Head Shadow, Squelch, and Summation Effects in Bilateral Users of the MED-EL COMBI 40/40+ Cochlear Implant

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Objective: The aim of the study was to investigate the impact of bilateral cochlear implant use on speech perception in noise in bilateral users of the MED-EL COMBI 40/40+ cochlear implants.

Design: Speech reception thresholds were measured in 21 subjects using the Oldenburg sentence test. Speech was always presented from the front. Noise was either presented from the front, from the left side, or from the right side. Each condition was measured for unilateral and bilateral implant use.

Results: For three subjects, the test was too difficult to be administered. The 18 subjects from whom a complete data set could be obtained showed a significant head shadow effect and summation effect for all test conditions, whereas the squelch effect was significant for noise from the left side only. Average effect sizes were significant for all effects and amounted to 6.8 dB for the head shadow effect, 0.9 dB for the squelch effect, and 2.1 dB for the summation effect. Effect sizes were not correlated with duration of deafness.

Conclusions: Bilateral cochlear implant users can at least qualitatively benefit from the effects that are known from normal-hearing subjects, that is, head shadow, summation, and squelch effect. Bilateral cochlear implantation also reduces the performance gap between cochlear implant users and normal-hearing subjects.

Unilateral cochlear implantation has been shown to be an effective method for the treatment of severe to profound hearing loss (Helms et al., 1997; Helms et al., 2001). From normal-hearing subjects, it is known that binaural hearing leads to improved speech perception in noise (Arsenault & Punch, 1999; Bronkhorst & Plomp, 1988; Bronkhorst & Plomp, 1989; Carhart, 1965; Cox, DeChicchis & Wark, 1981; MacKeith & Coles, 1971). The overall gain usually is attributed to three effects, the head shadow effect, the squelch effect, and the binaural (or diotic) summation effect (Dillon, 2002). In general, most noise reduction and acoustical orientation abilities of the human auditory system crucially depend on the access to time, level, and spectral differences between the sound signals sensed by the two ears and the binaural processing of these signals.

Apart from any advantage of new technical developments, bilateral cochlear implantation is one option to further improve the performance of cochlear implant users. Recently, studies have shown the clear benefit that bilaterally implanted subjects have in understanding speech in quiet and noise (Gantz et al., 2002; Müller, Schön, & Helms, 1998; Müller, Schön, & Helms, 2002; Schön, Müller, & Helms, 2002). In addition, reports indicate that bilateral cochlear implant users benefit from all effects available to normal-hearing subjects (Müller et al. 2002). However, these studies were conducted at a fixed signal-to-noise ratio (SNR) of 10 dB, so that the benefit is expressed as an increase in the percent-correct score at 10 dB SNR instead of a gain in the speech reception threshold (SRT), that is, the SNR at a speech reception score of 50%. In addition, with this method, only some subjects in a sample are probably investigated in the most sensitive range (30% to 70%) of their psychometric function. Subjects with floor or ceiling effects at that SNR will show limited or no benefit.

This paper presents data using an adaptive sentence test to investigate the impact of bilateral cochlear implant on speech perception in noise in bilateral cochlear implant users. Different noise conditions are used to determine to what extent bilateral cochlear implant users benefit from head shadow, squelch, and binaural summation effects.

Subjects

Twenty-one native German-speaking adults (10 female, 11 male) with age ranging from 17.5 to 66.5 yr (mean, 44 yr) were included in the study (Table 1). Twenty subjects were postlingually deafened, and one subject (2) was prelingually deafened. The duration of deafness across all ears ranges from 0.6 to 47.8 yr (mean, 12.9 yr). Etiological factors covered a wide range, including meningitis, silvian aqueduct syndrome, scarlet fever, morbus meniere, progres-
sive hearing loss, sudden hearing loss, temporal bone fracture, middle ear infection, and otosclerosis. All subjects used MED-EL COMBI 40 or COMBI 40+ implants and had at least 1 mo of experience with their most recently implanted cochlear implant system (mean, 34.2 mo). All of them used their standard clinical TEMPO+ speech processor (Helms et al., 2001) with the MED-EL CIS+ strategy (MEDEL, Reference Note 1). The subjects had to sign an informed consent form and were reimbursed for travel expenses.

**Test Set-up**

Speech tests were performed in the anechoic chamber (width × length × height = 6.4 m × 6.4 m × 6.78 m) of the Department of Hearing, Speech, and Voice Disorders at the University Clinic of Innsbruck, Austria, and in a similarly equipped single-walled audiometric test room (width × length × height = 3.1 m × 7 m × 2.3 m) at the ENT department at the University Clinic of Würzburg, Germany, in one subject (13). The chamber in Innsbruck is equipped with 1 m wedges lining the walls, the floor, the ceiling, and a steel mesh floor. The tests were performed with a loudspeaker set-up that is also used for localization tests. 9 WESTRA audiometry loudspeakers were mounted on a steel ring of 2 m diameter at a height of 1.2 m above the mesh in the frontal horizontal plane from −90° (left) to 90° (right). Separation of the loudspeakers was 22.5°.

Subjects were positioned on an adjustable chair in the center of the semicircle of loudspeakers. The height of the chair was adjusted until the subject’s ears were at the height of the center of the loudspeakers. The hardware for generating the signals and for data acquisition was placed in a control room outside the chamber. The experimenter and the subject could communicate through a bidirectional line and the experimenter monitored the subject using a video surveillance system.

**Test Material**

The Oldenburg sentence test was used to measure speech reception thresholds, for example, the SNR at a speech reception score of 50%. This test consists of 40 lists of 30 sentences each (Wagener, Brand, & Kollmeier, 1999a; Wagener, Brand, & Kollmeier, 1999b). Each sentence consists of 5 words and is generated by permutations of 50 words. Speech signals were presented from WAV files (sampling rate, 44.1 kHz) through a 16-bit sound card. The noise signal was generated by lining up the short noise sequence taken from the Oldenburg sentence test. This sequence was originally compiled by randomly overlaying all words constituting the sentence test for 30 times so that the noise matches the long-term spectrum of the sentences (Wagener et al., 1999a). This continuous noise signal was presented from a CD and was started 5 seconds before the first sentence. The signal was not muted between consecutive sen-

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**TABLE 1. Overview of subjects included in the study**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yr)</th>
<th>DOD (yr)</th>
<th>Implant use (mo)</th>
<th>Implant type</th>
<th>Etiology</th>
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<td>13</td>
<td>27</td>
<td>17</td>
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All times are given with respect to the time of testing. Left and Right indicate the use of the implant. DOD = duration of deafness; M = meningitis; CMV = cytomegalovirus; O = otosclerosis; SHL = sudden hearing loss; SAS = sylvian aqueduct syndrome; P = progressive; MM = Morbus Meniere; U = unknown; TBF = temporal bone fracture; MEI = middle ear infection; SF = scarlet fever.
tentences. Levels were adjusted by means of two programmable attenuators (Tucker-Davies Technologies, PA4) and connected to the appropriate loudspeaker using a custom-built programmable 2-to-12 multiplexer.

**Procedure**

Speech tests were performed for three different noise conditions. The speech signal was always presented from the front (0° azimuth). The noise signal was presented from either the front (S₀N₀), from the left (−90° azimuth, S₀N₋90), or from the right (90° azimuth, S₀N₉₀). For each noise condition, three different listening conditions were tested: the left cochlear implant alone, the right cochlear implant alone, and both cochlear implants. The sequence of measurement conditions (noise and listening conditions) and test lists was quasi-randomized. The noise signal was presented at a constant level of 60 dB SPL measured in the free field at the position of the center of the subject's head. The level of the speech signal was varied to achieve a percent correct score of 50% calculated over the last 20 sentences of each list. The initial speech level was 70 dB SPL, that is, the start SNR was 10 dB.

The subject was instructed to look straight toward the front loudspeaker during the tests. Head movements were not allowed and were prevented by the use of a headrest. If head movements occurred during testing, the condition was repeated. After each presentation, the subject's response was recorded and the signal level was adjusted according to the number of words understood correctly, as specified in the Oldenburg sentence test (University Oldenburg, Reference Note 2), for example, 5 words correctly understood leads to a 2 dB reduction of SNR; 4 words, −1 dB; 1 word + 1 dB; and 0 words correct leads to an increase of 2 dB. SNR is kept constant when 2 or 3 words are understood correctly. The tests were presented sound-only, and no feedback as to correct or incorrect responses was given.

**Implant Fitting**

The goal of the study was to assess a subject's everyday speech perception. Thus, all subjects were tested with their normal everyday program of their speech processor. These maps were obtained during clinical device fitting in which implants are normally first fitted on each side individually. After that, the volume on each side is usually set to a comfortable level so that no difference in loudness exists between sides.

The only aspects in which processor settings were manipulated before the tests concern volume and automatic gain control (AGC). To have equal and well-defined microphone sensitivities in all subjects, the AGCs of the TEMPO+ processors were set to maximum sensitivity. With this, the onset of compression is at approximately 45 dB SPL, and the compression ratio for levels exceeding this level is 1:3 (Stöbich, Zierhofer, & Hochmair, 1999). The volumes of the processors were then aligned by the subject before testing. Continuous CCITT noise (Fastl, 1993) was presented from 0° azimuth at a level of 70 dB SPL. This standardized speech–shaped noise was also used for calibration of the system and for localization tests. Before testing for bilateral implant use, the subject was instructed to adjust the volumes of the TEMPO+ speech processors so that the overall volume was at a comfortable level and no loudness difference could be sensed. For unilateral implant use, the volume of each speech processor was individually adjusted to a comfortable level. Thus, two different volume settings per speech processor were determined. The subject was advised to use the "unilateral" volume settings during unilateral listening conditions and the "bilateral" volume setting during bilateral listening situation.

**Data Processing**

For each test, the speech reception threshold SRT was calculated by averaging the signal levels of the last 20 sentences in each list and subtracting the noise level of 60 dB SPL, as specified in the manual of the Oldenburg test. SRT was measured as a function of noise condition (nc) and listening condition (lc), for example, SRT(lc,nc), with nc out of S₀N₀, S₀N₋90, or S₀N₉₀ and lc out of left, right or both (Table 2). In the following, the term ipsilateral/contralateral refers to the condition in which the noise source and the cochlear implant are on the same side/opposite sides of the head, respectively, for example, in listening condition left (left cochlear implant only) and noise condition S₀N₋90 is ipsilateral. From the estimated SRTs, three effects were calculated as described below.

For each unilateral listening condition lc (left, right), the head shadow effect is calculated by subtracting the unilateral SRT obtained when the noise was on the contralateral side to the cochlear implant used from the SRT obtained when the noise was on the ipsilateral side:

\[ HS(lc) = SRT(lc, \text{ipsilateral}) - SRT(lc, \text{contralateral}) \] (1)

Thus, HS describes the benefit in SRT when the noise source moves from the ipsilateral side to the contralateral side, so that the cochlear implant in use is shielded from the noise by the head.

For each noise condition nc with lateral noise presentation (S₀N₋90, S₀N₉₀), the squelch effect is calcu-
whether or not subjects showed a significant head
lateralized by subtracting SRT when listening with both cochlear implants from SRT when listening with the contralateral cochlear implant only (Bronkhorst & Plomp, 1988):

$$SQ(nc) = SRT(\text{contralateral, } nc) - SRT(\text{Both, } nc)$$

(2)

SQ describes the benefit resulting from the spatial separation between the signal source and the noise source. SQ is also referred to as binaural intelligibility difference.

For each listening condition (left, right), the binaural summation effect is calculated by subtracting SRT obtained with both cochlear implants from SRT obtained with one cochlear implant in the S0N0 condition:

$$SU(\text{lc}) = SRT(\text{lc, S0N0}) - SRT(\text{Both, S0N0})$$

(3)

SU refers to the advantage of hearing with two cochlear implants with identical signals arriving at the two sides.

Note that for all measures, positive values express a beneficial effect on speech perception.

Statistics

The main factor of interest in this study was whether or not subjects showed a significant head shadow effect, squelch effect, and summation effect. As some of the resulting distributions of the data were markedly skewed, the Wilcoxon signed rank test was used to assess whether or not a certain effect was significantly different from 0.

**RESULTS**

In 18 subjects, SRT could be measured for all conditions (Table 3). In two subjects (3, 21), SRT could not be obtained in any condition as these subjects scored less than 50% even in quiet. Subject 3 does not yet have open speech understanding on both sides and subject 2 shows no open speech understanding when listening with her right ear. For subject 21, the sentence test was performed without noise, with speech presented from the front.

**TABLE 3. Wilcoxon signed rank test results**

<table>
<thead>
<tr>
<th></th>
<th>Left CI</th>
<th>Right CI</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head shadow effect</td>
<td>&lt;0.001*</td>
<td>&lt;0.001*</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Noise left</td>
<td></td>
<td>Noise right</td>
<td></td>
</tr>
<tr>
<td>Squelch effect</td>
<td>&lt;0.001*</td>
<td>0.265</td>
<td>0.024*</td>
</tr>
<tr>
<td>Both vs. left CI</td>
<td></td>
<td>Both vs. right CI</td>
<td></td>
</tr>
<tr>
<td>Summation effect</td>
<td>&lt;0.001*</td>
<td>&lt;0.001*</td>
<td>&lt;0.001*</td>
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</table>

* Results indicating significance (p < 0.05).
(left cochlear implant: 22%, both cochlear implants: 26%, right cochlear implant: 18%). For subject 2, SRT could only be determined for listening with both cochlear implants and the left cochlear implant alone. Missing data sets are labeled N/A in Table 3. The group data given on the bottom of Table 3 show that SRT is best (i.e., lowest) for bilateral implant use in all noise conditions.

Binaural effects were calculated for those subjects from which complete data sets could be obtained, and the results are shown in Figure 1. Mean values of the effects can be directly calculated by applying Equations 1 through 3 to the averaged SRTs in Table 3. For all effects, positive values indicate a beneficial effect on speech perception. When averaged across listening conditions and noise conditions, respectively, the head shadow effect HS amounts to 6.8 dB, the squelch effect SQ to 0.9 dB, and the summation effect SU to 2.1 dB. Excluding subject 13, who was tested in the single-walled room, from statistics does not introduce changes in the mean values and in significance levels of HS, SU, and SQ.

The results of the Wilcoxon signed rank tests are presented in Table 3. The only effect that was not significantly different from zero was the squelch effect in noise condition S0N90. A statistically significant difference between conditions could be found for HS only (left cochlear implant versus right cochlear implant, \( p = 0.014 \)).

**DISCUSSION**

Our results show that bilateral cochlear implant users significantly benefit from effects that are known for normal-hearing subjects. The fact that the squelch effect is not statistically significant for noise from the right side is probably due to the relatively small number of subjects. These asymmetries probably were not produced by the test environment because loudspeakers were selected on the basis of their frequency response and were matched in level, and the test chamber and set-up were perfectly symmetrical. There is no theoretical reason to assume that the squelch effect should depend on the noise azimuth in principle. Subject-specific differences between left and right performance caused by factors such as auditory nerve and hair cell survival or differences in processor fittings are on average expected to be zero.

Effect sizes can be calculated with respect to the side of the cochlear implant with the better performance obtained in noise condition S0N0. HS(better) amounts to 6.6 dB and HS(worse) to 6.9 dB. SQ(better) was found to be 1.1 dB, SQ(worse) 0.8 dB, SU(better) 1 dB and SU(worse) 3.2 dB. All effects with exception of SQ(better) are statistically different from zero. Currently, no sufficient preoperative criteria for predicting postoperative performance exist (Gantz, et al., 2002). This suggests that effect sizes calculated with respect to the better or worse ear are also not sufficient to describe the benefits experienced by a user of bilateral cochlear implants.

Current bilateral cochlear implant literature details effect sizes for head shadow, squelch, and summation effects in terms of gain in speech perception at a fixed SNR. This somewhat limits comparisons with our results. Müller et al. (2002) found a head shadow effect of 20.4 percentage points and a squelch effect of 10.7 percentage points when using a sentence test at 10 dB SNR in 9 bilateral users of MED-EL COMBI 40/40 cochlear implants. Monosyllables in quiet showed a summation effect of 18.7 percentage points. Schön et al. (2002) calculated a slope of 7 percentage points/dB SNR at the speech reception threshold by fitting a Chi-square function with 3 degrees of freedom to their speech test scores. Using a linear approximation of the psychometric function with the above calculated slope, an HS of 2.9 dB and an SQ of 1.5 dB can be calculated. Although this SQ is well within the range of results shown above (Fig. 1), the HS considerably underestimates the head shadow effect that we have found. The latter result most probably is due to the fact that at 10 dB SNR, not all subjects had been assessed in the most sensitive range of their psychometric function, that is, performance at 10 dB SNR of some subjects is probably low, so that the gain in speech understanding by increasing SNR is underestimated.

Using the HSM sentence test (Hochmair-Desoyer, Schulz, Moser, & Schmidt, 1997) in quiet and at SNRs ranging from 0 dB to 20 dB in a specialized four-loudspeaker set-up, Schön et al. (2002) found a bilateral benefit of 4 dB in 9 users of MED-EL COMBI 40/40+ implants. They argue that this ben-

**Fig. 1.** Head shadow effect (HS), squelch effect (SQ), and summation effect (SU) (bars, mean values; diamonds, median values; error bars, 1st and 3rd quartiles).
benefit is mainly due to the summation effect but that a
correction due to the squelch effect could also be
present. Taking this into account, their result is in
qualitative agreement with what has been found in
the present study.

From the data given in Gantz et al. (2002) for 10
bilateral Nucleus 24M users, a head shadow effect of
28.7 percentage points ($p < 0.01$, CUNY sentences
at 10 dB SNR), a squelch effect of 1.7 percentage
points (not significant, CUNY sentences at varying
SNR), and a summation effect of 10.6 percentage
points ($p < 0.05$, CUNY sentences at varying SNR)
can be determined (squelch and summation were
calculated with respect to the better ear, as this is
the only data given for unilateral use). In tests on
four bilateral users of the Nucleus 24M implant, van
Hoesel (Reference Note 3) found HS = 4.5 dB and
SQ = 1.5 dB, using open set sentences in noise. No
details on the statistical significance of these results
are given, and the summation effect was not as-
essed in these subjects. From the data published by
van Hoesel, Ramsden, & O’Driscol (2002) for one
bilateral Nucleus 24M user, a head shadow effect of
about 49 percentage points (no significance given), a
squelch effect of about 7 percentage points (not
significant), and a summation effect of about 8
percentage points (not significant) can be calculated
(CUNY-like sentences at 5 dB SNR). Data published
earlier by van Hoesel, Tong, Hollow, & Clark (1993)
for one bilateral user of the Nucleus CI-1 implant on
the right side and CI-2 implant on the left side yield
a summation effect of 19.6 percentage points (BKB
sentences at 10 dB SNR). We can transform these
results approximately to comparable benefits in dB
if we assume a 7 percentage points/dB slope of the
discrimination function similar to the HSM sen-
tences. The results by van Hoesel et al. (1993) sug-
uggest an HS in the order of 4 to 7 dB, SQ in the
order of 1 to 2 dB, and SU in the order of 1 to 3 dB,
which at least qualitatively confirms the results
reported here.

We can compare our data with those found previ-
ously for normal-hearing and hearing-impaired lis-
teners. In literature about normal-hearing subjects,
HS ranges from 8.9 dB to 10.7 dB (Arsenault &
Punch, 1999; Bronkhorst & Plomp, 1988), SQ from 2
dB to 4.9 dB (Arsenault & Punch, 1999; Bronkhorst
& Plomp, 1988; Carhart, 1965; MacKeith & Coles,
1971), and SU from 1.1 dB to 1.9 dB (Bronkhorst &
Plomp, 1989; Cox et al., 1981; MacKeith & Coles,
1971). Effects sizes were calculated from speech test
results according to Equations 1 to 3, except for
MacKeith and Coles (1971), where an SQ of 2 dB
was calculated for $S_{90N_0}$. In the studies cited above,
different methods for deafening one ear have been
used. These include earplugs (Carhart, 1965; MacK-
eith & Coles, 1971) and broadband masking noise
(Cox et al., 1981). Mannequin (KEMAR) recordings
and head phones for the simulation of unilateral
listening situations had been used by Bronkhorst
and Plomp (1988), Bronkhorst and Plomp (1989),
and Arsenault and Punch (1999).

Effect sizes for hearing-impaired subjects with a
mean pure-tone hearing (PTA) (averaged across 500,
1000, and 2000 Hz) of 38 dB are given in Arsenault
& Punch (1999) and for subjects with asymmetrical
hearing loss (mean PTA better ear: 21.7 dB, worse
ear: 40.5 dB) and symmetrical hearing loss (mean
PTA: 37.4 dB across ears) in Bronkhorst & Plomp
(1989). In hearing-impaired subjects, mean values of
the effects range from 5.6 dB to 8.5 dB for HS, from
1.7 dB to 3 dB for SQ, and from 1 dB to 2 dB for SU.
When calculating SU for asymmetrical hearing loss
from the data of Bronkhorst & Plomp (1989), the
effect of adding the worse ear to the better ear, for
example, SU(better), amounts to 1 dB and SU-
(worse) equals 3 dB. For symmetrical hearing impair-
ment, SU equals 1.2 dB. At least SU seems to
depend on the asymmetry of hearing loss and is
larger for asymmetrical hearing impairment. These
results for asymmetrical impairment match the ef-
effect sizes found in our group of bilateral cochlear
implant users. In a group of subjects (11 of 18) with
an asymmetry in performance of more than 1 dB
between left and right in noise condition S_{90N_0}
(better) was 1.1 dB and SU(worse) 4.1 dB. In the
with symmetrical performance (<1 dB difference)
SU amounts to 1.4 dB, which is also consistent
with the findings in subjects with symmetrical hear-
ing loss. Subjects with asymmetrical performance
benefit more from adding the “better” ear to the
“worse” ear in noise condition $S_{90N_0}$ than vice versa.

In the present study, HS is approximately 3 dB
smaller than found in normal-hearing subjects and
about 0.3 dB smaller than in hearing-impaired sub-
jects. SQ is approximately 2 dB smaller than in
normal-hearing subjects and 1.4 dB smaller than in
hearing-impaired subjects, and SU is approximately
0.5 dB larger than found in normal-hearing and
hearing-impaired subjects. These differences could
be due to a variety of reasons. In our study, all
subjects used the TEMPO+ speech processor with
the microphone situated above the pinna. Therefore,
no spectral and temporal cues introduced by the
pinna could be used by these subjects. To a certain
extent, the differences in HS (3 dB) and SQ (2 dB)
between normal-hearing subjects and cochlear im-
plant users can be explained by the position of the
microphone. Simulations with head-related transfer
functions (HRTF) measured from a KEMAR dum-
my-head microphone (Gardner & Martin, 1994)
showed that for the speech simulating CCITT noise
signal, the acoustical head shadow in the frequency range around 1 kHz is on average about 1 dB higher for HRTFs including the pinna than for HRTFs not including the pinna. A similar result can be obtained by using a spherical head model suggested in Duda (1993) and a pinna model with model parameters taken from Brown & Duda (1997). Here the difference in HS amounts to 1.2 dB when comparing HRTFs with and without pinna effects. These results suggest that the difference in HS reported above can at least in part be attributed to the fact that cochlear implant users currently do not benefit from their pinna.

In addition to the differences in the acoustic situations for normal-hearing listeners and cochlear implant users, there are differences in the signal presented to the two types of listeners. Signals presented to the cochlear implant electrodes are compressed by the AGC and the map law within the speech processor for cochlear implant users, which might affect the SNR presented to the subject. These parameters have not been taken into account in this study and should be the subject of further investigations.

Compared with normal-hearing subjects, the performance of cochlear implant users is less robust in noise; they benefit more from the redundancy of the signals presented to the left and right speech processor. Signals arriving at the electrodes of both sides might even contain some amount of complementary information, especially when signal sources are positioned in front. There the envelopes of the signals arriving at the electrodes should be identical. Assuming that identical electrodes left and right might stimulate different regions in the cochlea because of slightly different insertion depths, the information transferred to the cochlear nerves might contain complementary information. Thus cochlear implant users benefit more from the summation effect, which could explain the difference of 0.5 dB in SU found above. A similar conclusion is drawn in Schön et al. (2002).

The squelch effect takes advantage of the spatial separation between the signal source and the noise source. Thus, a relation could exist between a subject’s ability to localize sound sources in space and the benefit caused by the squelch effect. To test this hypothesis, a correlation was calculated between SQ found here and the average unsigned localization error in the frontal horizontal plane obtained in a localization study (Nopp, Schleich, & D’Haese, 2003). Using the data from those 16 subjects who both participated in the localization study and yielded complete data sets in the present study, no significant correlation could be found ($r = -0.16, p = 0.56$). This suggests that at least for this subject sample, SQ is not related to a subject’s ability to localize sounds in the frontal horizontal plane.

No correlation was found between any of the effects (HS, SQ, SU) and the duration of deafness of the first and second deafened ear or the average duration of deafness across ears. Further, no correlation was found between any of the effects and the duration of deafness of the first and second deafened ear or the average duration of deafness across ears, expressed as a fraction of age. For HS, this might be expected because the head shadow effect is a purely monaural effect. For SQ and SU, these results suggest that once binaural hearing is acquired, the ability to benefit from binaural processing is robust and does not vanish or even deteriorate over the time of unilateral and bilateral deafness, which parallels what has been found for sound localization (Nopp et al., 2003). In addition, no significant correlation was found between the difference in SRT for the left cochlear implant and right cochlear implant only in the $S_0N_0$ condition and the absolute or age-related difference in duration of deafness between ears. This indicates that duration of deafness is not a predictor for the ear with better or worse performance after implantation, which corresponds to what has been reported in Gantz et al. (2002).

Speech perception in cochlear implant users is sometimes compared with that of normal-hearing subjects, and the question can be asked, to what extent does bilateral cochlear implantation close the gap between normal-hearing subjects and cochlear implant users? In one sense, this question has been answered insofar as it was shown that bilateral cochlear implant users benefit from effects that are known for normal-hearing subjects. In another sense, this question can be answered with the use of comparison data for normal-hearing subjects. In a group of untrained normal-hearing subjects, Wagen er et al. (1999b) demonstrated an SRT of −7.1 dB, using the Oldenburg sentence test in noise condition $S_0N_0$. Thus, with bilateral implant use, the difference in SRT is 5.9 dB, which compares to 8.00 dB for unilateral implant use (Table 3). In other words, bilateral cochlear implantation brings cochlear implant users 2.1 dB closer to normal-hearing subjects. When discussing differences between normal-hearing subjects and cochlear implant users, however, it should be mentioned that bilateral cochlear implantation can restore another important aspect of binaural hearing, that is, spatial hearing and sound localization (Nopp et al., 2003).

**Conclusion**

The results indicate that bilateral implantation offers a substantial benefit in speech perception in
noise to cochlear implant users that reduces the performance gap between cochlear implant users and normal-hearing subjects. Bilateral cochlear implant users can qualitatively benefit from head shadow, squelch, and summation effects, effects that are also seen in normal-hearing subjects. However, further work is necessary to determine the mechanisms underlying these effects.

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REFERENCES


REFERENCE NOTES

