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Turn an Ear to Hear: How Hearing-Impaired Listeners Can Exploit Head Orientation to Enhance Their Speech Intelligibility in Noisy Social Settings

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Abstract

Turning an ear toward the talker can enhance spatial release from masking. Here, with their head free, listeners attended to speech at a gradually diminishing signal-to-noise ratio and with the noise source azimuthally separated from the speech source by 180° or 90°. Young normal-hearing adult listeners spontaneously turned an ear toward the speech source in 64% of audio-only trials, but a visible talker's face or cochlear implant (CI) use significantly reduced this head-turn behavior. All listener groups made more head movements once instructed to explore the potential benefit of head turns and followed the speech to lower signal-to-noise ratios. Unilateral CI users improved the most. In a virtual restaurant simulation with nine interfering noises or voices, hearing-impaired listeners and simulated bilateral CI users typically obtained a 1 to 3 dB head-orientation benefit from a 30° head turn away from the talker. In diffuse interference environments, the advice to U.K. CI users from many CI professionals and the communication guidance available on the Internet most often advise the CI user to face the talker head on. However, CI users would benefit from guidelines that recommend they look sidelong at the talker with their better hearing or implanted ear oriented toward the talker.

Keywords

cochlear implant, listening tactic, head orientation, spatial release from masking, hearing impairment

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Introduction

Spatial release from masking (SRM) improves intelligibility through spatial separation of target speech and interfering sources. Past studies of SRM have typically required the listener to face the speech head on because it has been assumed by researchers and professionals that facing the speech was a more natural attitude (Bronkhorst & Plomp, 1990). However, Kock (1950) found a large benefit of orienting the head away, a benefit also predicted by the Jelfs, Lavandier, and Culling's (2011) model of SRM (Grange & Culling, 2016b). These observations raise the question of whether listeners naturally use head orientation, and if not, whether better advice on this listening tactic would benefit patient groups in real life.

Grange and Culling (2016b) demonstrated that young normal-hearing (NH) listeners could reach up to 8 dB in head-orientation benefit (HOB) in a sound-treated room with a single, azimuthally separated speech-shaped noise interferer. Most of this HOB could be obtained with a modest 30° head turn. Grange and Culling (2016a) showed that a significant HOB was also obtained by cochlear implant (CI) users in the same, low-reverberation environment. Unilateral CI users obtained the same HOB (~4.5 dB) as age-matched NH controls. Bilateral CI users obtained a smaller but still statistically significant HOB (~2 dB). Comparing speech reception

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thresholds (SRTs) in audiovisual (AV) modality to audio-only, Grange and Culling (2016a) confirmed that a 30° head turn had no detrimental impact on the listeners' lip-reading ability. Therefore, for CI users, the benefits of head orientation and lip reading could be combined to improve SRT by up to 9 dB.

Having measured HOB for NH listeners at a range of head orientations, Grange and Culling (2016b) investigated whether or not young NH listeners spontaneously made head turns in a challenging listening task. The listeners attended to a long audio clip with gradually diminishing signal-to-noise ratio (SNR), in a spatial configuration of noise and speech for which the measured HOB was close to 10 dB. Their task was to follow the clips as far as they could and flag when they lost track of the thread of the clip. The authors found that young NH listeners spontaneously turned their head in 56% of trials but rarely adopted optimal head orientations.

To test the robustness of HOB in a realistic environment, Grange and Culling (2016a) tested whether HOB would occur for young NH listeners in a typical noisy and reverberant social setting. In a realistic restaurant simulation, NH listeners benefited from a 30° head orientation with a ~1.5 dB improvement in SRT at the predicted best head orientation.

These studies left open several questions. Do hearing-impaired (HI) groups make better or worse use of HOB than NH listeners? What is the influence of seeing the talker on their behavior? How much HOB might HI groups gain in realistic conditions? Is existing advice on hearing tactics optimal, or does it need refinement to take HOB into account?

Experiment 1 of this study tested whether CI users make spontaneous head turns when placed in a challenging listening task using an experimental protocol similar to that employed in Grange and Culling (2016b). CI users typically exhibit SRTs in noise 10 to 20 dB higher than NH listeners. A HOB of 2 to 5 dB would significantly reduce the listening challenge they face in noisy settings, so we hypothesized that CI users would be more likely to exploit their HOB than NH listeners and make greater use of head orientation in the behavioral task. Moreover, both groups were tested with and without visual input in order to test whether being able to see the talker would influence their behavior.

Experiment 2 measured whether HOB remains robust for CI users and for HI listeners in a complex, reverberant environment. For direct comparability with the headphone study previously conducted with NH listeners, the latter experiment simulated CI use over headphones using a vocoder (Grange, Culling, Harris, & Bergfeld, 2017).

Finally, in order to assess current advice given to patients with respect to head orientation, three surveys were conducted. One survey examined the materials on hearing tactics that we could find on the World Wide Web (WWW). Two more surveys administered questionnaires to U.K. CI patients and professionals regarding the existing advice delivered in U.K. clinics.

Experiment 1: Head-Orientation Behavioral Task

Participants

The same participants as in Grange and Culling (2016a, Experiment 1) were tested according to the rules of our Institutional Ethics Committee. Twelve young NH adult listeners (aged 18–22 years), 17 CI users (9 unilateral [mean age of 57 years] and 8 bilateral [mean age of 67 years]), and 10 NH listeners age matched to the CI users (mean age of 62 years). The specifics of participating CI users are shown in Table 1. All unilateral CI users had severe to profound hearing loss (HL) in their nonimplanted ear and so were unilaterally hearing for the purpose of our study. The data from one unilateral CI user (U6) were excluded because the user could not perform the task from the beginning of any run, even after increasing the starting SNR to 24 dB. All CI processors (except that of participant U9) had microphone directionality disabled. The data from U9 were retained because it did not differ significantly from that of other unilateral CI users.

Stimuli and Equipment

Passages from the *The Wonderful Wizard of Oz* were audiovisually recorded by a male, British-accented target talker (the second author). Each 3 to 4 s segment of the audiostream was normalized for root-mean squared (RMS) power. Gaps in speech (30 dB below running average RMS) exceeding 100 ms were excluded from the RMS calculation. Masking noise was filtered to match the long-term spectrum of the voice. The sum of the at-source target and masker levels was kept constant such that it measured 65 dBA at the center of the loudspeaker array.

The experiment was conducted in a sound-treated room ($RT_{60} \approx 60$ ms). Loudspeakers were placed at the cardinal points of a 1.2-m radius circle (Figure 1), centered on the listener's head, and 1.3 m above the floor, thereby placing all loudspeakers on the listeners' azimuthal plane. Listeners were sat on a swivel chair; the height of which was adjustable and the orientation of which, when they entered the room, was purposely randomized. A video screen was located below the loudspeaker at 0° azimuth.

Spatial Configurations

Selected spatial configurations were the same as those employed in Grange and Culling's (2016a) objective

Table 1. Specifics of CI Users Who Participated.

		Left CI				Right CI				
CI user	Age (years)	Year fitted	Make	Processor	Implant	Year fitted	Make	Processor	Implant	Etiology
B1	78	2013	Cochlear	Nucleus6	CI-500	2013	Cochlear	Nucleus6	CI-500	Unknown
B2	64	1995	MedEl	Tempo+	Pro short-h	2000	MedEl	Tempo+	CIS Pro+	Meniere
B3	48	2005	Cochlear	Nucleus6	N24	2012	Cochlear	Nucleus6	CI24-RE	Genetic
B4	71	2009	AB	Harmony	HiRes90K	2011	AB	Harmony	HiRes90K	Usher
B5	67	2004	Cochlear	Nucleus5	N24	2006	Cochlear	Nucleus5	CI24-RE	Meniere
B6	66	2001	MedEl	Opus2	Combi40+	2005	MedEl	Opus2	Pulsar	Unknown
B7	66	2001	MedEl	Opus2	Combi40+	2001	MedEl	Opus2	Combi40+	Unknown
B8	78	2007	AB	Harmony	HiRes90K	1995	Cochlear	Freedom	N22	Unknown
U1	39	–	–	–	–	2003	AB	Harmony	C2	Sensorineural
U2	60	2010	MedEl	Opus2	Pulsar	–	–	–	–	Meniere
U3	67	2004	MedEl	Opus2	Combi40+	–	–	–	–	Unknown
U4	67	2008	AB	Harmony	HiRes90K	–	–	–	–	Unknown
U5	32	2004	AB	Harmony	HiRes90K	–	–	–	–	Unknown
U6	74	1996	Cochlear	Nucleus5	N22	–	–	–	–	Streptomycin
U7	59	–	–	–	–	2008	Cochlear	Freedom	N24	Unknown
U8	65	1997	Cochlear	Freedom	N22	–	–	–	–	Unknown
U9	66	2002	Cochlear	Esprit 3 G	N24	–	–	–	–	Viral inf.

Note. CI = cochlear implant.

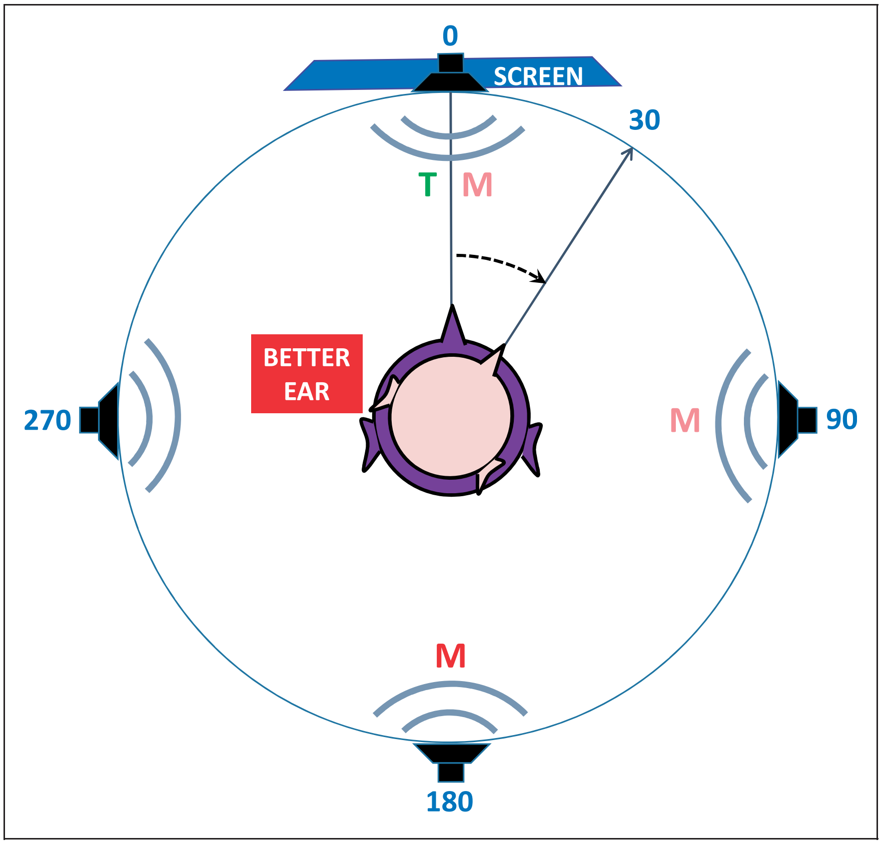

Figure 1. Schematic representation of the Experiment 1 spatial setup, where target would always be placed at 0°, together with the fixed video screen; collocated and separated spatial configurations are illustrated. Highlighted in a darker shade is the 180° masker azimuth for the T_0M_{180} configuration (first and second configuration subscripts denote target and masker azimuths). Also illustrated is a 30° head turn that makes the left ear the better ear (i.e., the acoustically favored ear) in both T_0M_{180} and T_0M_{90} separated configurations.

SRT runs. They are denoted T_0M_α, where subscripts 0 and α define azimuths in degrees, of the target (T) and masker (M), respectively, when a listener faced the target. The free-head task was run in both the collocated (T_0M_0) and the separated (T_0M_{90} and T_0M_{180}) spatial configurations. T_0M_0 served as a reference condition, in which listeners were not predicted to benefit from head orientation. Figure 1 shows the three possible spatial configurations or sound source positions as well as an example 30° head turn that would favor the left ear. Dummy runs were performed prior to test runs, for practice purposes, but also to identify a CI user's better performing ear in noise. Should a CI user's right ear be their better performing ear, that ear would be favored by testing at T_0M_{270} instead of T_0M_{90}; the data would later be flipped so it would appear as though all listeners had a better left ear. NH listeners were pseudorandomly allocated an arbitrary better ear.

Figure 2 shows the Jelfs et al.'s (2011) model predictions for SRM as a function of head orientation in the separated spatial configurations. The model sums better ear SNR and NH binaural unmasking benefit, both computed from binaural-room impulse responses to predict SRM. It was demonstrated in Culling, Jelfs, Talbert, Grange, and Backhouse (2012) to be adequate for CI predictions, for which the binaural unmasking component is neglected. The model predicts that NH listeners should benefit equally from a rightward or leftward head turn in the T_0M_{180} configuration. An asymmetry in speech intelligibility performance (in noise) would cause both separated configurations to lead to more HOB when the better performing ear is turned toward the target. For unilateral CI users, turning their implanted ear toward the target talker would lead to nearly as much HOB as that available to NH listeners, but turning the other way would reduce SRM. When turning the better ear toward the target talker, a substantial HOB was predicted with a modest, 30° head turn (cf., Grange & Culling, 2016a).

Procedure

Listeners were presented with a set of six 6-min clips, starting at SNRs of 6 dB for NH and 16 dB for CI users. SNRs diminished at a rate of 6 dB/min so that the SNR would reach the listener's 50% intelligibility point in the collocated condition about 2 min into a clip and no listener could follow a clip all the way to its end, regardless of head orientation and spatial configuration. In separate conditions, the presentation modality was either audio-only or AV. As in Grange and Culling (2016b), listeners were instructed as follows: "Please listen normally, as in a social situation, and do whatever you would normally do in such a context in order to follow the target speech as long as you can," but "please, keep your back against the chair's back rest and keep your arms resting on your lap." Listeners were informed that they would be quizzed on the last three to five words they felt they correctly understood. Presentation was stopped when listeners flagged that they had lost the thread of the story; listeners were then asked to recall the last three to five words thought to be correctly understood, thereby providing a subjective measure of SRT: The SNR at which the last correctly recalled word was presented. All but one CI user (U6, whose data were excluded) succeeded in the task.

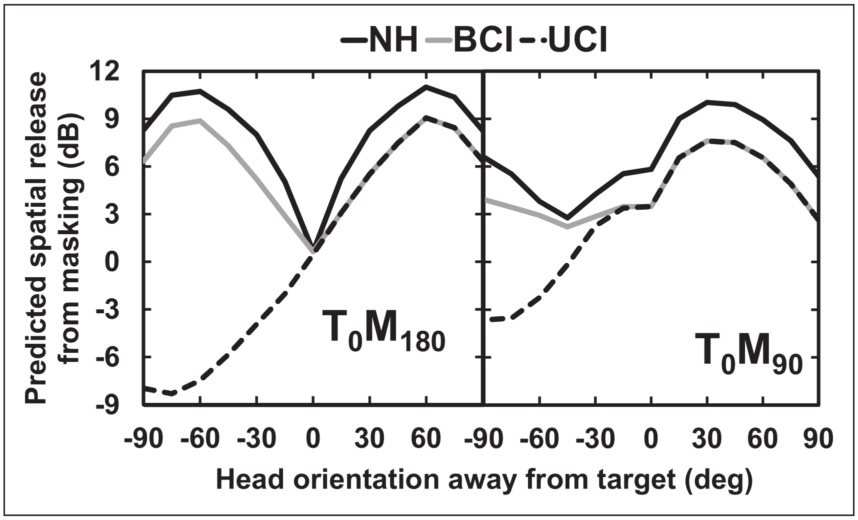

Figure 2. Predicted SRM in the sound-treated room for all listener groups as a function of head orientation and for a masker separated from the target by 180° (T_0M_{180}) or 90° (T_0M_{90}). NH = normal hearing; CI = cochlear implant.

The listeners were not told where the target speech would come from, but they consistently and spontaneously faced the video monitor at the start of each trial. The six conditions (3 Spatial Configurations × 2 Presentation Modalities) were rotated for each new participant, against a fixed material order, and so within two presentation modality blocks, the starting modality being counterbalanced.

Once all conditions had been completed without instruction regarding head orientation, the listener was informed that head orientation might be beneficial. The listener was invited to "explore the potential benefit of orienting the head away from the target speech source" and the free-head trials were repeated using the same materials. Both source separation and prior knowledge of the speech material in the postinstruction runs enabled unmasking and could interact in a complex way. However, it can be assumed that the effect of repeating the material was reduced by the SRM calculation: postinstruction, an SRT improvement from preexposure to the material in a spatially separated condition may be compensated for by a similar improvement in the collocated condition. The strong semantical context present even in the first presentation of the material should also help reduce the effect of material reuse. The rest of the instructions remained the same as for the first test so that the only manipulation was the instruction to explore their potential HOB. Hence, the head-orientation and performance data were analyzed for the effect of instruction as a factor. The other factors of interest were spatial configuration and listener group.

Results

As in Grange and Culling (2016b), overhead video recordings were postprocessed using MATLAB to recover head orientation. Over two passes, an operator tracked with the mouse pointer the locations of the center of the listener's head and then the listener's nose. The two sets of coordinates obtained were combined to extract the listener's head orientation with respect to the target direction. This measurement proved to be accurate within ±5° (see Grange & Culling, 2016b).

An analysis of the variance of the amounts of head movements (mean, unsigned head orientation) for the factors listener group (NH_y, NH_{am}, and CI users), presentation modality (audio-only and AV), spatial configuration (T_0M_0, T_0M_{180}, and T_0M_{90}), and instruction revealed a fivefold increase in head movements after instruction, $F(1,35) = 190.5$, $p < .001$, and halving of head movements by AV presentation, $F(1,35) = 90.0$, $p < .001$. Listener type and spatial configuration had no significant effect. Instruction reduced the inhibiting effect of the AV modality, $F(1,35) = 6.73$, $p < .02$, particularly for CI users, $F(2,35) = 5.80$, $p < .01$. Differences in the amount of head movement between spatial configurations were also reduced by instruction, $F(2,70) = 3.43$, $p < .05$. Listener group interacted with the effect of instruction, $F(2,35) = 3.68$, $p < .05$, because young NH listeners appeared to make more spontaneous head orientations than other groups. To compare spontaneous head movement across groups, another analysis was restricted to preinstruction data. Spontaneous head movements were reduced by a factor of 6 by AV presentation, $F(1,35) = 20.02$, $p < .001$. Young NH listeners made around 3 times more head movements than CI users and NH controls, $F(2,35) = 3.79$, $p < .05$, between whom there was no significant difference. This went against our expectation that CI users would spontaneously turn their head more than NH listeners.

Example head-orientation tracks for unilateral and bilateral CI users, pre- and postinstruction to explore the potential benefit of head orientation, are displayed in Figure 3, as compared with those of their NH controls. Subjective SRTs were derived from the SNRs corresponding to the last three to five words correctly recalled by the listeners. Final head orientation (the ordinate of open circle and cross symbols) was computed as the average head orientation over the 10 s preceding the last correctly recalled word. The abscissa of these plots is normalized SNR because the tracks were adjusted to end at the subjective SRM reached at the final head orientation; this manipulation allowed placing the data in the context of SRM model predictions. Subjective SRM is the intelligibility improvement computed as the subjective SRT reached in the collocated configuration, minus that reached in the separated configuration. The head-orientation data preceding that point is aligned with normalized SNR on the abscissa by subtracting the separated-configuration SNR from the collocated SRT for each individual, in such a way that 1 min of material presentation corresponds to a 6 dB SNR drop, as the diminishing SNR rate of −6 dB/min dictates (see the 1-min bar in the top-left panel in Figure 3 for reference).

From the observation of head tracks and as found in Grange and Culling (2016b), some young NH listeners appeared to scan for intelligibility improvements (5 of the 12), but a few went straight to the predicted most beneficial head orientations (2 of the 12). In contrast, CI users made more conservative head turns than young NH listeners and except for one participant, CI users did not go straight to the predicted most beneficial head orientations, perhaps because of their poorer sound localization ability (Kerber & Seeber, 2012). Of NH listeners who appeared to scan for improvement, most (4 of the 12) settled at suboptimal orientations, even after passing through optimal orientations. Unilateral CI users mostly turned the correct way after

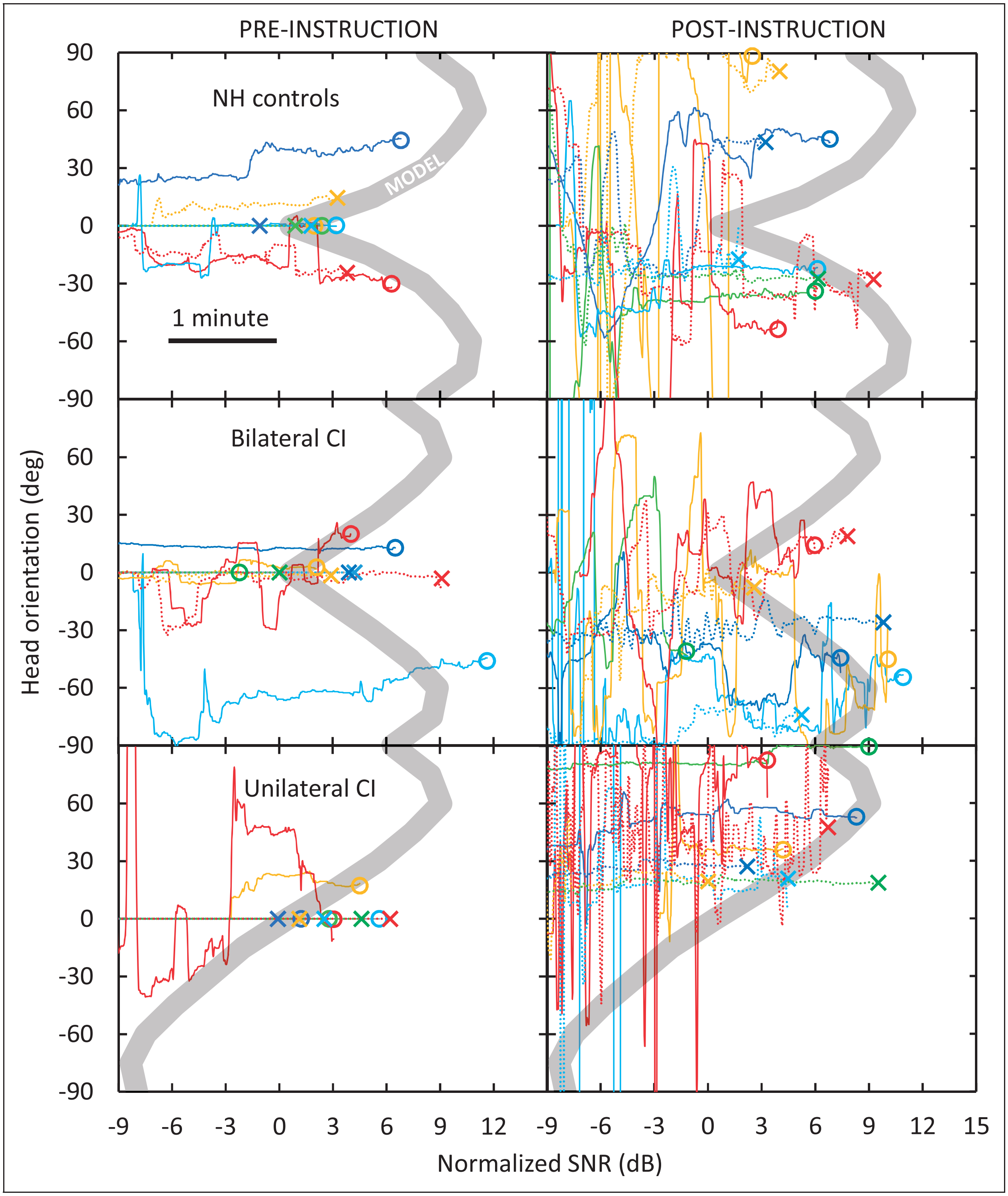

Figure 3. Example head tracks for NH controls (top panel) and CI users (unilateral and bilateral in the bottom and middle panels, respectively) in the T_0M_{180} spatial configuration. The time (abscissa) axis is replaced with normalized SNR, computed from the subtraction of source-separated, subjective SRTs from collocated (T_0M_0) subjective SRTs. Moreover, 6 dB in SNR reduction corresponds to 1 min of the clip. The left and right panels display the pre- and postinstruction head orientations adopted along the clip. Solid lines ending with an open circle and dotted lines ending with a cross correspond to audio-only and audiovisual runs, respectively. Each color (or shade of gray) is indicative of a given participant, within a given listener group. The data are superimposed on SRM model predictions (gray bands). NH = normal hearing; CI = cochlear implant; SNR = signal-to-noise ratio.

instruction. However, at T_0M_{90}, more than half of age-matched NH listeners and bilateral CI users turned away from the noise, as though they had tried to get away from it, when the optimal strategy was to point their head between speech and noise directions, thereby turning their better ear toward the target talker.

Figure 4 presents the mean preinstruction and postinstruction subjective SRM for each listener group and in each spatial configuration. Young NH, age-matched NH listeners, and CI users all improved as a result of instruction (by 1.6 dB, 0.8 dB, and 1.2 dB; $F(1,11) = 7.80$, $p < .02$; $F(1,9) = 11.05$, $p < .01$; and $F(1,15) = 5.27$, $p < .05$, respectively). Significant correlations between subjective SRMs and SRM predictions at final head orientations were found for each listener type, $r = .49$, $t(46) = 3.86$, $p < .001$; $r = .35$, $t(38) = 2.30$, $p < .03$; $r = .36$, $t(60) = 2.96$, $p < .005$, respectively, indicating that orienting the head to predicted better head orientations led to SRM improvement. Despite an overall positive effect of instruction, age-matched NH listeners and bilateral CI users did not significantly improve postinstruction at T_0M_{90}.

Figure 5 shows histograms of final head orientations for each listener group at T_0M_{180} and T_0M_{90}. Model predictions are superimposed to help the reader judge how well listeners discovered optimal HOB pre- and postinstruction. The inhibition of head movements by the presence of visual cues is demonstrated by the tight distribution of final head orientations around the speech-facing orientation in the AV modality. At T_0M_{180}, NH and bilateral CI users can get a benefit of turning either way. Unilateral CI users, however, need to turn to present their implanted ear, and it is clear that they generally turned the correct way postinstruction. At T_0M_{90}, all listeners should experience a benefit of pointing their head between speech and noise sources. Only in one of 16 postinstruction trials, did a unilateral CI user turn the wrong way. In contrast, bilateral listeners turned the wrong way in 12 of the 16 trials, age-matched NH listeners in 11 of the 20 trials, and young NH listeners in 10 of the 24 trials.

Experiment 2: Simulations in a Virtual Restaurant

The materials from Grange and Culling's (2016a) second experiment, in which the effect of head orientation for NH listeners was tested in a virtual restaurant, were employed. The restaurant simulation is based on binaural room impulse responses measured in a real restaurant ($RT_{60} \approx 400$ ms). In the simulation, listeners were sat across the table from the target talker at each of six tables in the virtual restaurant. Interferers came from another nine tables spread across the restaurant. Interferers were either speech-shaped noise or continuous voices. The combination of the nine interferers produced a spatialized babble or diffuse noise. Testing at several tables aimed at demonstrating the robustness of HOB in a highly realistic simulation. Due to a lack of access to CI users and the challenges a headphone experiment would have presented, we opted for simulating bilateral CI users. To extend the HOB demonstration to a broader range of listeners, HI listeners were also tested.

Participants

Sixteen young NH adult listeners (mean age of 21 years) and 14 unaided HI listeners (mean age of 68 years) with moderate-to-severe high-frequency loss (40–85 dB HL in at least one ear and increasing from 2 kHz) participated, in accordance with our Ethics Committee rules.

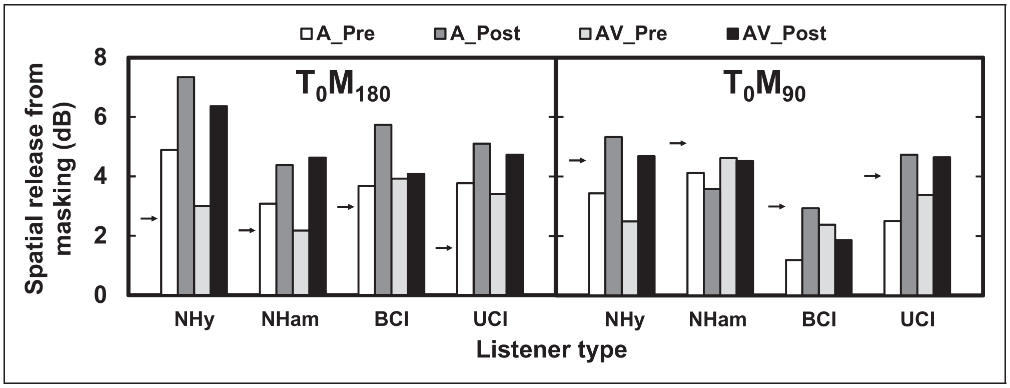

Figure 4. Subjective SRM reached at final head orientation by each group (NHy and NHam listeners; BCI and UCI users), in each spatial configuration for A and AV presentation modalities, preinstruction (A_Pre and AV_Pre) and postinstruction (A_Post and AV_Post). Arrows highlight the speech-facing SRMs from Grange and Culling (2016a). NHam = age-matched normal hearing; NHy = normal hearing young adult; BCI = bilateral cochlear implant; UCI = unilateral cochlear implant; A = audio-only; AV = audiovisual.

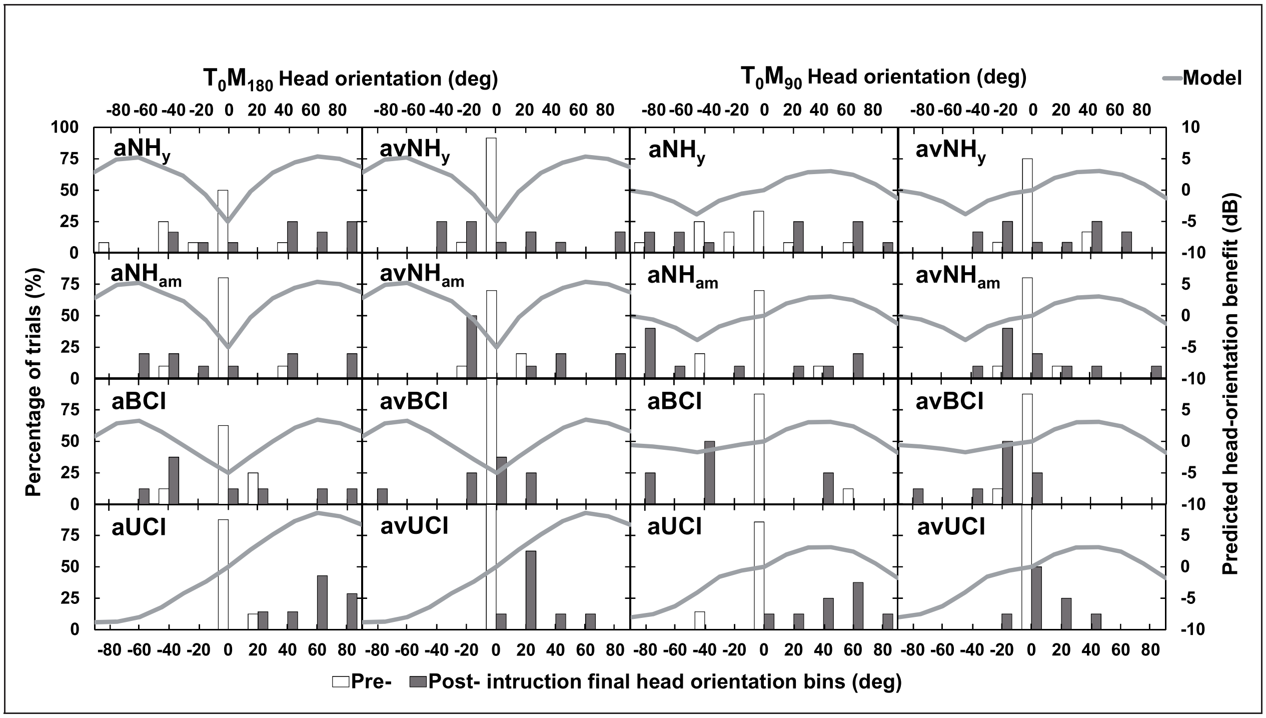

Figure 5. Histograms of the final head orientations of NH_y, NH_{am}, BCI, and UCI listeners for a and av, preinstruction (white bars), and postinstruction (dark gray bars). Predicted SRMs for the sound-treated room are light gray lines. NHam = age-matched normal hearing; NHy = normal hearing young adult; BCI = bilateral cochlear implant; UCI = unilateral cochlear implant; a = audio-only; av = audiovisual.

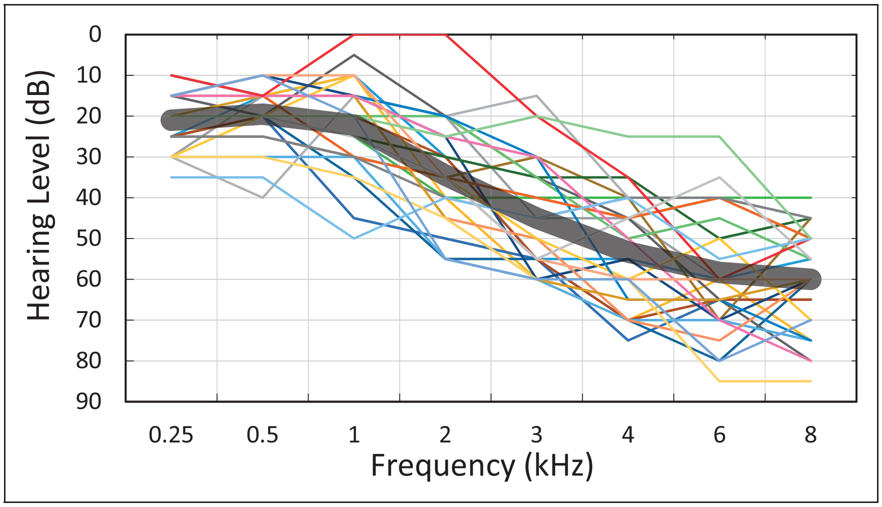

Figure 6. Pure-tone audiograms of our 15 HI participants (30 ears). Colored lines are for individual ears, and the broader, transparent gray line is the mean pure-tone average across all 30 ears.

The audiograms of our HI listeners are presented in Figure 6; all HI listeners displayed a sloping, high-frequency HL. The range represents typical age-related mild-to-moderate HL. HL asymmetry did not exceed 16 dB pure-tone average, with the left ear slightly more impaired than the right by 3.5 dB, on average.

Simulation of CI Users

The mixtures of target and interferers were passed through SPIRAL, a tone vocoder inspired by Oxenham and Kreft's (2014) that incorporates the threshold-elevating effect of current spread (set at

8 dB/oct. ≈ 2 dB/mm along the spiral ganglion) and uses 80 carrier tones for an improved representation of the spiral ganglion. For details of the vocoder, see Grange et al. (2017; cf., Supplemental Material for the MATLAB code). NH participants listened to the combined restaurant and CI simulation. For bilateral simulation, SPIRAL uses random carrier phases and independent simulation of the two ears to avoid risks of artifactual binaural fusion by NH listeners.

Results

The left and right panels in Figure 7 plot SRTs as a function of table number and head orientation (left, front, and right) for each interferer type for HI listeners and simulated CI users, respectively. SRTs were about 12 dB higher for simulated CI users than for HI listeners. The benefit of orienting the head was significant for each listener group, HI, $F(2,26) = 17.4$, $p < .001$; CI, $F(2,36) = 15.1$, $p < .001$. At the best predicted head orientation and in noise, the magnitude of HOB was 1.2 and 1.7 dB for HI and simulated CI users, respectively, and comparable to the 1.7 dB obtained by NH listeners in Grange and Culling (2016a). SRTs were significantly higher for speech than noise interferers, HI, +1.1 dB, $F(1,13) = 30.9$, $p < .001$; CI, +4.1 dB, $F(1,18) = 33.2$, $p < .001$. Simulated CI users benefited more from head turns in babble than in noise, 2.5 dB versus 1.4 dB HOB, $F(2,36) = 4.23$, $p < .5$, but such Interferer Type × Head Orientation interaction was not significant for the HI participants. The effect of table number was significant for both listener groups, HI, $F(5,65) = 141.0$, $p < .001$; CI, $F(5,90) = 15.48$, $p < .001$, as mean SRTs spanned 3 to 4 dB, lowest at table 14 and highest at table 9 for all listener groups. Table number interacted with interferer type for HI listeners (as the interferer type effect was not significant at tables 14 and 18) but not for simulated CI users, HI, $F(5,65) = 4.28$, $p < .002$; CI, $F(5,90) = 0.722$, $p = .609$. No other interaction was found.

Listening Tactics Advice Available to U.K. CI Users

Surveys of U.K. CI Users and Professionals on Communication Advice

To gauge existing patient and professional awareness of the HOB, two short questionnaires were created in 2014, prior to publication of our research demonstrating HOB. The questionnaires investigated what advice, if any, was given at that time to U.K. CI users regarding head orientation with respect to a speaker in a noisy environment such as a restaurant. Multiple-choice answers were made available regarding advice given or received and randomized so as to avoid bias. Questions regarding the rationale behind any given advice were also asked. One questionnaire was designed for CI users and the other for the CI professionals we thought likely to provide communication advice to service users. The first was completed by 95 CI users (55 unilateral, 14 bilateral, and 26 bimodal). The second was completed by 37 CI professionals (13 audiologists, 13 surgeons, 7 speech or language or hearing therapists, and 4 teachers of the deaf).

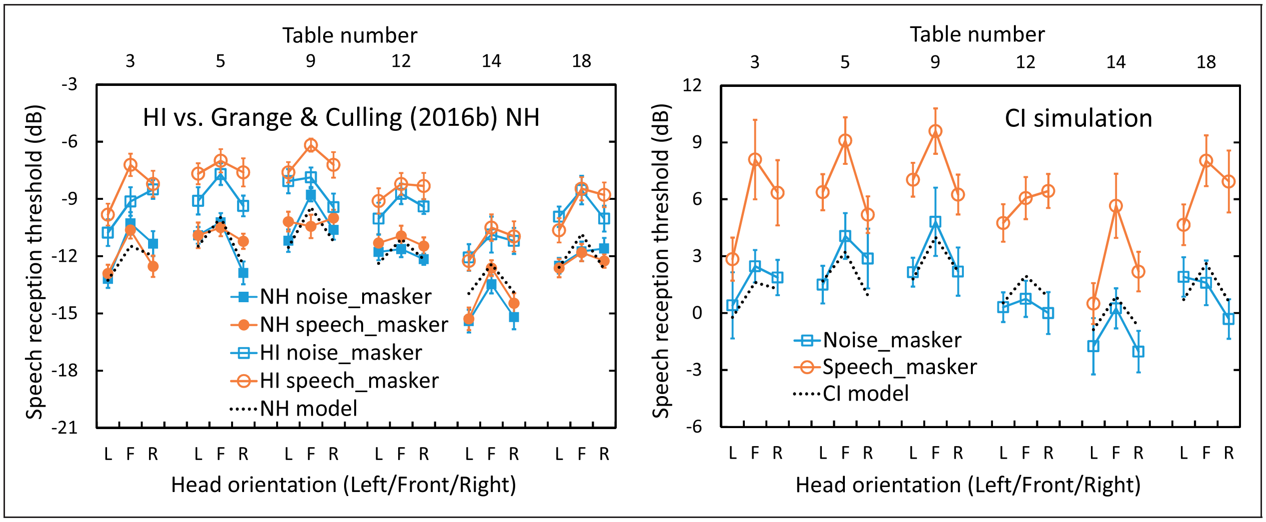

Figure 7. SRTs obtained for HI listeners in the context of Grange and Culling's (2016a, Experiment 2) NH data (left panel) and for simulated CI users (right panel) in the virtual restaurant, as a function of head orientation (30° to the left [L] or right [R], or facing [F] the target talker), interferer type (squares for speech-shaped noise, circles for babble, and filled symbols for the reference NH data), and table number. Jelfs et al.'s (2011) model predictions (dotted lines), with their mean equalized to mean SRTs in noise, include binaural unmasking for NH listeners but not for simulated CI users. HI = hearing impaired; NH = normal hearing; CI = cochlear implant.

Of the 31 professionals who declared having given advice on this topic, 27 indicated their advice was to 'frequently or always face the speaker and never to turn the head away from them.' Only 3 respondents declared occasionally advising patients to turn their head away from the speaker. Most of the professionals believed facing the speaker to be essential. Factors that respondents selected as influencing their responses included: 'ease of lip reading' (23), 'microphone directionality' (20), 'ease of maintaining eye contact' (17), 'SNR at the better ear' (15), 'training, lectures or presentations or literature' (11), and 'social acceptability of orienting one's head away from the speaker' (3).

Of the 95 CI users, 42 (44%) declared having never been advised on the subject of head orientation to improve their listening performance. Of the 53 CI users who recalled being given advice on head orientation, all indicated they were at least occasionally advised to face the speaker, and 41 (77%) 'frequently' or 'always' to face the speaker. However, 23 (43%) declared being advised at least occasionally to bring their better ear closer to the speaker and to carry on lip reading, of which 16 (30%) were 'frequently' or 'always' given this advice.

The CI users' survey was broadly consistent with the professionals' in that CI users declared being advised to face the speaker more often (>70% of the time) than to make use of head orientation. Moreover, when asked the reasons they recalled being given for the advice provided, those selected were 'ease of lip reading' (43), 'ease of maintaining eye contact' (23), 'benefit from their microphone directionality' (22), and 'SNR at the better ear' (13).

Review of Listening Tactics Guidance Available on the WWW

A review of information freely available on the WWW was also conducted to ascertain the advice available to consumers (the general public) and therefore to service users for optimizing listening in noise. Consistent with gray literature systematic search methods (Godin, Stapleton, Kirkpatrick, Hanning, & Leatherdale, 2015), the WWW was searched using the Google search engine on November 23, 2014 for webpages in English that contained patient information on head orientation as a strategy to facilitate speech intelligibility in noise. Search terms and relevant synonyms were combined using the Boolean operator "AND" (Table 2). Searching the WWW using Google presented unique challenges when compared with searches undertaken using standard academic databases and related to the large quantity of information available and a lack of consistency across websites. Furthermore, search strategy syntax used when searching academic databases was not applicable to searches in Google. The reviewer relied on the relevancy rankings within the Google search engine to retrieve the most relevant pages. Screening of pages ranked highest for relevance was limited in advance to the first 10 webpages listed for each of the returned searches. Eligible webpages were websites in English that were designed to provide information on the use of communication strategies for people with HL. All searches and data extraction were conducted by a single reviewer (author S.H.), an experienced professional working in a U.K. Cochlear Implant Clinic.

Table 2. Boolean Search Results Using a Standard Google Search Engine and Showing the Different Recommendations for Listening in Noise for the First 10 Sites Per Search.

Search strategy	Sites with patient information	Strategies to limit impact of background noise	Face the speaker	Head orientation
Head orientation; Head orientation and deaf; Head orientation and deafness and listening; Head orientation and deafness and speech; Head orientation and deafness and speech recognition; Head orientation and deafness and speech perception; Head orientation and deafness and speech intelligibility; Head orientation and deafness and noise; Head orientation and deafness and communication strategies	0	0	0	0
Head orientation and deafness and speech understanding	1	1	1	0
Head orientation and deafness and communication	1	0	1	0
How to listen in noise	1	1	1	1
Hearing loss and communication strategies	10	9	9	4
Aural rehabilitation	3	3	3	0
Aural rehabilitation and communication strategies	7	7	7	0
Totals	23	21	22	5

The data extracted from the webpages were presented in tabular format with a narrative summary. A total of 150 webpages were retrieved from 15 different Google searches. Twenty-three pages were identified as containing information for patients or the general public. The remaining sites were designed for professionals and excluded from the review. Of the 23 patient information sites, 5 (22%) included information specifically relating to head orientation as a communication strategy. Twenty-two of the 23 sites (96%) included information on the use of communication strategies relating to face-to-face communication, and 21 of the 23 sites (91%) included information on the reduction in background noise.

Recommendations on listener positioning in relation to the talker and head orientation varied. Guidance suggested positioning the listener directly in front of the talker or to the side of the better hearing ear. Most importantly, none of the included webpages suggested a head turn of 20° to 30° away from the talker to help increase intelligibility at the presented better ear while continuing with unencumbered lip reading.

Discussion

Contrary to our hypothesis, Experiment 1 found that CI users made significantly fewer spontaneous head turns than young NH listeners when speech was hard to follow, and no more than NH age-matched controls. CI users are a rather intensely studied population, and many experimenters ask participants to maintain a fixed head orientation, so one possibility is that our listeners had participated in such experiments previously and had carried this instruction into this study. However, only 1 of the 17 CI users reported consciously doing so. Another possibility is that their behavior has been influenced by advice from professionals to face the talker directly, as stated by 8 of the 17 CI participants. This interpretation is supported by the fact that AV presentation was found to further inhibit head movements and the fact that our survey of current advice indicated that the important message to look at the talker is often conflated with one to face them.

With a simple instruction to explore their HOB, all listener groups could follow the clips to significantly lower SNRs when a benefit from head orientation was to be gained (i.e., when target and interferer sources were azimuthally separated). Because the benefit of orienting the head was directly experienced by our participants within minutes, our findings suggest that simple training of CI users (and probably most mild to moderately HI listeners) to exploit their HOB could significantly improve their speech understanding in noisy environments. Due to the small sample size of Experiment 1, it was not possible to categorize listening strategies. Regardless of untrained strategies, the listening strategy required is simple: Turn the head somewhat away from the target talker, in such a way that lip reading is unaffected; if the interference predominantly originates from one side, turn *toward* that side; if the interference predominantly originates from the front hemifield, swap seats with the target talker to move the interference to the rear hemifield; if the listener has asymmetric hearing, they should position themselves such that when facing the target talker, the interference predominantly originates from the hemifield contralateral to their better hearing ear, preferably to the rear of that hemifield.

According to 98 U.K. CI users surveyed in 2014, many U.K. professionals typically advised their CI patients to face the speaker primarily because of preconceptions regarding lip reading or microphone directionality. The 2014 survey of 37 U.K. professional also points to professionals' preconceptions on the requirements of lip reading or directional microphones. However, Grange and Culling (2016a, Figure 4) demonstrated that lip reading was unaffected by head orientation of 30° away from the talker (Grange & Culling, 2016a, Figure 7) and that maximum sensitivity of a directional microphone on a behind-the-ear hearing prosthesis is in fact shifted to 30° to 50° azimuth by the acoustic diffraction of the head. The WWW search for publicly available advice on the use of head orientation when listening in noise showed that more often than not, the same suboptimal advice was provided. Our search had several limitations. First, the search was not undertaken as a systematic or systematized review and is not an exhaustive search. The review was undertaken to gain appreciation of the information available freely on the WWW on head orientation as a communication strategy. A systematic review to identify and comprehensively evaluate the clinical interventions delivered specifically to mitigate the impact of background noise when listening with a HL may be warranted. To the authors' knowledge, no such review has been undertaken before. As the reported surveys and WWW-based advice review were completed just over 3 years ago, it is the authors' intention to repeat the exercises and incorporate the outcomes in a further publication as part of a planned impact study.

Experiment 2 tested the robustness of HOB with reverberation and multiple interferers. Regardless of the table position within the restaurant or of the interferer type, a significant HOB could be obtained, in the 1.2 to 3.2 dB range. The significantly higher reverberation of the restaurant, combined with multiple, spatialized interferers, generated diffuse interference, which reduced the head shadow or better ear benefit by about 2 dB. The model informed us that the binaural unmasking component of SRM available to NH listeners was essentially removed by reverberation. This is why model predictions in Figure 7 appear identical in the two panels. Comparing results to Experiment 2 of Grange and Culling (2016a), SRTs were significantly elevated by mild-to-moderate high-frequency HL and CI simulation. In addition, HI and simulated CI listeners exhibited even higher SRTs when immersed in a spatialized babble than in speech-shaped noise. Qin and Oxenham (2003) concluded from their CI simulations that in order to segregate a target voice from background interferers, both F0 segregation and good frequency resolution were required. The HI listeners may also be more susceptible to modulation masking and somewhat less able to exploit F0 differences. For our simulated CI users, not only is their frequency resolution significantly reduced by CI simulation, but their access to the F0 cue is so limited that only gender discrimination is possible (Gaudrain & Başkent, 2018). Exploiting the F0 cue to assist in the spatial segregation of a given talker among many others is rendered impossible by the coarseness of low-frequency sound processing in CIs. In addition, Qin and Oxenham (2003) showed that modulated interferers were more disruptive to speech understanding than steady noise under CI simulation. These factors, and in particular susceptibility to modulation masking, may explain the greater SRT elevation found in simulated CI users with voiced interferers. Despite a large variability in thresholds and in access to available cues between listener groups, HOB remains mostly unaffected. In diffuse interference, HOB mostly stems from the acoustic benefit of orienting the better ear toward the target. Culling (2016) showed that such a benefit was not due to the acoustic shadow of the head sheltering one ear from the interfering sound but instead to an amplification of the target level at the better ear (see also Culling et al., 2012).

Two things remain unclear. First, why did simulated CI users appear to benefit more from head orientation (3.2 dB HOB) than their NH or HI counterparts in the spatialized babble of Experiment 2? The simulated CI data suggest that the masking by babble changes faster with head orientation than energetic masking by steady noise. This may warrant further studies designed to investigate intelligibility, as a function of interferer modulation rate or depth, of potential for informational masking and of head orientation.

Second, why did simulated bilateral CI users in the restaurant simulation gain as much HOB as NH listeners, when real bilateral CI users in Experiment 1 of Grange and Culling (2016a) gained *less* HOB than NH listeners or unilateral CI users? There are two key differences between the two experiments. The present experiment employed simulated CI users and also a diffuse interferer, composed of multiple sources in a reverberant room. These changes may have affected the benefit available from "squelch," the improvement in SRT due to addition of the ear with the poorer SNR. Grange and Culling (2016a) speculated that the reason bilateral CI users gained less HOB than unilateral CI users was due to a loss of squelch with head orientation: As the better ear is turned toward the target, an increase in interferer level and a decrease in target level cause the SNR at the poorer ear to decrease, which makes useful target information in the poorer ear less accessible. In the diffuse interference of the restaurant simulation, turning the head will have little effect on the interferer level at the poorer ear, reducing the loss of squelch described earlier, allowing simulated CI users to express a comparable level of HOB to the NH listeners. Another possibility is that the different experimental outcomes are due to asymmetries in the hearing of real CI users that have not been included in the simulation. Asymmetric vocoding that simulates differences in insertion depth and ganglion cell survival could be used to explore this possibility.

Conclusion

Overall, the experiments described herein demonstrate that (a) HOB in a realistically simulated social setting is robust with moderate-to-severe high-frequency HL or for a simulated CI listener; (b) simulated CI users benefit from HOB as much as NH or mild-to-moderate HI individuals, and perhaps even more in diffuse babble; and (c) CI users tend to make spontaneous head turns less than young NH listeners in challenging listening situations, possibly because (d) guidance provided to CI users by professionals and communication advice available on the WWW show that the most frequently offered advice is to "face the talker head-on." Such advice appears to be based on misconceptions relating to lip-reading requirements and BTE microphone directionality. Guidance on listening tactics for CI users, in particular, and possibly for the HI, in general, should be revised in light of our findings.

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