants are equipped with an extracochlear electrode lying on the skull beneath M. Temporalis. The electrodes are activated by an implanted receiver-stimulator, which receives digitally encoded signals from the speech processor via a transcutaneous inductive link. In the case of the Combi 40+ implant the current pulses are delivered to the electrodes in monopolar mode whereby the extracochlear electrode serves as a reference. The CI24M implant electrode wiring can be configured in different ways. The most common electrode configuration is the MP1+2 mode which is used by subject DT. This mode still produces monopolar stimulation, but with reference to two remote electrodes rather than one.

All of the subjects used a BTE speech processor (Med-El: Tempo+, Cochlear: Esprit). The Tempo+ speech processor delivers a high-rate continuous interleaved sampling strategy (CIS) to the implant with 1515 pulses per second (pps) per channel, whereas the Esprit device employs the SPEAK processing strategy with a lower rate of approximately 250 pps per channel (Skinner *et al.*, 1994; Zierhofer *et al.*, 1995).

Within the scope of the study all subjects of the bimodal group were fitted on the non-implanted ear with an identical, digitally programmable hearing aid with directional microphone (Phonak PZ A 4 "Power Zoom," max. amplification 79 dB, max. sound pressure level on output 144 dB/SSPL, DIN IEC 118-0). Program 1 (P1) was adjusted for the omnidirectional microphone, whereas program 2 (P2) used the same setting with a directional microphone. The first adjustment of the amplification was made according to NAL RP procedure (Keidser *et al.*, 1996). After a habituation time of at least one week, a fine tuning of the fitting of the hearing aid was performed for each subject.

B. Bimodal subjects

Eleven postlingually deafened adults (eight female, three male) participated in the bimodal localization experiments. All but one were implanted with the Combi 40+ device. Subject DT received the Nucleus/Cochlear Corporation implant model CI24M operating in MP1+2 mode. The electrode array was fully inserted for all but one subject. For subject JJ three basal electrodes were not available for stimulation because they were external to the cochlea.

Further demographic information regarding the subjects is listed in Table I in which the subjects are ranked according to their hearing loss at the ear fitted with the hearing aid. All subjects had used their cochlear implant a minimum of 6 months. The speech processor programs were the same during and outside the experiments.

The subjects had a wide range of speech perception abilities. For reference, the audition-alone scores when using either HA, CI, or both for a sentence test in quiet are shown in Table I (Baumann, 2001) [Oldenburg sentence test, Wagener *et al.* (1999a, b, c)].

Patients DT and HS show higher-than-average residual hearing on the non-implanted ear of 73 dB and 66 dB PTA, respectively (PTA: pure tone average at 500 Hz, 1 kHz, and 2 kHz). Subject HS was deafened on his right ear due to a blow to the head in his childhood. The blow caused severe

TABLE I. Overview of subjects with bimodal hearing instruments. Subjects are sorted for PTA.

Subject	Age (years)	CI experience[a]	Deafness duration[b]	Aethiology[c]	CI type	CI side	HA use	Pure tone threshold 500	1000	2000	dB HL 4000 Hz	PTA (dB[d])	Sentence HA	CI	CI+HA[e]
HS	28.8	0.8	5.9	Trauma	C40+	r	yes	50	68	80	85	66	100	99	100
DT	79.4	2.0	2.8	pd	CI24M	l	yes	61	78	81	120	73	100	81	100
PG	61.7	3.6	0.3	SHL	C40+	l	no	80	80	75	72	78	2	95	98
BH	34.2	0.5	1.8	pd	C40+	r	no	76	72	90	100	79	0	82	76
JJ	49.8	1.3	1.3	toxic	C40+	l	yes	79	80	80	69	80	0	69	81
RM	27.8	4.2	10.5	pd	C40+	l	yes	91	92	90	72	91	1	72	77
EK	76.2	2.9	0.7	pd	C40+	l	no	105	89	80	81	91	18	94	91
AB	33	0.5	20.9	pd	C40+	l	yes	90	100	110	×	99	44	2	43
RL	63.0	1.1	2.5	pd	C40+	r	no	90	108	118	×	105	6	84	93
EM	22.5	2.0	0.8	Cogan	C40+	l	no	105	105	112	110	107	10	90	95
IS	76.3	0.7	0.7	pd	C40+	r	yes	105	120	×	×	113	6	65	79

[a]Experience with CI in years. AB and RL also conducted a second session 1.9 years later.
[b]Duration of deafness in years before implantation.
[c]For HS and DT see text, pd: progressive degenerative, SHL: sudden hearing loss, toxic: toxic effects of Gentamycin treatment, Cogan: Cogan syndrome.
[d]PTA: Pure tone average at 500 Hz, 1 kHz, and 2 kHz in dB.
[e]Oldenburg sentence test: speech reception in percent (Baumann, 2001).

head trauma and led to a fraction of his skull and cochlea on the right side with immediate deafness and an ongoing tinnitus. His hearing capabilities on the left side were only minorly affected shortly after the accident, but over the years a progressive degeneration of his hearing occurred. The rationale to consider a cochlear implant in the right ear was (1) HS had no residual hearing, which could be damaged by insertion of the electrode; (2) it was expected that due to the progressive hearing loss the left ear will deafen in the next years; and (3) the use of the cochlear implant might mask the annoying tinnitus on the right. Subject DT was not satisfied with the fitting of his hearing aids, although his benefit in terms of speech perception was considerable. He expected a major improvement from the CI. The costs of the implantation were covered by his insurance, and he was implanted at a major German CI center.

As indicated in the row "HA use," six patients (HS, DT,JJ,RM,AB,IS) used their private HA on the non-implanted ear on a regular basis before the beginning of the study. All subjects were fitted with the same type of hearing aid utilized within the study (see above). One week after the first fit of the study HA a fine tuning was accomplished. The localization experiments were executed 2–6 weeks after the fine tuning. All subjects used the study HA/CI combination before the study had started, although BH did not use the study HA on a regular basis.

C. Bilateral subjects

Four subjects wearing cochlear implants bilaterally participated in the localization experiments. Demographic data of the subjects are given in Table II (age 20–65 years, Med-El C40/C40+). All subjects had worn their first implant for 2.2 to 6.7 years. The experience with bilateral CI was at least 0.8 years. All bimodal and bilateral subjects received a payment for their participation.

D. Apparatus

The localization experiments take place in a completely darkened anechoic chamber (dimensions L×W×H=7.5 ×4.2×2.8 m^3) in which the apparatus is installed. Eleven identical closed-cabinet loudspeakers are mounted on a circular tube with a radius of $r = 1.95$ m at ear level of the subject. The speakers span an angle of $-50°$ left to $+50°$ right with a spacing of 10°. The frequency response of each speaker is individually equalized by an FIR-filter to 125 Hz to 20 kHz in ±2.5 dB at the subject's head position. The speakers are switched by a custom-made relay-unit using a PC-type computer. Light emitting diodes (LEDs) are mounted at a distance of 10 cm concentric in front of each speaker. A laser spot is projected onto a curtain in front of the loudspeakers. The curtain is opaque for the subject's gaze but acoustically transparent and translucent for the light of the

TABLE II. Overview of subjects with bilateral CI. Subjects are sorted for experience.

Subject	Age (years)	CI first[a]	CI second[b]	Deafness first[c]	Deafness second[d]	Aethiology First	Aethiology second	Implant first	Implant second	CI first[e]
BW	49.1	2.9	1.9	1.1	2.1	otosclerosis		C40+	C40+	r
IB	65.1	2.2	1	>20	10	prog. degen.	Menier	C40+	C40+	r
KH	51.3	6.5	0.9	21	21	prog. degen.	head inj.	C40	C40+	r
RL	19.8	6.7	0.8	>10	>10	prog. hereditary		C40+	C40+	l

[a]Experience with first CI in years at time of first session. BW also conducted a second session 1.3 years later.
[b]Experience with bilateral CI in years.
[c]Duration of deafness before implantation on the first implanted ear in years.
[d]Duration of deafness before implantation on the second implanted ear in years.
[e]First implanted ear.

LEDs. The laser beam is deflected in the x and y direction by two laser-scanner galvanometers which are controlled by a digital-to-analog converter from a computer. Subjects indicate the perceived position of the sound source by a trackball. The projected laser spot is moved smoothly according to the rotation of the trackball on a horizontal track in front of the speakers. The laser spot can be positioned with a precision better than 0.2° at any point on the track within an angle of $-70°$ left to $+70°$ right. A computer performs the coordinate transformation between the angle of the laser spot seen by the subject and the deflection of the laser beam using calibration data. The filtered digital sound data (16 bit, $f_s = 44\,100$ Hz) are written out through a digital soundcard to an external D/A-converter. The speaker signal is amplified and calibrated with a voltmeter before reaching the switching unit. The experimental procedure is controlled by a Matlab routine with the help of customized interface software for the experimental setup. A detailed description of the apparatus and the method can be found in Seeber (2002).

E. Procedures

During the experiments, the subject sat on a chair in the center of the speaker array. The head was stabilized by a head rest and the subject was instructed not to move his or her head. The subject was monitored through an infrared camera which allowed the detection of movements. The sensitivity adjustment of the speech processor for the CI and the amplification of the HA were adjusted prior to the experiments to give the perception of equal loudness at both ears for a speech signal arriving from the front of the subject. However, this was difficult to achieve for some subjects who had a small amount of residual hearing, because feedback problems limited the amplification of the HA.

At the beginning of an experiment, a light appeared directly in front of the subject for 5 s in a completely darkened anechoic chamber. This allowed the subject to align his or her head to the frontal direction. After a pause of 500 ms a target sound was presented in a randomly selected angle within $-50°$ left to $+50°$ right in 10° intervals. Gaussian white noise (125 Hz to 20 kHz) served as a target sound which was divided into five pulses (pulse duration 30 ms, duration of pauses 70 ms, 3-ms Gaussian-shaped slopes). The wide-band noise stimulus was chosen in order to provide the subject with interaural level (ILD) and time difference (ITD) cues used for localization, that are consistent throughout the audible frequency range. Further, the stimulus was pulsed to give information through interaural temporal envelope differences for localization (Middlebrooks and Green, 1991). The pause duration in pulsation was chosen to be long enough for most CI patients to allow for the detection of the gap (Busby and Clark, 1999).

The sound pressure level of the noise was randomly varied in 3-dB steps between 64 and 76 dB SPL. This roving level paradigm should prevent the subject from using information about the sound level obtained by the ear next to the speaker. This range of levels was selected to correspond to the level difference of 12 dB that produces a complete lateralization of wide-band noise for subjects with normal hearing (Blauert, 1997). Due to recruitment effects, the level could not be increased beyond 76 dB SPL. In some conditions subjects reported this stimulus to be very loud whereas few subjects had difficulties in detecting the soft stimulus with the monaural HA.

After the target presentation and a pause of 500 ms, a light spot appeared at 0° in front of the subject. The subject's task was to adjust the light spot with the trackball to the perceived direction of sound incidence. By pressing one of the trackball buttons the subject acknowledged the indicated direction and the light spot disappeared. The procedure was intuitive for all subjects. After a pause of 500 ms, the next trial started with the presentation of the target sound from a different angle. The presentation of all 11 directions formed a block. Between blocks an LED for the head alignment of the subject lit up for five seconds to prevent an incorrect head orientation. In total, subjects conducted ten blocks (110 trials $=10$ blocks $\times 11$ directions). To accomplish the roving level paradigm for each direction five different levels were randomly assigned to the ten repetitions, whereas every level step occurred twice. One experiment with a total of 110 trials was performed in about 11 min.

Prior to the experiment, a randomized presentation of every sound source direction was given to the subject. For a better familiarization with the experimental method, feedback was given in this part through an LED that showed the position of the correct response after pressing the input button.

The bimodal subject group performed the localization experiments in the conditions: CI only (captioned in Table III as CI), CI and HA in omni-directional mode (CI+HA P1), and CI and HA in directional mode (CI+HA P2). Due to the limited time, not all subjects were able to perform the experiment in the HA only condition (HA). Subjects AB and RL conducted the HA only condition 1.9 years later (cf. Table III). The experimental order of the conditions CI only, CI +HA, and HA only was varied between subjects.

The bilateral subject group performed the experiment in three conditions: CI bilateral (CI+CI), or monolateral on both sides (1st CI/2nd CI). Experimental order was varied. Due to time limitations RL conducted only the bilateral test.

Subjects BW and KH were additionally tested in a fixed level condition whereby instead of the roving level paradigm a fixed level of 70 dB SPL was used for the presentation of the stimuli. Subject BW performed a retest 1.3 years later (see Table IV for details).

III. RESULTS

A. Localization with bimodal aids

Figure 1 displays the individual localization results for all subjects. The median responses for the different conditions are depicted with different symbols [CI only (○), HA only (□), and the bimodal configuration CI plus HA (∗), HA with omnidirectional microphone], the errorbars show the quartile range.

A detailed statistical analysis of the localization results is provided in Table III. Purely error-based statistics are given in the first three columns: the absolute localization error calculated for all responses, the mean deviation of the

TABLE III. Statistical analysis of localization results of bimodal hearing aid users: absolute and arithmetical (relative) localization error, quartiles, correlation coefficient, coefficients of regression line, and test for side differentiation.

Subject	Condition	Error (°) Absolute[a]	Error (°) Arithmetical[b]	Quartiles (°)[c]	Correlation coefficient[d]	Regression line Slope	Regression line Offset	Side differentiation[e]
HS	CI	22.2	10.2	11.4	0.51**	0.41	9.6	**
	CI+HA P1	10.3	8.5	4.5	0.94**	0.80	6.9	**
	CI+HA P2	9.4	6.7	5.1	0.95**	0.83	6.1	**
	HA P1	20.7	−8.9	15.7	0.42**	0.36	−11.0	*
DT	CI	27.3	−9.4	1.5	0.16	0.02	−9.5	+
	CI+HA P1	18.6	8.7	5.7	0.77**	0.36	6.5	**
PG	CI	20.6	10.0	12.4	0.46**	0.29	3.4	**
	CI+HA P1	13.8	−1.4	10.8	0.74**	0.76	−2.3	**
	HA P1	26.1	−9.1	4.8	−0.10	−0.02	−6.6	
BH	CI	31.9	14.5	19.9	0.01	0.01	10.5	
	CI+HA P1	28.4	−0.3	14.8	0.01	0.01	3.0	
	HA P1	36.1	−11.7	19.4	0.11	0.11	−9.6	
JJ	CI	27.6	−14.0	5.6	0.02	0.01	−13.9	
	CI+HA P1	29.4	−10.4	4.5	−0.21+	−0.07	−9.5	+
RM	CI	23.6	−7.4	7.8	0.21+	0.17	−8.2	
	CI+HA P1	33.4	−23.7	9.9	0.03	0.03	−21.8	
	HA P1	23.7	16.9	19.6	0.39**	0.43	20.4	**
EK	CI	20.7	−7.7	12.0	0.36**	0.26	−8.2	*
	CI+HA P1	19.1	0.0	13.2	0.44**	0.36	−0.1	**
	HA P1	24.4	8.3	13.1	0.06	0.03	3.9	
AB	CI	22.8	2.0	13.3	0.36**	0.25	−1.7	*
	CI+HA P1	26.2	−6.2	15.0	0.12	0.08	−4.9	
	HA[f]	28.4	−2.7	16.7	0.19+	0.16	−0.6	
RL	CI	22.3	9.3	13.4	0.08	0.06	8.6	
	CI+HA P1	19.3	4.1	7.8	0.32**	0.21	6.2	+
	HA[f]	22.6	−5.7	13.0	0.30*	0.17	−2.4	+
EM	CI	21.5	−7.6	13.6	0.34**	0.31	−10.7	+
	CI+HA P1	24.2	4.5	12.0	0.43**	0.50	−4.3	**
IS	CI	29.0	10.1	8.8	−0.04	−0.02	13.3	
	CI+HA P1	21.5	2.6	8.0	0.34**	0.36	1.4	**

[a]Absolute error: mean absolute deviation of single localization results from presented direction.
[b]Relative, arithmetical error: mean deviation of single localization results from presented direction.
[c]Average value of single quartiles.
[d]Significance of correlation coefficient: ** 0.001, * 0.01, +0.05.
[e]Differentiation of side of sound origin: Wilcoxon rank sum test on identity of the results of −50° and −40° (pooled) vs. +40° and +50° (pooled). Results for both sides are significantly different at ** 0.001, * 0.01, +0.05.
[f]Results of second session 1.9 years later.

responses from the presented direction (relative error), and the average size of a single quartile. Additionally, the correlation coefficient calculated between responses and presented positions is added in the next column. A linear regression has been carried out furthermore for each observer and condition to calculate the best fitting slopes. The results of this regression are included in terms of slope and offset. Although a single regression line cannot model some of the data, it shows how far the indicated positions follow the presented positions on average for the entire span. The last column of Table III presents a statistical measure for the discriminability of the side of sound origin. The level of significance is given by which the pooled results for −50° and −40° on the left side are not equal to the results for +50° and +40° on the right side (Wilcoxon rank sum test).

The individual localization results of the bimodal subject group in Fig. 1 differ to a large extent. While subjects BH, JJ, AB, and RM show no localization ability at all, subjects EM, IS, EK, and RL are able to discriminate the side of sound origin using both devices. Subjects DT and PG demonstrate limited localization ability, whereas subject HS is able to localize with high accuracy in the bimodal condition.

The left part of Fig. 2 displays the responses of subject HS in the monaural conditions CI only and HA only in detail. Even in the monaural conditions the response positions correlate relatively well with the presented positions (CI

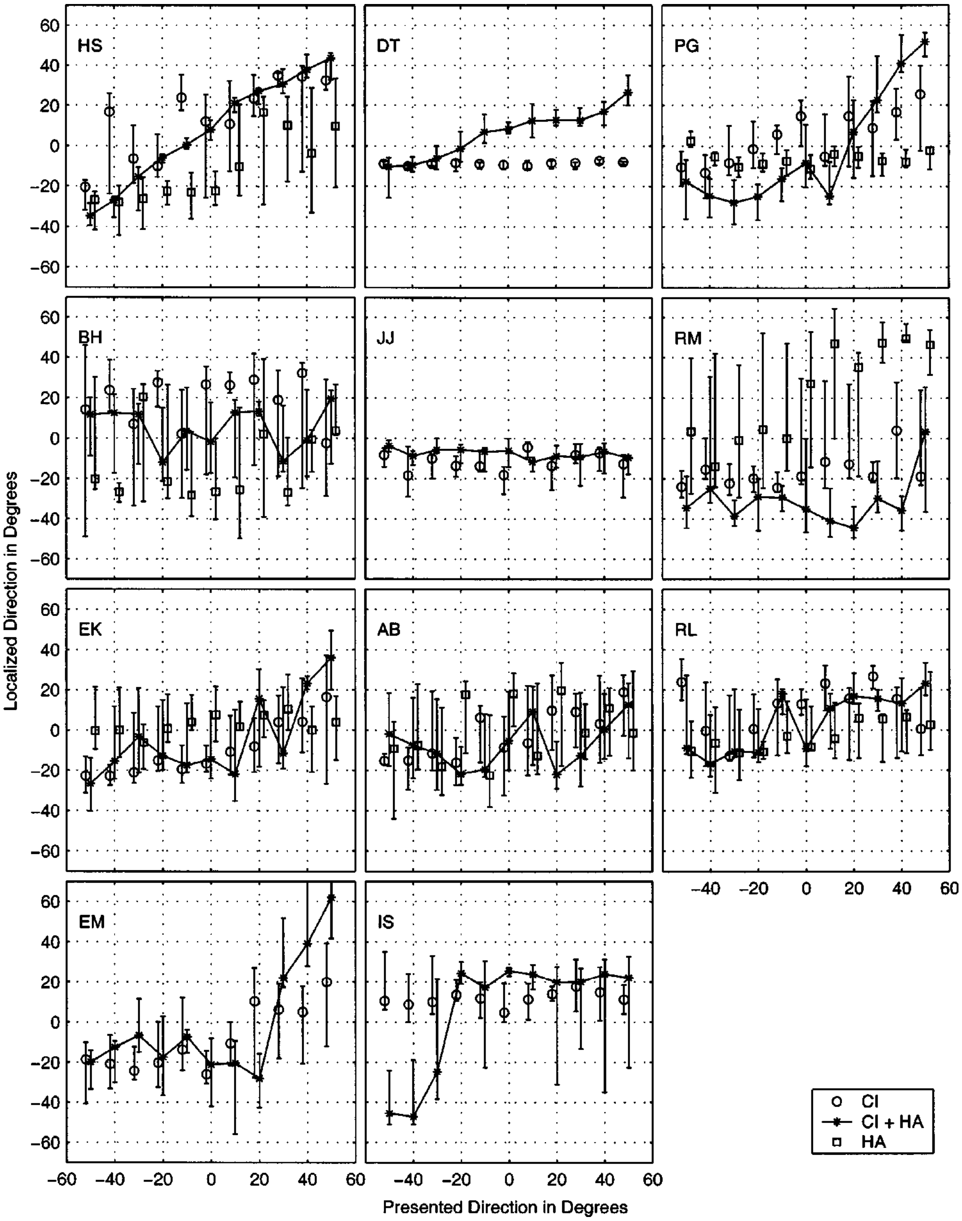

FIG. 1. Medians and quartile ranges of localization responses of the bimodal subject group. Conditions: CI only (○), CI+HA P1 omni (∗), HA only P1 omni (□).

only: 0.51, HA only: 0.42). The monaural information seems to be sufficient to allow for a rough discrimination of the side of sound origin, as can be deduced from the slope of the regression line and further statistical testing (last column of Table III).

The bimodal condition (Fig. 2, right) allows subject HS to respond with high accuracy to the presented position. In the bimodal condition the correlation of response position with presented position increases to 0.94 and the slope of the regression line to 0.8. The average quartiles decrease from

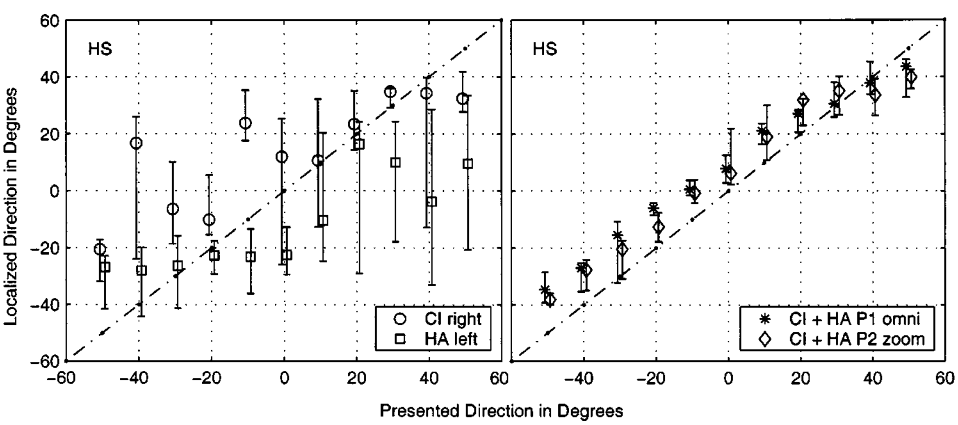

FIG. 2. Localization responses of subject HS. Left: monaural conditions (replotted from Fig. 1): CI only (○), HA only P1 (□). Right: impact of the directional microphone setting, bimodal condition: CI+HA P1 omni (∗) or CI+HA P2 zoom (◇). Medians and quartile ranges.

TABLE IV. Statistical analysis of localization results of bilateral cochlear implant users (CI): absolute and arithmetical (relative) localization error, quartiles, correlation coefficient, coefficients of regression line, and test for side differentiation. The data are calculated as in Table III.

Subject	Condition	Error (°) Absolute	Error (°) Arithmetical	Quartiles (°)	Correlation coefficient	Regression line Slope	Regression line Offset	Side differentiation
BW	1st CI[a]	30.0	−17.3	25.7	0.36**	0.48	−8.6	*
	CI+CI	6.2	0.6	4.4	0.97**	1.15	−0.5	**
	CI+CI fix SPL[b]	4.9	−0.7	4.0	0.97**	1.06	−1.8	**
	2nd CI	25.9	8.3	19.4	0.14	0.15	5.3	
	2nd CI fix SPL[b]	24.5	10.3	15.9	0.02	0.02	3.3	
IB	1st CI	21.4	−8.4	14.5	0.39**	0.27	−6.8	+
	CI+CI	19.5	−15.4	6.3	0.75**	0.53	−16.4	**
	2nd CI	36.6	−36.6	10.0	−0.18	−0.09	−37.5	
KH	1st CI	38.6	−0.0	18.0	0.01	0.01	−1.1	
	CI+CI	16.9	0.0	8.4	0.72**	0.57	0.2	**
	2nd CI	28.1	10.7	15.5	0.21+	0.23	3.3	+
RL	CI+CI	17.3	−3.8	11.6	0.53**	0.45	0.4	*

[a]Results of second session 1.3 years later.
[b]Condition with fixed level of 70 dB SPL.

11.4° (CI only) or 15.7° (HA only) to 4.5° (CI+HA P1) and 5.1° (CI+HA P2) in the bimodal conditions. The response distributions for the monaural and binaural conditions differ significantly (Wilcoxon rank sum test on responses per direction, α-corrected for 11 directions, significant at 5% for the conditions: CI only vs. HA only, CI only vs. CI+HA P1, and HA only vs. CI+HA P1). The test for side discrimination is highly significant at $p<10^{-7}$. These results confirm the high localization ability of HS in the bimodal condition.

The localization ability of HS remains unchanged if the directional microphone setting (P2) is used instead of the omnidirectional program (P1) in the CI+HA condition (Wilcoxon rank sum test, α-corrected, *not* significant at 30%). As the directional microphone setting shows also no substantial influence on the localization results for the other subjects, further results with CI+HA P2 are not presented.

Subjects DT and PG show limited localization ability with reduced discrimination of sound source direction in the bimodal condition. The slope of the responses of DT is shallow (0.36) with low variance (CI vs. CI+HA P1 significant at 1%, side discrimination for CI+HA P1 at $p<10^{-7}$). In the CI only condition, subject DT is unable to indicate the side of sound origin properly, rather he responded to every stimulus by pointing to approximately −10° with a very small variance (average quartile of 1.5°). Subject PG distinguishes the side using the CI only but not using the HA only. Although the slope of the regression line is higher in the bimodal condition for subject PG, the high variability of the responses indicates limited localization capability (CI vs. CI+HA P1 and HA vs. CI+HA P1 significant at 1%, side discrimination for CI+HA P1 at $p<10^{-7}$).

Subjects EM, EK, IS, and to a limited extent RL, show some benefits in the bimodal condition. Using both devices they are able to discriminate the side of sound origin, especially for more lateral positions (side discrimination test for CI+HA P1 significant at 1% for EM, EK, IS; at 5% for RL; Wilcoxon rank sum test, α-corrected: RL and EK: 5% significance for HA vs. CI+HA P1; EK 5% significance for HA vs. CI). The results of subject EM also show a high regression slope (0.50) in the bimodal condition, but a discrimination of directions can only be seen between +20° and +50°. Subject EK, and with less accuracy EM and RL, are able to discriminate the side of the sound source in a monaural condition.

Subject RM shows a reduction in localization performance in the bimodal condition compared to the HA only condition. However, this reduction is probably not based on a reduction in localization ability; RM reported not being able to hear any directional change in any test condition. The data for RM indicate that this subject used a loudness criterion in the HA only condition; extremely loud sounds were indicated towards the HA side, whereas soft sounds were reported at the contralateral side. In this way, the applied roving level paradigm may have been overridden.

Subjects BH, JJ, RM, and AB were not able to improve their localization skills in the bimodal condition. None of the statistical parameters in Table III show a clear improvement in comparison to the HA only or CI only condition.

In summary, about half of the subjects showed improvement over unilateral performance, but one subject (HS) showed dramatic improvements and was able to perform nearly as well as normal-hearing subjects.

B. Localization with bilateral cochlear implants

The localization results of the bilaterally implanted subject group are presented in Fig. 3. Different symbols depict median responses for the monolateral conditions (either condition 1st CI or 2nd CI only) or the bilateral condition. Errorbars show quartile ranges. The results of the statistical analysis of the responses are shown in Table IV. Compared to the monolateral responses, all three subjects tested both monolaterally and bilaterally were better in the bilateral CI condition in terms of absolute error, quartile range, and correlation coefficient. The slope of the linear regression increased as well.

Using the first implanted CI, subject BW is able to differentiate the side of sound origin; the direction of sounds coming from the nonsupplied side can be roughly estimated, but sounds originating at the CI side are judged to the front. Using only the second implanted CI no side discrimination seems possible, but in the bilateral condition, BW's localization ability improves significantly (Wilcoxon rank sum test, α-corrected: 1st CI only vs. bilateral CI condition at 1%; 2nd CI only vs. bilateral CI condition at 5%). Compared to the results of the other three subjects of the bilateral group, BW's localization ability is very accurate. In the bilateral CI condition the quartile range is 4.4° and the averaged error amounts to 6.2° absolute, and 0.6° relative. The correlation between presented direction and localization response is as high as 0.97 using the roving-level procedure.

Figure 4 displays BW's localization results in the 2nd CI only and bilateral CI condition with fixed level presentation of the target sounds. As can be seen, this additional level cue does not improve localization in either condition. No change in the responses with and without the level rove is observed (Wilcoxon rank sum test, α-corrected: roving vs. fixed level presentation 2nd CI condition: $p > 40\%$, bilateral CI condition: $p > 10\%$).

Subject IB (Fig. 3, upper right) is also able to discriminate the side of sound origin in the 1st CI only condition. Like BW, IB did not show this ability in the 2nd CI only condition. In the bilateral CI condition, IB is able to perform minimal localization, which is reflected in an increase of the regression slope to 0.53 and also in a reduction of the quartiles from 10–15° to 6.3°. Furthermore, the correlation between presented direction and localization response increases from 0.39 to 0.75 (Wilcoxon, α-corrected, significant at 1% for 2nd CI only vs. bilateral CIs condition and 1st CI only vs. 2nd CI only condition).

Subject KH shows similar results as IB, although KH is not able to discriminate the side of sound origin in the 1st CI only condition. In the bilateral CI condition the average quartile range is substantially smaller than in the two monolateral CI conditions. The correlation between presented direction and localization response increases from 0.21 to 0.72. (Wilcoxon, α-corrected, significant at 5% for 1st and 2nd CI only vs. bilateral CI condition). RL's localization abilities are limited compared to the other subjects. His data shows the weakest correlation between presented direction and localization response (0.52), but he is still able to discriminate the side of sound origin ($p = 0.01$).

To summarize, all four subjects show the ability to localize sounds with bilateral CIs, whereas subject BW shows localization ability close to normal-hearing subjects.

IV. DISCUSSION

A. Bimodal aids

The localization results of the bimodal subject group demonstrate an unexpected high localization ability in several subjects. In particular, subject HS shows an excellent localization ability. This is to our knowledge the first report of such highly skilled localization abilities in a subject with a cochlear implant in one ear and a hearing aid in the opposite ear. This is reflected by small average quartiles for his localization responses (4.5°) and by a strong correlation between presented direction and localization response (0.94). The average quartiles are close to the accuracy of normal-hearing subjects (1.7°), as reported by Seeber (2002), obtained with the same experimental setup. Compared to HS's outstanding accuracy, DT and PG show poorer localization performance, although it is well above chance. Subjects EM, EK, IS, and RL can discriminate the side of sound origin correctly, whereas BH, JJ, AB, and RM respond without any relation to the presented sound direction. Considering monolateral performance, five subjects, HS, PG, EK, AB, and EM, discriminated the side of sound origin using the CI alone, whereas only HS did so reliably using the HA alone.

Subjects HS, DT, and PG especially benefited from the bimodal configuration. These subjects have the highest amount of residual hearing and the smallest PTA hearing loss in our bimodal subject group (Table I). Audiograms were collected for all of our subjects to assess the amount of residual hearing on the implanted side. The majority of the subjects including subject HS showed no residual hearing. Several subjects showed a "left corner audiogram" (70 dB HL at 125 Hz, 120 dB at 500 Hz). At these high sound levels the mechanical vibration of the headphone and the skull might lead to a sensation of vibration which is often difficult to differentiate from residual hearing. In any case, it seems impossible that the subjects might have used residual hearing at the implanted side during the experiment. This is because the presentation level of the test signals was below their residual hearing threshold. Somewhat surprising is the fact that three subjects (IS,EM,RL), who are able to differentiate sides, are the subjects with the worst PTAs >105 dB. The data are consistent with the hypothesis that a high amount of residual hearing is a prerequisite for bimodal localization although not necessary for a bimodal advantage in terms of side discrimination.

Tyler *et al.* (2002b) showed an improvement of side discrimination with bimodal aids in two of three subjects in a source identification task using two speakers at ±45° positions. The subject without improvement in the bimodal condition performed already above chance using the implant alone, whereas the other two subjects were at chance level in the monolateral condition. As the task involved only two speakers, the localization ability of the subjects cannot be inferred in terms of error and variance. Although the study reported here used a more demanding localization task the results for side discrimination of our bimodal subject group seem to be in line with the results obtained by Tyler *et al.* The statistical test for side discrimination showed significant results at a 0.1% significance level in 6 out of 11 subjects of our bimodal subject group.

B. Bilateral cochlear implants

The bilateral CI subject group demonstrated localization abilities with varying accuracy and one top performing subject (BW). BW's localization accuracy in the bilateral CI condition, as shown with our experimental setup, is to our

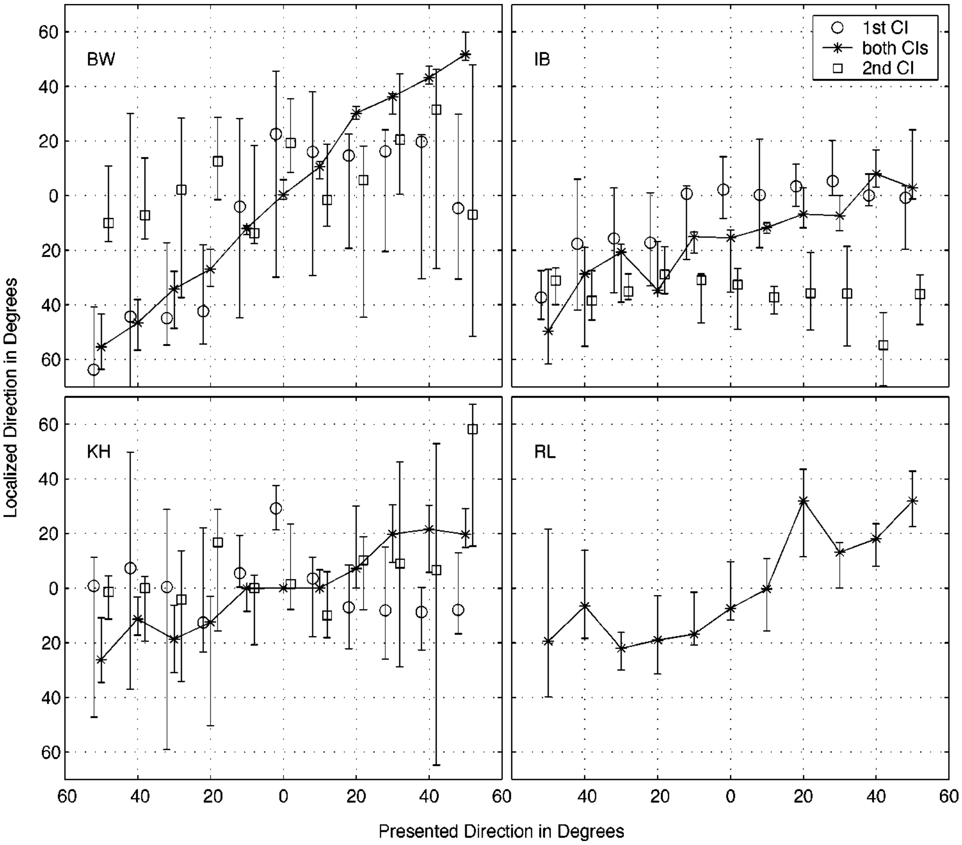

FIG. 3. Medians and quartile ranges of localization results of the bilateral CI subject group for the conditions 1st CI only (○), bilateral CIs (∗), or 2nd CI only (□).

knowledge unparalleled in the CI literature. The average quartiles of BW's localization responses amount to 4.4° and the slope of the regression is 1.15.

Side discrimination tests done by the Iowa group show a bilateral benefit for most of their bilateral CI users. All subjects in one group showed a nearly 100% correct score for the identification of speakers at ±45° (Gantz *et al.*, 2002). In a similar study the performance of six out of seven subjects increased with bilateral CIs (Tyler *et al.*, 2002a). A source identification study with only one subject of van Hoesel *et al.* (2002) in an 11-speaker array showed a level-dependent localization rms-error of about 16° at 70 dB SPL and 8° at 60 dB SPL. The standard deviation was 18° and 13°, respectively. In the monolateral CI conditions the subject was not able to discriminate the side of sound origin. A more recent identification study of van Hoesel and Tyler (2003) showed varying localization ability in five subjects. Average rms errors were about 10°, with one top performing subject who was able to identify the two frontal speakers at 2.5° rms-error. Three of five subjects demonstrated a limited localization ability in the monolateral CI condition. However, the remarkable localization accuracy reported by van Hoesel and Tyler (2003) should not be interpreted in terms of a characterization of the parameters of the underlying localization process, i.e., variance, error, and bias, as the distance of the loudspeakers in the array was much higher (15.5°) than the observed error/variance (down to 2.5°). Using a numerical model of identification methods, Hartmann *et al.* (1998) found that the experimentally observed localization error can be significantly smaller than the actual error of the localization process if the variance of the localization process is small compared to the source's separations (cf. their Fig. 1). According to their simulation the observed rms-error will underestimate the true rms-error by 30% for a source spacing

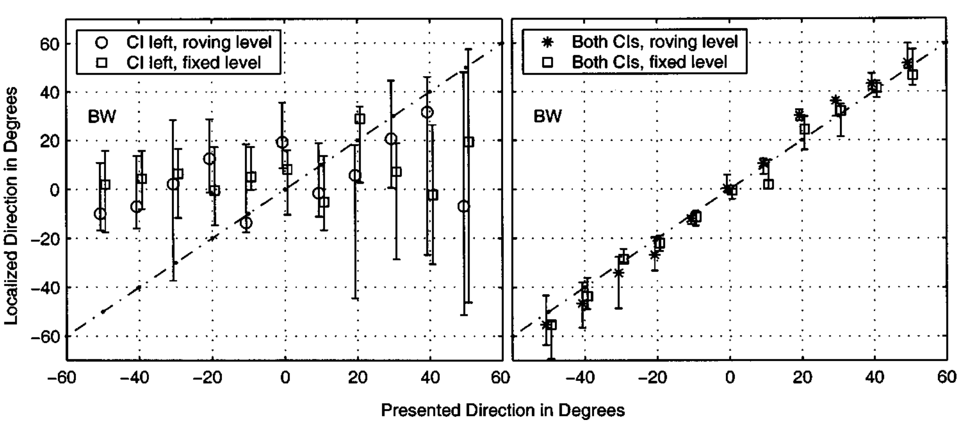

FIG. 4. Influence of the roving level paradigm in the localization results of subject BW. Left: 2nd CI only condition for the roving (64–76 dB SPL, ○) and the fixed (70 dB SPL, □) level condition. Right: bilateral CI condition roving (∗) and fixed (□) level presentation. Medians and quartile ranges.

about four times the error, e.g., for a 15.5° spacing and errors about 3.5° as in van Hoesel and Tyler (2003). The simulation has further shown that in some conditions with bias, the characteristics of the auditory system cannot be recovered from the observed localization responses [cf. Fig. 6 in Hartmann *et al.* (1998)]. Because bias effects are common in CI studies (e.g., with monaural devices or through slightly different adjustment of the AGCs or the amplification of both devices), the results from identification methods should be interpreted with caution. Thus, currently used source identification methods with a fairly large speaker spacing cannot characterize the localization ability of top performing subjects. On the contrary, the continuous localization method employed in our study allows a more straightforward interpretation of the localization data in terms of error and variance as the spacial resolution of the responses is virtually unlimited.

The outstanding localization results of the bilateral CI subject BW might be partly due to an intense localization training in his daily life. BW works as a teacher in a secondary school and needs to address his pupils in response to their comments even when standing at the blackboard with his back to them.

C. Utility of available cues

The observed improvement of localization abilities in the bimodal or bilateral conditions compared to the monolateral conditions indicates the capability of the auditory system to use degraded information from binaural stimulation for localization. Since the overall level is randomized, this information could be derived from (1) monaural spectral information at each ear, (2) interaural time differences (ITDs), and (3) interaural level differences (ILDs).

1. Monaural information

The results of the tests conducted in the monolateral conditions showed that monaural spectral information is sufficient only for the detection of the side of sound origin. Only one subject (HS) was able to use monaural cues in both monolateral conditions. Thus monaural spectral information at two ears is an unlikely cue to explain the high localization accuracy observed in our best performing subjects.

2. ITD cues

Subject BW of our study shows a precision of localization of 4.4° (quartiles) which corresponds to an ITD of about 40 μs (Feddersen *et al.*, 1957).

The mapping of temporal information through cochlear implants is influenced by the pulsatile stimulation employed. The CIS strategy samples the temporal envelope information in frequency bands at a fixed, continuous pulse rate. A population of spiral ganglion cells is stimulated phase-locked to the pulses with an interpulse-interval of about 660 μs or multiples thereof. In normal hearing instead, the discharge pattern on the auditory nerve is phase-locked to certain phases of the sound stimulus (Klinke and Hartmann, 1997). Therefore the electric pulsatile stimulation does not allow a direct temporal coding of phase-related ITD. A temporal change in the envelope in a certain frequency channel, however, will still maintain an amplitude change in the stimulating current. Due to the refractory characteristic of ganglion cells, this will result in a temporal correlation of activity in the auditory nerve to the maximum of the temporal envelope of the band-pass filtered acoustic signal. Assuming that differences of the interaural temporal envelope are integrated over several stimulus pulses, localization could be based on this process in the bimodal and bilateral conditions. An integrative behavior in terms of envelope analysis could overcome the limitations in ITD mapping due to unsynchronized stimulation in the bilateral CI condition. The expected sensitivity to envelope ITDs would therefore depend on the pulse rate and the mechanism that is hypothesized. In the bimodal condition different processing times of CIs and HAs will result in offsets and additionally affect the interpretation of ITDs. However, if these offsets are small, the subjects could potentially adapt their localization to this offset (Gold and Knudsen, 2000; Hofman *et al.*, 1998; Shinn-Cunningham, 2001; Welch, 1986).

Lawson *et al.* (2001) demonstrated the ability to detect changes in envelope-ITDs in unsynchronized pulse trains as low as 25 μs in two of their bilateral CI subjects. Van Hoesel and Tyler (2003) in contrast measured with their subjects detection thresholds of 120 μs for ITDs in envelope and pulse train. For synchronized pulse trains containing a purely envelope-based ITD the threshold rose to 290 μs (one subject).

The ITD detection thresholds for pulse trains using synchronized processors vary highly. Early studies found thresholds of 0.5 to 1.5 ms (van Hoesel and Clark, 1997), whereas the best thresholds are often lower in more recently published studies: 150 μs (Lawson *et al.*, 1998), 90–180 μs (van Hoesel and Tyler, 2003), and 50–150 μs for selected electrode combinations (Lawson *et al.*, 2000). Subject BW also participated in the study of Lawson and co-workers (2000). He showed ITD JND's down to 50 μs for one electrode combination. On most electrode pairs, however, ITD JND's were raised to several hundred microseconds (median 500 μs). In our study, the precision of localization of subject BW would correspond to about 40 μs (quartiles 4.4°, cf. Feddersen *et al.*, 1957) and is thus nearly a magnitude more exact than the average detection threshold with synchronized stimulation. Wightman and Kistler (1996) emphasize that the binaural system always refers to the most reliable available cue. Obviously, the auditory system could base localization on the ITD-evaluation at few electrode combinations with good ITD-detection thresholds, but as ITD-detection thresholds are highly different on different electrodes it seems more likely that this inconsistent ITD information is completely ignored as unreliable. In fact, in a subsequent study BW was not able to localize pulsed low-pass noise that provided ITD cues through evaluation of the interaural phase and the envelope of the signal. In contrast, high-pass noise with a slow envelope rise-time of 200 ms was localized. This emphasizes the importance of evaluation of ILD cues (Seeber, 2003).

3. ILD cues

The CI stimulates regions corresponding to relatively high characteristic frequencies due to its limited insertion depth. The sensorineural hearing loss limits the usable frequency range on the contralateral side fitted with the HA instead to lower frequencies (Table I). Only a limited overlapping frequency range can thus be used for the processing of binaural cues in the bimodal condition. For subjects of the bimodal group with PTAs >79 dB hearing loss (7 of the 11 subjects), the hearing aid cannot provide sufficient amplification for frequencies $\geqslant 2$ kHz. All these subjects show no localization ability, which might be due to a limited availability or the distortion of ILDs at higher frequencies. Subjects JJ, EM, and EK show a decrease of their hearing loss with increasing frequency. Therefore they might be able to evaluate ILDs. Actually, EM and EK were able to discriminate the side of sound origin.

HS, DT, and PG had considerably lower hearing loss than the other subjects of the bimodal group and the hearing aid allowed a partial loudness compensation. They were able to localize. If the localization process in the bimodal condition relies on ILDs, it has to compare the signals from two different stimulation schemes for intensity. To compensate for the limited pitch matching at both sides, an integrative behavior to form a gross-ILD over several frequency channels could be employed (Macpherson and Middlebrooks, 2002).

Concerning the bilateral CI condition, it has been reported that the ILD-detection thresholds are generally low. The neural ILD thresholds are usually in the range of 1–3 current units, which is equal to 16 μA (0.125 dB) at 1.1 mA (9.5 dB) dynamic range (Lawson *et al.*, 2000, 1998). Since the internal signal processing and generation of the receiver is digital, the resolution of the current pulse amplitude is limited by the size of the digital steps. In the case of the MED-EL Combi40+ device, this resolution is 7 bit linear providing 128 current steps resulting in a current amplitude range of 42 dB. The minimal current step size is adjusted for each electrode channel by the fitting program to either 2.4, 4.2, 7.7, or 13.6 μA depending on the specific current pulse amplitude a patient requires for gaining a comfortable loudness sensation (MED-EL, 2000). Since this fitting is set for each channel individually, a situation can occur where a CI user can detect a small ILD in one channel, whereas the same difference presented on another channel cannot be detected (Lawson *et al.*, 2000).

The preprocessing in the speech processor maps the large acoustical dynamic range to the smaller electrical dynamic range at electrode level. This compression is realized by an analog compression scheme as well as by a mapping of the channel envelope information to current levels according to a logarithmic function. Assuming the same compression ratio is employed in CI processor and the HA, it is obvious that ILDs are reduced. More complicated, the compression change at the onset level (kneepoint) which marks the start of the compressive behavior may also distort ILDs. This distortion occurs if compression is employed on one side while the head shadow effect damps the signal below kneepoint-level on the other side. As a result, the ILD is dependent on the input level, which might affect localization ability (van Hoesel *et al.*, 2002).

To estimate the usefulness of ILD cues for localization the level transformation in the processor has to be considered. If a 3:1 compression of the analog dynamic range of about 40 dB to an electrical dynamic range of 10–20 dB is assumed, an acoustical ILD detection threshold of about 0.4 dB follows for an internal ILD threshold at the nerve of 0.125 dB (Lawson *et al.*, 2000, 1998). For changes of the physical overall ILD of 0.1 dB/° (van Hoesel *et al.*, 2002) a theoretical minimum audible angle of 4° results. This is well in line with the results of top performing subject BW (quartiles 4.5°).

V. CONCLUSIONS

We have shown that a successful restoration of the localization ability in the frontal horizontal plane in deaf patients is possible by means of bilateral cochlear implantation or, in the case of sufficient residual hearing for one ear, by means of a bimodal fitting with a cochlear implant on one ear and a hearing aid on the other ear. The best performing subjects showed an accuracy (average quartiles of localization responses 4.4°) near to normal-hearing subjects (quartiles 1.7°). We believe that ILDs are the most likely cue to enable this high localization precision, when ITD information is restricted to the interaural time differences in the envelope of the signal.

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