Benefit of contralateral routing of signals for unilateral cochlear implant users

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One way to improve speech understanding in noise for HI with a unilateral hearing loss is by contralateral routing of signals (CROS). Such a CROS-system captures sounds with an additional microphone at the worst hearing ear and transmits these to the better one. The better ear is then provided with a mix of signals originating from both ears. The goal of this study is to quantify the effect of a CROS-system on speech reception thresholds (SRTs) with unilaterally implanted CI-users in diffuse and directional noise as a function of speaker location. Listening tests are performed and an accurate directional intelligibly model is proposed used for further analysis. In diffuse noise it is concluded that the use of a CROS system results in a maximum gain in SRT of 7.9 dB when speech comes from the CROS side compared to a maximum loss in SRT of 2.1 dB when speech comes from the implanted side. In the case of directional noise, the effect of the CROS is symmetric and the maximum loss or gain in SRT was around 9 dB. The study therefore shows a clear potential of using the CROS system in diffuse noise.
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I. INTRODUCTION

For both hearing impaired (HI) and cochlear implant (CI) users, understanding speech in noise remains a challenge. One way to improve speech understanding for the HI with a unilateral hearing loss in certain noisy conditions is by contralateral routing of signals (CROS) (e.g., Kuppler *et al.*, 2013; Bishop and Eby, 2010; Rintelmann *et al.*, 1970). In such a CROS-system sounds from the worst hearing ear are captured with an additional microphone and transmitted to the better ear by means of a hearing aid (HA). The better ear is then provided with a mix of signals originating from both ears (Hol *et al.*, 2010; Lin *et al.*, 2006; Arndt *et al.*, 2011; Niparko *et al.*, 2003).

A CROS system can also be used with CI users (e.g., Arndt *et al.*, 2011; Arora *et al.*, 2013; van Loon *et al.*, 2014; Grewal *et al.*, 2015; Guevara *et al.*, 2015). For example, sounds from the non-implanted ear can be transmitted to the implanted side. Although it may not have the same benefits as bilateral implantation (van Loon *et al.*, 2014), it may be a cost-effective and non-invasive alternative to achieve head-shadow compensation in certain conditions (Arora *et al.*, 2013). In addition, the majority of CI-users only have one implant which indicates the relevance of this study.

The measurements in noisy conditions done by Arora *et al.* (2013) and Grewal *et al.* (2015) are performed with frontal speech and noise from the implanted or non-implanted ear (i.e., the ear with the CROS microphone). The gain in performance when noise comes from the CI side turns out to be smaller than its loss in performance in the case of CROS-sided noise (Grewal *et al.*, 2015). Guevara *et al.* (2015) performed experiments with frontal speech in silence and frontal speech in noise. The noise was played from four loudspeakers simultaneously located at the CI side and the CROS side (−90°, 90°) and between the front and the sides (−45°, 45°). Small significant improvements due to the CROS were found both in noise and in silence in the rage of 2%–9% consonant-vowel-consonant correct scores. van Loon *et al.* (2014) also measured conditions where speech is presented at either the implanted or non-implanted ear, and noise origins from the opposite direction. They conclude that the CROS-system is only beneficial when speech is presented at the CROS-side, however, this benefit comes with a drop in performance in other noisy conditions. Overall, van Loon *et al.* (2014) do not advise a CROS-system for unilateral CI users.

It is clear that the conclusions by Arora *et al.* (2013), Grewal *et al.* (2015), and van Loon *et al.* (2014) are not always in favor of the CROS-system as an addition to a unilateral CI-system. However, it must be noted that these conclusions are drawn based on directional noise sources only.

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TABLE I. Patient demographics.

Subject	Age (years)	Deafness duration (years)	CI side	CI Experience (years, months)	Etiology	Phoneme scores in quiet (%)
S1	50	32	left	(11, 3)	Unknown	93%
S2	52	7	left	(1, 5)	Unknown	95%
S3	57	10	left	(10, 4)	Heriditary	93%
S4	62	10	right	(9, 3)	Ménière's disease	87%
S5	61	53	right	(5, 9)	Unknown	85%

Many noise sources in daily life are non-directional, diffuse noise sources (Soede *et al.*, 1993; van der Beek *et al.*, 2007), such as babble noise in a restaurant or vehicle noise in, e.g., a car, a train, or a plane. Such diffuse noise sources are likely to influence the performance in a different way. Moreover, in the aforementioned references only three speech and noise angles are taken into account (−90°, 0°, and 90°, where 0° denotes from the front). It is of interest to investigate the effect of the CROS-system when, due to the head-movements, users can direct noise sources to the posterior hemisphere.

The aim of this work is to do an exhaustive speech recognition analysis of the CROS-system for unilateral CI-users in (1) diffuse noise with directional speech and in (2) directional noise with directional speech. First, in Sec. II a listening test is described where certain conditions are measured in directional noise and in diffuse noise with a similar setup as in (Soede *et al.*, 1993). In addition, in Sec. III a model of speech intelligibility is proposed, which can accurately predict the speech-reception thresholds (SRTs) of the performed listening tests. The model facilitates a further analysis of the CROS-system for all speech directions in diffuse noise and in all noise directions. A discussion of the results and conclusions are provided in Sec. IV.

II. INTELLIGIBILITY LISTENING TEST

Eighteen CI-users who had been implanted at the Leiden University Medical Centre and had more than six months of experience with the implants, were invited to participate in the experiments. The first five respondents were included in the test (see Table I for additional demographic details). All subjects were postlingually deafened adult users of the Advanced Bionics HiFocus CII or HiRes 90 k CI and a Harmony processor. In total, speech understanding is measured in three conditions in quiet, six conditions in diffuse noise and one condition in directional noise. All conditions are denoted in Table II. Note that for frontal speech no CROS condition is included, since the perceived signals will be equal to the case where no CROS is used, except for an overall amplification factor. The is due to the symmetry of the HRTFs. The experiment has been approved by the Leiden Medical Ethics Committee.

TABLE II. Listening test conditions in quiet and in noise. Numbers indicate the direction of the signal, where the CI and CROS are always located at −90° and 90°, respectively.

Quiet/Noise properties	Speech direction	CI with or without CROS
Quiet	−90°	CI only
Quiet	90°	CI only
Quiet	90°	CI+CROS
Noise (0°)	−90°	CI+CROS
Noise (diffuse)	−90°	CI only
Noise (diffuse)	−90°	CI+CROS
Noise (diffuse)	0°	CI only
Noise (diffuse)	0°	CI+CROS
Noise (diffuse)	90°	CI only
Noise (diffuse)	90°	CI+CROS

A. Setup

Experiments were performed in a sound-treated room with nine loudspeakers where a diffuse noise field is simulated with a similar setup as described in Soede *et al.* (1993). Figure 1 sketches the experimental setup. Eight loudspeakers

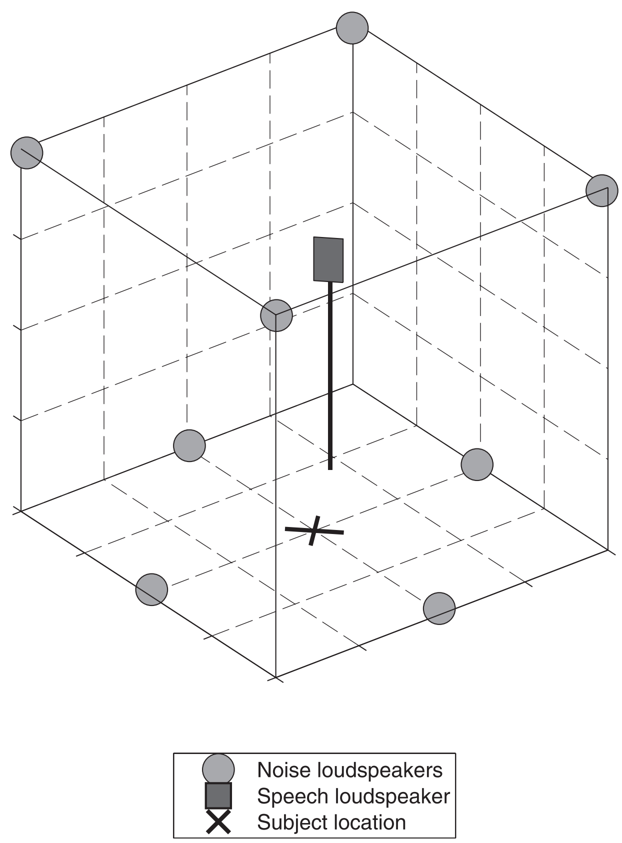

FIG. 1. Illustration of the listening room setup. Loudspeakers are directed to the subject, where the distance between the subject and the speech-loudspeaker is 1 m and the speech-loudspeaker is placed at a height of 1.2 m.

are attached to the edges of an imaginary box and are used for producing the noise signals. The ninth loudspeaker, from which the speech material was presented, was placed at 1 m distance from the center and at 1.2 m from the floor. The direction of the speech is altered by the use of a rotational chair.

A Phonak Ambra hearing aid (HA) with an additional CROS microphone is used to facilitate the CI users with a CROS-system. Note that the CI microphone is therefore turned off since it is replaced by the mixed input signal originating from both HA microphones. The users are provided with the HA at the implanted ear and with the additional CROS microphone at the contralateral ear. This contralateral microphone signal is fed into the HA processor via a wireless link. Subsequently, the mixed signals from both ears at the output of the HA processor are send to the CI input via a wired connection. All signal processing algorithms in the HA device are turned off, such that the processor only acts as a mixing device of both microphone inputs. It was observed that, when placing the HA processor next to the CI processor, wireless signal interferences occurred resulting in audible distortions. To overcome this, the HA is placed next to the contralateral ear in the same orientation as the CROS.

B. Stimuli and procedures

To measure the speech understanding for one subject in one particular condition (both in noise or in quiet), two list are presented to the subject. An average percentage of phonemes correct is calculated for each list based on the last 11 words per list. Subsequently, the average score of two list is obtained. To determine the 50% SRT, the noise level is adjusted adaptively from low to high levels in steps of 5 dB such that the psychometric curve is sampled around the 50% correct score (Levitt, 1971). The SRT is obtained by using a log-likelihood interpolation procedure as described by Brand and Kollmeier (2002).

The listening test excerpts consist of standard speech in noise material as used by the Dutch Society of Audiology (Bosman and Smoorenburg, 1995). In total, 45 lists are available with 12 monosyllabic consonant-vowel-consonant words. All words are loudness balanced on root mean square level and each individual list is homogenous with regard to the 50% SRT. The speech material is stored on a computer and played at a fixed level of 65 dB sound pressure level, measured at the position of the head position of the listener. The speech-shaped noise provided with the listening test data (Bosman and Smoorenburg, 1995), is divided in eight individual fragments such that the noise signals for each loudspeaker are uncorrelated.

C. Results

Figure 2 shows the phoneme scores for all CI-users in silence where the markers indicate whether the CI only (white squares) or the CI+CROS (filled circles) is used. In the condition where the speech is coming from the CI side (−90°), the average phoneme score is 81.7 ± 6.3%. Whenever the deaf ear was directed towards the speech loudspeaker, the phoneme score dropped to 75.4 ± 11.9%. An

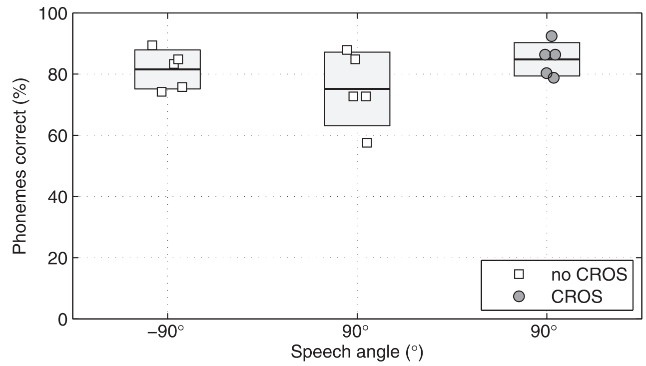

FIG. 2. Individual percentages of phonemes correct for conditions in quiet. Bars denote sample mean and standard deviation. CROS microphone is located at 90°.

additional CROS microphone in this particular condition resulted in a phoneme score of 85.0 ± 5.4%. As indicated in Fig. 4(a), this implies an improvement of the mean phoneme score by 9.6%, but this improvement was non-significant ($p = 0.13$).

Figure 3 shows the listening test results for the conditions in noise. These results we can summarize as follows. On average, the best performance is measured when no CROS is used and speech is presented at the CI side (SRT of −2 dB ± 5 dB). Contrary, the worst performance is observed in the case where the speech is presented at the opposite of the CI when no CROS is used (SRT of 12 dB ± 8 dB). Note, that there is no significant difference between directional noise from the front and diffuse noise, when using a CROS ($p = 0.23$). This is expected, since the subject cannot use binaural hearing to exploit the fact that the left and right ear noise signals are uncorrelated in the diffuse case.

The differences in performance due to the addition of the CROS microphone in noise are further quantified in Fig. 4(b). Here, a positive difference in SRT implies better performance in speech understanding due to the CROS microphone. When speech originates from the CROS side, a significant improvement in SRT of 10.4 dB on average is measured due to the CROS ($p < 0.005$). This is achieved by compensation of the head-shadow effect due to the CROS system. Furthermore, when speech is played at the CI side, a significant loss in SRT of 4.2 dB is found due to the CROS ($p < 0.005$). Apparently, this is caused by the fact that additional noise is fed into the CROS system which decreases performance. When speech originates from the front, no significant effect of the CROS is observed ($p = 0.15$).

III. INTELLIGIBILITY PREDICTIVE MODEL

A model is used to further investigate the effect of the CROS-system for other speech-in-noise conditions, which were not included in the listening experiment. The particular method employed for intelligibility prediction is based on a frequency-weighted SNR, e.g., as used in the articulation index (AI) (Kryter, 1962) and the speech intelligibility index (SII) (ANSI, 1997), originally meant of normal-hearing listeners. It is shown in Sec. III D that, except for an overall decrease in predicted speech intelligibility, no additional

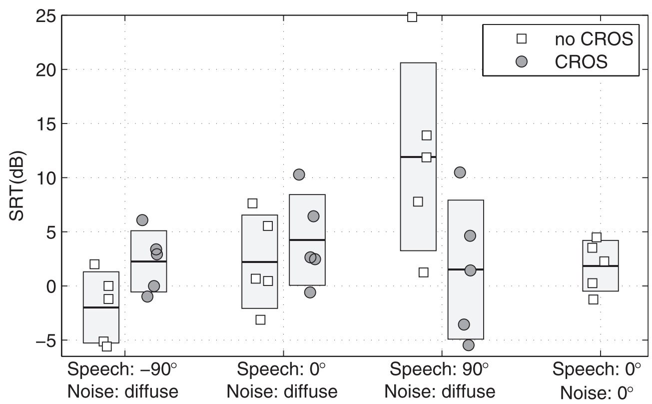

FIG. 3. Individual 50% SRTs for conditions in noise, where lower SRT implies more intelligible speech. Bars denote sample mean and standard deviation. CROS microphone is located at 90°.

changes are required to let the model correctly predict the results for CI-users.

The choice for such an SNR-based approach is motivated by its good results for predicting the effect of linear filtering and additive noise on speech intelligibility (Taal *et al.*, 2009). Since stationary noise is used in the listening experiment and the effects of the pinna and the head-shadow can be well described by linear filtering Wightman and Kistler (1989a,b), it is therefore expected that the model can also give accurate predictions for the performed experiments. Moreover, good results are obtained with a similar approach by Culling *et al.* (2012) by letting the model predict the benefit of bilateral versus unilateral cochlear implantation.

A. Notation and implementation details

Let x and ε denote the time-domain signals of the clean speech and noise, respectively, sampled at 20 kHz. A windowed version of x is denoted by x_m where m denotes the window frame-index. A Hann-window is used with 50% overlap, and 32 ms length. A capitalized notation is used to denote a discrete Fourier transform (DFT), e.g., the DFT of x is denoted by $X(k)$ with frequency bin index k. Short-time frames are zero-padded to 64 ms before applying the DFT.

The impulse response of the ith auditory filter is denoted by h_i, where $i \in \{1, \ldots, n\}$ and n is the total number of auditory filters. In total, 64 auditory filters are used where center frequencies are linearly spaced on an equivalent rectangular

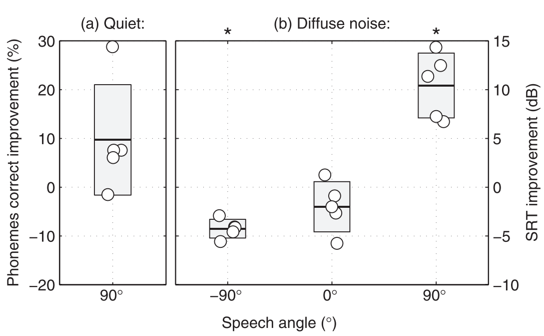

FIG. 4. Circles denote individual improvements due to the CROS system [(a) results in quiet, (b) results in noise]. Bars denote sample mean and standard deviation. CROS microphone is located at 90°.

bandwidth (ERB) scale between 150 and 8500 Hz Glasberg and Moore (1990). Its squared magnitude responses $|H_i(k)|^2$ are taken equal to fourth order gammatone filters (e.g., Patterson *et al.*, 1992), as described in van de Par *et al.* (2005).

The impulse response of the directional filter, i.e., the head-related transfer function (HRTF), at the CROS and implanted ear is denoted by $h_{CR}(\phi)$ and $h_{CI}(\phi)$, respectively, where ϕ represent the azimuthal angle. HRTFs are taken from the CIPIC database (Algazi *et al.*, 2001), where only impulse responses from the azimuthal plane are used.

B. Long-term average spectra calculation

The perceived energy at the implanted ear, for a given time-frequency (TF) unit and direction, is calculated by mixing the power spectra of the CROS and CI signal as follows:

$$X_{m,i}^2 = \sum_k |X_m(k)|^2 |H_i(k)|^2 (|H_{CI}(\phi, k)|^2 + |H_{CR}(\phi, k)|^2). \quad (1)$$

The direction ϕ is omitted in $X_{m,i}$ for visual clarity. The average energy within one auditory filter is then based on a long-term sample mean over many short-time frames (e.g., several minutes) and is denoted as follows:

$$\sigma_{X_i}^2 = \frac{1}{M} \sum_m X_{m,i}^2, \quad (2)$$

where M equals the total number of short-time frames. Similar definitions hold for a directional noise source, denoted by $\sigma_{\mathcal{E}_i}^2$. In the case of diffuse noise, a filter is used with the average power spectrum over all available directions in the CIPIC database.

C. Calculation of objective score

To map the noise and speech spectra to one objective output score, first the SNR within one auditory band is calculated denoted by

$$\xi_i = \frac{\sigma_{X_i}^2}{\sigma_{\mathcal{E}_i}^2}. \quad (3)$$

This SNR is used to calculate an intermediate measure to determine the audibility of the speech in presence of the noise within one band. Following ANSI (1997), the SNR is log-transformed, clipped between −15 and +15 dB and normalized such that its range is between zero and one. This gives

$$d(\xi_i) = \max\big(\min\big(10\log_{10}(\xi_i), 15\big), -15\big)/30 + \frac{1}{2}. \quad (4)$$

Subsequently, a weighted average is calculated as follows:

$$D = \sum_i \gamma_i d(\xi_i), \quad (5)$$

where γ denotes the band-importance function as given in the critical-band SII procedure as found in Table I in ANSI

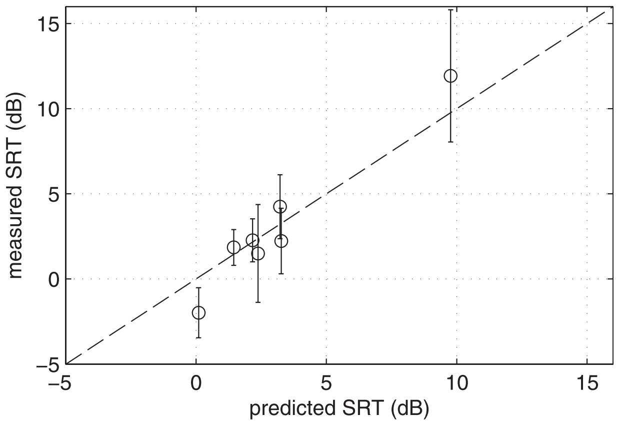

FIG. 5. Scatter plot of model-predicted SRTs versus measured SRTs (user averages as shown in Fig. 3). Error bars denote standard error of the mean.

(1997). In summary, this weighting-function reduces the importance of bands with center frequency below 450 Hz and above 4000 Hz. It is expected that Eq. (5) is a monotonic increasing function of the intelligibility of the speech in noise (ANSI, 1997). Model predictions, as in Eq. (5), are obtained for an average set of HRTFs by determining the scores for all 45 subjects in the CIPIC database (Algazi *et al.*, 2001). Subsequently, an average score over all HRTF sets is used as one objective output.

D. Calibration for CI-users

The output range of the predictive model is between 0 and 1, where 0 corresponds to unintelligible speech and 1 to maximum speech intelligibility. With the conventional SII the exact output score related to the 50% SRT depends on many factors like, for example, the type of speech material and listening conditions (Rhebergen and Versfeld, 2005). In this work, the output score related to the 50% SRT is determined by calibration with the SRTs from the previously explained listening experiments. This is done by calculating model scores for all the SNRs between −30 and 30 dB SNR with steps of 1 dB. In this manner, a psychometric curve is obtained for the model, for a given speech-in-noise condition. Subsequently, for a given output score between 0 and 1, the corresponding level in dB is determined, which equals the SRT prediction by the model. A minimum RMSE of 1.1 dB between the model predicted SRTs and the SRTs based on the listening experiments was found for $D = 0.5$.

A scatter plot between the predicted and measured SRTs is shown in Fig. 5, which includes all the speech-in-noise conditions from the listening experiment. The error-bars denote the standard errors of the means. These results show, that the errors of the predicted SRTs are approximately within the same range as the standard errors of the means from the actual listening experiment measurement.

E. Results

SRTs were predicted by the model where speech is corrupted by diffuse noise as a function of noise direction. Furthermore, SRT was predicted where the speech signal is played simultaneously with a directional noise source. All directions available in the CIPIC database from the azimuthal plan were considered for the speech and noise directions. From the front direction this includes −80°, −65°, −55°, from −45° to 45°, in steps of 5° (Algazi *et al.*, 2001). Directions that were in the back of the subject are sampled at similar positions. Results for intermediate directions not available in the CIPIC database were obtained by means of linear interpolation. All conditions were predicted with and without the CROS system.

1. Speech in diffuse noise

The results for diffuse noise are shown in Fig. 6 (a) (recall that the CROS microphone is located at 90°). For the results

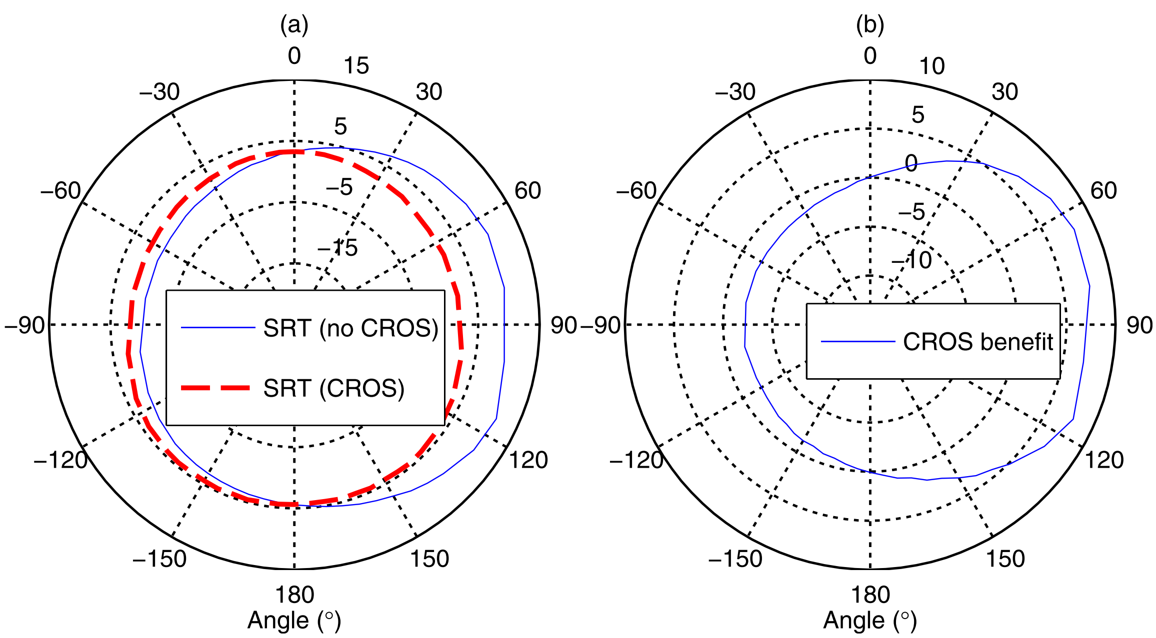

FIG. 6. (Color online) (a) SRTs predicted by the model for directional speech in diffuse noise with and without the CROS system. (b) Benefit due to the CROS system in SRTs. Higher difference in SRT implies more intelligible speech due to the CROS system. CROS microphone is located at 90°.

without the CROS system the head-shadow effect is clearly visible, where an SRT of 0.1 dB is predicted at −90° and an SRT of 9.8 dB at 90°. This is a difference of around 10 dB. Best and worst speech understanding without the CROS is obtained at 65° (SRT = −0.38 dB) and 115° (SRT = 11.4 dB), respectively, which is a typical result also due to the head-shadow effect and the shape of the pinna Algazi *et al.* (2001). When the CROS-system is turned on the SRT predictions are symmetrical around 0°, since the head-shadow effect is not present anymore. Also the difference between best and worst performance is only around 3 dB in contrast to the 10 dB when no CROS-system is used. Best performance is obtained from ±65° with SRTs around 1.8 dB and worst performance comes from the back (180° ± 40°) with an SRT of 5 dB.

The difference in performance due to the CROS-system is shown in Fig. 6(b). Here, a positive SRT difference indicates better speech understanding due to the CROS-system. From the figure it can be observed that SRTs are not affected due to the CROS microphone when speech is either from the front or the back. When speech comes from the CROS side, the largest improvements of around 7.9 dB are found within the directional range of 65°–115°. A smaller loss in speech understanding is predicted by the model for the non-CROS hemisphere with a maximum loss of −2.1 dB in the directional range between −65° and −115°. On average, over all directions, the gain in performance due to the CROS microphone is 1.25 dB.

2. Speech in directional noise

Figure 7(a) shows the predicted SRTs for directional noise and directional speech without the CROS system, where a lighter color denotes a lower SRT, i.e., better performance. As was the case with diffuse noise, the head-shadow effect is also clearly visible with directional noise shown by the light and dark regions in the two-dimensional plot. Best performance (SRT = −9.8 dB) is obtained when speech and noise have approximately the directions of the implanted (−90°) and implanted (−90°) ear, respectively. Worst-case scenario (SRT = 13.3 dB) is the case where speech and noise come approximately from the opposite directions, i.e., from the non-implanted and implanted ear, respectively. Hence, the difference in performance between these two extremes is around 23 dB, which is much larger than the 10 dB difference found in diffuse noise.

Figure 7(b) shows the predicted SRTs when the CROS-system is turned on. To clarify the difference between (a) and (b), the same color range is used between −10 and 15 dB. As a result, it is clear that there are no such extreme differences in terms of SRT as with the previous case due to the absence of the head-shadow effect. In addition, the SRTs are symmetrical around the frontal speech and noise directions. Best performance is obtained when speech comes from the front (0° ± 90°) and the noise from the back (<−90° and >90°) with an SRT varying between 0 and −1 dB. In the figure, these conditions are revealed by the dark crosses in these regions. Worst performance is again obtained in the opposite case when speech comes from the front and noise from the back with an SRTs in the range of 3 and 4 dB. The difference in best and worst performance is around 5.2 dB.

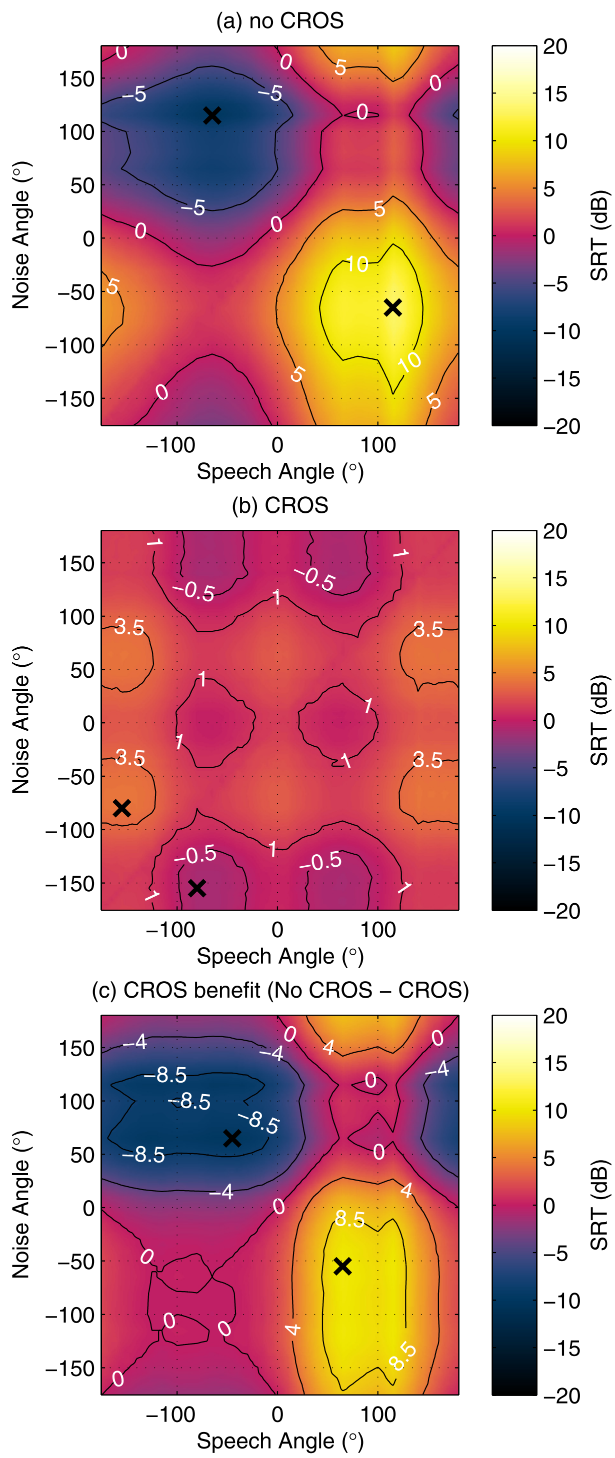

FIG. 7. (Color online) Predicted SRTs for directional speech in directional noise (a) without the CROS system, (b) with the CROS system, and (c) benefit due to the CROS system. In (c) higher difference in SRT implies more intelligible speech due to the CROS system. Black crosses indicate maxima and minima. CROS microphone is located at 90°.

The benefit due to the CROS-system compared to no CROS is illustrated in Fig. 7(c). Here, a lighter color indicates better performance due to the CROS system. From the figure it can be seen that there is no difference in performance between the two systems when noise and speech directions are equal. This is indicated by the diagonal "line"-shape in the figure between (−180°, −180°) and (180°, 180°). The CROS is most beneficial (SRT improvement of 10.4 dB), when speech is from the CROS side and noise from the implanted side. In the opposite case, when speech comes from the implanted side and noise from the opposite direction, an SRT loss of 9.9 dB is observed. Note that the difference in maximum gain and maximum loss in performance due to the CROS is only around 0.5 dB which is substantially smaller as was the case with diffuse noise. Averaged over all noise and speech directions, the gain in performance due to the CROS microphone is approximately 0 dB, i.e., there is no difference in performance.

IV. DISCUSSION

Similarly as results reported in other experiments, it was found that the CROS system can either result in a gain or in a loss in speech understanding, depending on the noise and speech directions (Arndt *et al.*, 2011; Arora *et al.*, 2013; van Loon *et al.*, 2014; Grewal *et al.*, 2015). However, the results presented in this work for diffuse noise are significantly different than in directional noise. In the case of diffuse noise, the gain in performance (7.9 dB) is much larger than its loss in performance (−2.1 dB), while in the case of directional noise this difference is more or less symmetrical with a difference in performance of around 9 dB for both conditions. Although slightly smaller (around 6 dB), this symmetrical effect with directional noise is in line with the results from van Loon *et al.* (2014). This difference in performance between these noise types, implies that the use of a CROS system may be of more interest in the case of diffuse noise.

This study also contributes by using the model predictions to explore the full space of possible noise and speech directions, rather than only measuring particular conditions due to time/cost constraints. These results show that, when using a CROS, speech intelligibility becomes less dependent on direction than using CI only. In the case of diffuse noise and directional noise the difference between maximum and minimum performance with a CROS system is 2.8 and 5.5 dB, respectively. In the case of CI-only, for the same conditions, these differences are 11.7 and 23 dB. Since the average improvements due to the CROS compared to CI only, over all speech and noise directions, was around 0 dB, this more constant performance with the CROS-system may be less exhaustive for the user.

It was also found that maximum attenuation of a sound source for a microphone located at −90° occurs at 115°, while maximum gain is obtained at 65°. As a consequence, maximum and minimum performance is measured when speech and noise sources are positioned at one of these locations. However, existing studies typically position sources at ±90°. According the model predictions this may result in a difference of around 2.5 dB. If one is interested in the extreme conditions of the CROS-system this difference should be taken into account.

A. The effect of head rotations

In many CROS evaluation experiments the listening test is performed by altering either the noise or speech direction and measure the speech intelligibility while the head position is fixed. However, in practice users are also able to direct their head such that speech intelligibility is maximized (Brimijoin *et al.*, 2012). In addition, users may also use lip-reading to improve speech-understanding. For example, in the case of frontal speech in diffuse noise it can be concluded from 6 (right) that best performance is obtained without the CROS when moving the head slightly to the right such that speech is located at −60°. Results for directional noise are less clear from just the results presented in this work. Therefore, an additional preliminary experiment is performed by letting the model predict SRTs in the case of directional noise source with frontal speech. Head-movements are tolerated within the visual range of ±60° such that speech intelligibility is maximized.

Model predictions are shown in Fig. 8 where the benefit of the CROS system is illustrated with and without tolerated head-movements. Values larger than 0 dB indicate a benefit due to the CROS-system [similarly as in Figs. 6 (right) and 7 (bottom)]. It is clear that the original benefit of the CROS-system (approximately 2 dB) with noise from the non-CROS hemisphere, completely disappears when head-movements are tolerated. In fact, the CROS-system only shows comparable behavior (i.e., 0 dB benefit in the plot) with the CI only case for noise directions in the range of −90° to 0°. For the remaining noise directions the CI-only has better performance where the biggest loss in performance is measured in the back hemisphere (−9 dB).

Note that users do not necessarily rotate their head in the optimal direction (Brimijoin *et al.*, 2012). Furthermore, restricting head-movements within the visual range of 60° is also an initial choice, which should be further investigated. However, these results show a significant impact of tolerating head-movements which is an important topic for future research.

B. Reliability of intelligibility model

In Fig. 5 it was already shown that the proposed model is able to predict the SRTs of the listening tests with a good

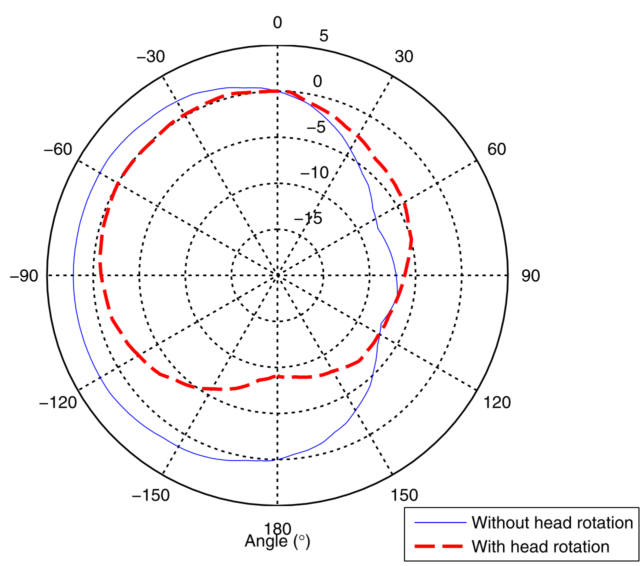

FIG. 8. (Color online) Benefit of CROS with frontal speech (0°) and directional noise. In one case optimal directed head-movements are tolerated within the visual range (±60°). Values above 0 dB indicate better performance due to CROS. CROS microphone is located at 90°.

accuracy. It is also of interest to compare our model predictions results from other studies. In the case of frontal speech and noise van Loon *et al.* (2014) measured similar performance for both systems (1.4 dB difference in favor of CI only). Also Grewal *et al.* (2015) draw this conclusion. This is in line with the model predictions where no difference in performance was found. In the case of (speech −90°, noise 90°) and (speech 90°, noise −90°) improvements measured by van Loon *et al.* (2014) due to the CROS system were equal to −5.7 and 6.7 dB, respectively. The model predicted a similar trend of −8.6 and 9.5 dB improvements for these particular conditions. Hence, both the model and the listening test results show a symmetrical effect with a small favor of 1 dB towards the CROS system. A possible reason for the slightly higher differences predicted by the model may be due to the fact that no absolute thresholds are taken into account, e.g., thresholds in quiet and clipping behavior of the CI for high input levels. This may be included in the future, however, conclusions drawn for the CROS system evaluation remain the same.

One may observe that the used model for intelligibility prediction is originally meant for NH and basically contains no aspects of hearing impairments. These conclusions are in line with the findings by Culling *et al.* (2012), who also used an SII-based directional predictive model with NH critical bandwidths and NH band-importance functions for predicting SRTs with CI users. Culling *et al.* (2012) only discussed the assumption in their model that in the case of bilateral implementation both CIs contribute equally. However, since this is not relevant in our unilateral study it can therefore be omitted. The only included model adaptation related to HI (besides ignoring one ear), as observed in Sec. III D, is that the overall model scores related to the 50% SRT for CI-users are relatively higher compared to NH. Although it is not argued that HI-aspects should not be included in a predictive model, these results suggest that the effect of hearing impairments in evaluating the CROS-system is only of minor importance compared to the impact of, e.g., the head-shadow effect.

V. CONCLUSIONS

In this work various listening tests were performed in diffuse and directional noise to quantify the effect of a CROS system with unilateral implanted CI users. A directional-dependent intelligibility model was proposed based on the SII for further analysis. It is concluded that the predictive model is able to accurately predict the listening test SRTs (RMSE of 1.1 dB) and that additional predictions are in line with existing results in the literature.

In diffuse noise, it was found that the gain in performance due to the addition of a CROS system is larger than its loss in performance. A maximum gain in SRT of 7.9 dB was found when speech comes from the CROS side, where a maximum loss in SRT of 2.1 dB was found when speech comes from the implanted side. In directional noise the effect of the CROS system is symmetric where the maximum gain and minimum loss in SRT was around 9 dB. This reveals a clear potential of using the CROS system in diffuse noise in terms of SRT.

From the results it also clear that the cancellation of the head-shadow effect due to the CROS system has a different impact on SRT for each noise type. In diffuse noise, the difference in SRT between best and worst performance with a CROS system is only around 3 dB in contrast to the 10 dB when no CROS-system is used. With directional noise the differences between best and worst performance are even larger. With the CROS system 5 dB difference was found in contrast to 20 dB without the CROS system. Further studies are needed to measure the impact on the user experience of these directional dependencies on SRT.

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