Characterizing the binaural contribution to speech-in-noise reception in elderly hearing-impaired listeners

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Abstract: To scrutinize the binaural contribution to speech-in-noise reception, four groups of elderly participants with or without audiometric asymmetry $<2\,\text{kHz}$ and with or without near-normal binaural intelligibility level difference (BILD) completed tests of monaural and binaural phase sensitivity as well as cognitive function. Groups did not differ in age, overall degree of hearing loss, or cognitive function. Analyses revealed an influence of BILD status but not audiometric asymmetry on monaural phase sensitivity, strong correlations between monaural and binaural detection thresholds, and monaural and binaural but not cognitive BILD contributions. Furthermore, the N_0S_π threshold at $500\,\text{Hz}$ predicted BILD performance effectively.
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1. Introduction

Although hearing-impaired listeners can differ substantially in terms of their speech-in-noise abilities, the responsible factors are yet to be fully understood (e.g., Dillon, 2012). In principle, monaural, binaural, and cognitive factors can all play a role. More recently, sensitivity to phase (or temporal fine structure) information has emerged as a promising predictor of speech-in-noise abilities (e.g., Strelcyk and Dau, 2009; Santurette and Dau, 2012). Phase information is encoded monaurally and then transmitted to the auditory brainstem where the two ear signals are combined. Good monaural coding fidelity is required for an accurate representation of binaural phase information, and some studies indicate that this underlies the ability to hear out speech against spatially separated noise or speech maskers (e.g., Strelcyk and Dau, 2009; Neher *et al.*, 2012). The binaural contribution to speech reception in noise, which depends on a processing mechanism below $\sim 1.5\,\text{kHz}$, can be assessed using the binaural intelligibility level difference (BILD) measure (e.g., Kollmeier *et al.*, 1990). Interaural audiometric differences have been related to impaired binaural hearing abilities (Jerger *et al.*, 1984), suggesting that ear asymmetries in monaural coding fidelity affect this mechanism. Relations between cognitive abilities and speech reception in spatially complex situations have also been reported (e.g., Neher *et al.*, 2012).

A better understanding of the factors involved in binaural speech-in-noise reception could promote individually tailored diagnostics and treatments (e.g., with hearing devices). However, this requires good experimental control over the factors of interest. In an effort to accomplish this, the current study recruited four groups of elderly participants with or without near-normal BILD and with or without audiometric asymmetry $<2\,\text{kHz}$ that were matched in terms of age and overall degree of hearing loss. Using measures of monaural and binaural phase sensitivity as well as cognitive function, these groups were then characterized further to shed more light on the underlying processes.

2. Methods

The current study was approved by the ethics committee of the University of Oldenburg. All participants provided written informed consent and received financial compensation.

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2.1 Participants

Initially, 77 sensorineurally hearing-impaired participants aged 61–85 with a large spread in audiometric asymmetry <2 kHz were recruited. All of them reported normal or corrected-to-normal vision, and all but six of them were bilateral hearing aid users. Pure-tone average hearing loss as calculated across 0.5, 1, 2, and 4 kHz as well as left and right ears (PTA4) ranged from 34 to 69 dB hearing level (HL) (mean: 53 dB HL). Low-frequency (LF) pure-tone average hearing loss as calculated across 0.125, 0.25, 0.5, 0.75, 1, and 1.5 kHz as well as left and right ears (PTALF) ranged from 19 to 69 dB HL (mean: 42 dB HL). The absolute difference across left and right ears (ΔLR) in PTALF (PTALF$_{\Delta LR}$) ranged from 0 to 41 dB (mean: 12 dB). (Results would be very similar if PTALF was calculated across 0.125, 0.25, 0.5, and 1 kHz.) Following the BILD measurements, 40 of these participants were tested further.

2.2 Test setup and amplification

Testing was carried out in a well-lit soundproof booth. A computer screen was used for displaying the user interfaces and visual stimuli. Audio playback was via an Auritec (Hamburg, Germany) Earbox Highpower soundcard and a pair of Sennheiser (Wennebostel, Germany) HDA200 headphones. The BILD and psychoacoustic stimuli were spectrally shaped according to the "National Acoustic Laboratories-Revised Profound" prescription rule (National Acoustic Laboratories, Sydney, Australia; Dillon, 2012) to ensure audibility similar to that provided by many clinical hearing aid fittings.

2.3 BILD measurements

To quantify BILD performance, 50%-correct speech reception thresholds (SRTs) were measured. Using free-field head-related impulse responses (Gardner and Martin, 1994), the speech, S, was simulated to come from 0° and the noise, N, from 90° (S$_0$N$_{90}$) or 270° (S$_0$N$_{270}$) azimuth. Stimuli were presented either binaurally or monaurally to the ear opposite N. The Oldenburg sentence material (Wagener *et al.*, 1999) was used for S and stationary speech-shaped noise for N. N was calibrated to a nominal sound pressure level (SPL) of 65 dB in the 0° direction. The level of S was varied adaptively (nominal starting level: 68 dB SPL). Initially, three training runs were carried out, followed by one test run per condition in randomized order. Each time, a test list consisting of 20 five-word sentences was used. Following Kollmeier *et al.* (1990), the BILD was obtained by taking the difference between the binaural and monaural SRTs per spatial configuration (S$_0$N$_{90}$ or S$_0$N$_{270}$), yielding the change in signal-to-noise ratio (SNR) due to binaural interaction. For the analyses, the two resultant BILD estimates were averaged. Typically, normal-hearing listeners achieve BILDs of ∼4 dB (Kollmeier *et al.*, 1990; Santurette and Dau, 2012).

2.4 Psychoacoustic measurements

Sensitivity to phase information in the presence of noise was assessed using monaural random frequency modulation detection (RFMD) and binaural masking level difference (BMLD) measurements. A 3-interval 3-alternative forced-choice paradigm coupled with a 1-up 2-down procedure was used. Intervals were 500 ms long, included 25-ms raised-cosine ramps, and were separated by 333 ms of silence. On each trial, one randomly chosen interval contained the target stimulus and the other two intervals the reference stimulus. Following a training run, two measurements (test, retest) were performed per condition. A measurement was terminated after ten reversals and the threshold estimated by taking the geometric mean of the last six reversal points.

The RFMD measurements mimicked those of Kortlang *et al.* (2016). They were performed at test frequencies, f_c, of 0.5 and 1 kHz. As maskers, 8-equivalent-rectangular-bandwidths-wide (Glasberg and Moore, 1990) Gaussian noises centered at f_c were used. The tones and noises were presented at 62 and 65 dB SPL (nominal), respectively. Random amplitude modulation (AM) with a root-mean-square (RMS) depth of −12 dB was applied to each tone. The reference stimuli contained a tone without frequency modulation (FM) but with AM. The target stimuli contained a tone with AM and FM. In the adaptive procedure, the RMS frequency excursion from f_c was varied (starting value: 30% of f_c). Multiplicative step sizes of 2, 1.5, and 1.25 were used, and the step size was decreased after an upper reversal.

The BMLD measurements were also performed at 0.5 and 1 kHz with noise signals essentially identical to those used for the RFMD measurements. The noise, N, and tone, S, were either presented diotically (N$_0$S$_0$) or N was presented diotically and S with an interaural phase shift of 180° (N$_0$S$_\pi$). The reference stimuli contained only N and the target stimuli both S and N. In the adaptive procedure, the level of S was

varied. The starting SNR was 0 dB. Additive step sizes of 6, 3, and 1 dB were used, and the step size was decreased after an upper reversal. The BMLD was obtained by taking the difference between the N_0S_0 and N_0S_π thresholds.

2.5 Cognitive measurements

To check for any top–down influences on BILD performance, two visual cognitive measures were included: A reading span test (Carroll *et al.*, 2015) and a "distractibility" test (Zimmermann and Fimm, 2012). The reading span test measures the ability (in %-correct) to recall a series of first and final sentence words. The (nonverbal) distractibility test measures the change in response time (in milliseconds) to target stimuli due to preceding distractors. Both measures are described in detail in Neher (2014).

3. Results

3.1 BILD data and definition of subgroups

The BILD data ranged from -0.4 to 5.2 dB (mean: 2.6 dB). They were only weakly correlated with age (Spearman's correlation coefficient, $\rho = -0.30$, $p < 0.009$), PTA4 ($\rho = -0.24$, $p < 0.036$), and PTALF ($\rho < -0.42$, $p < 0.001$). For further testing, four subgroups were defined. In doing so, the aim was to (1) achieve orthogonal variation in BILD and $PTALF_{\Delta LR}$, (2) control for age and PTA4, and (3) obtain a reasonably large sample size of $N = 4 \times 10$. This approach maximized the experimental contrast within and between BILD and $PTALF_{\Delta LR}$ for the available sample, under the constraint that the subgroups were not allowed to differ in age or PTA4. This resulted in two subgroups with "near-normal" mean BILDs of $\sim$3.7 dB and two subgroups with "abnormal" mean BILDs of 1.5 dB (see Table 1 and Fig. 1). Furthermore, two subgroups had a "symmetrical" mean $PTALF_{\Delta LR}$ of 3 dB and the other two an "asymmetrical" mean $PTALF_{\Delta LR}$ of $\sim$24 dB.

3.2 Psychoacoustic and cognitive data

Out of 640 measured thresholds, three RFMD thresholds and one N_0S_0 threshold from four different listeners were discarded due to large tracking excursions around the threshold estimates. Reliability of the remaining data was very good, as indicated by strong test-retest correlations (all $\rho > 0.88$, all $p < 0.00001$). For all further analyses, either the geometric mean of the test–retest measurements or the single remaining threshold was used. Furthermore, the RFMD thresholds were averaged across ears (interaural asymmetry in RFMD was also considered but not found to be predictive). Analyses revealed an influence of BILD status on many of the psychoacoustic measurements, with the near-normal subgroups outperforming the abnormal subgroups. In contrast, an influence of $PTALF_{\Delta LR}$ status was only evident in the BMLD data. Results were similar across the two test frequencies. The differential effects of BILD and $PTALF_{\Delta LR}$ status are evident from Fig. 1, which shows the RFMD, N_0S_0, N_0S_π, and BMLD data of the four subgroups averaged across 0.5 and 1 kHz together with statistical results.

Regarding the cognitive data, the subgroups had mean recall performances of 31% to 44% correct on the reading span task and mean response time changes of 4 to 46 ms on the distractibility task. Subgroup status did not affect the mean scores (both $\chi^2_{(3)} < 2.5$, both $p > 0.4$).

3.3 Correlation and regression analyses

To examine potential relations among age, hearing threshold levels (HTLs), and the psychoacoustic and cognitive measures, a correlation analysis was performed. Following Bonferroni ($N = 44$) correction, no correlations with age or the cognitive

Table 1. Means (and ranges) for the age, PTA4, $PTALF_{\Delta LR}$, and BILD data of each subgroup.

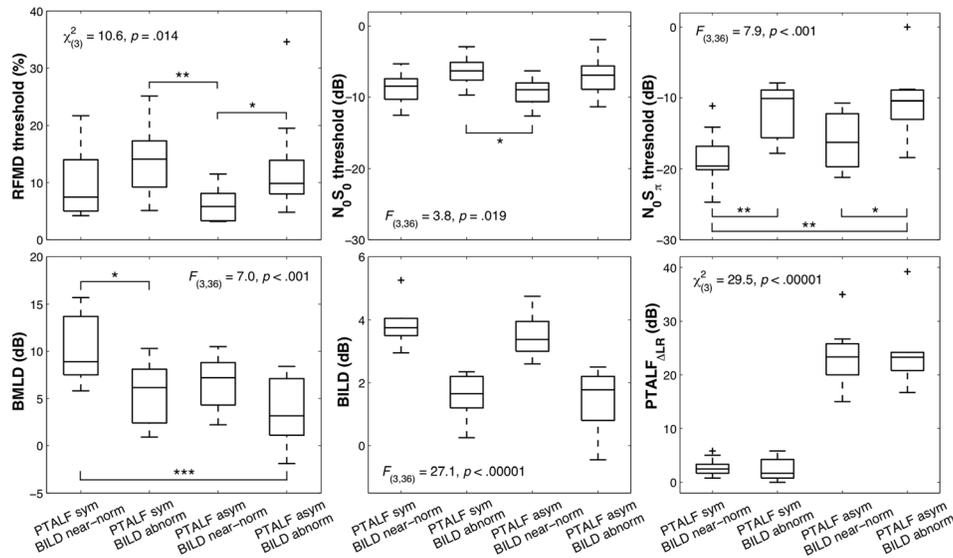| Subgroup	N	Age (yr)	PTA4 (dB HL)	$PTALF_{\Delta LR}$ (dB)	BILD (dB)
PTALF symmetrical BILD near-normal	10	74 (63, 80)	52 (46, 59)	3 (1, 6)	3.8 (2.9, 5.2)
PTALF symmetrical BILD abnormal	10	75 (70, 80)	52 (45, 61)	3 (0, 6)	1.5 (0.2, 2.3)
PTALF asymmetrical BILD near-normal	10	70 (62, 75)	49 (35, 57)	23 (15, 35)	3.5 (2.6, 4.7)
PTALF asymmetrical BILD abnormal	10	75 (67, 80)	56 (49, 58)	24 (17, 39)	1.5 (−0.4, 2.5)

Fig. 1. Boxplots of the RFMD, N_0S_0, N_0S_π, and BMLD data of the four participant subgroups averaged across 0.5 and 1 kHz ($*p < 0.05$, $**p < 0.01$, $***p < 0.001$). Also shown are the BILD and $PTALF_{\Delta LR}$ data. Differences among subgroups with different BILD or $PTALF_{\Delta LR}$ status were all significant at $p < 0.0001$.

measures were found (all $\rho < |0.27|$, all $p > 0.05$). Table 2 shows the correlations among the psychoacoustic measures and HTLs. It is noteworthy that the RFMD thresholds were only moderately correlated with HTLs, strongly correlated with the N_0S_0 and N_0S_π thresholds, and not correlated with the BMLDs. Correlations between BILD performance and the various predictors were also examined. Following Bonferroni ($N = 13$) correction, no correlations with the cognitive measures were found (both $\rho < |0.25|$, both $p > 0.05$). The strongest correlations emerged with N_0S_π, BMLD, and RFMD at 500 Hz (Table 3).

To test for independent BILD contributions of these predictors, linear regression analyses were carried out. For reasons of statistical rigor, maximally four predictors were used, and age and PTALF were always controlled for. The most predictive model included N_0S_π at 500 Hz ($R^2 = 52\%$; $p < 0.0001$), age ($R^2 = 8\%$; $p = 0.010$), and PTALF ($R^2 = 0\%$; $p > 0.6$). The second most predictive model included BMLD at 500 Hz ($R^2 = 39\%$; $p = 0.005$), age ($R^2 = 10\%$; $p = 0.010$), RFMD at 500 Hz ($R^2 = 7\%$; $p = 0.034$), and PTALF ($R^2 = 0\%$; $p > 0.8$). Analyses of the residuals revealed that both models satisfied the requirements for linearity and normality.

4. Discussion and conclusions

Consistent with earlier findings (Kollmeier *et al.*, 1990; Santurette and Dau, 2012), inter-individual BILD differences were large (>5 dB). Standard audiological measures were ineffective predictors of these differences, as reflected by the relatively weak correlations with age, PTA4, and PTALF (Sec. 3.1) and the fact that it was possible to define four subgroups with marked BILD differences that were independent of the effects of $PTALF_{\Delta LR}$, age, and PTA4 (Table 1). For auditory profiling purposes, a measure of binaural processing abilities in noise thus appears to be informative.

Table 2. Spearman's correlation coefficients for the psychoacoustic and HTL data (top cell entries: 0.5 kHz; bottom cell entries: 1 kHz). $*p < 0.05$, $**p < 0.01$, $***p < 0.001$, $****p < 0.0001$, $*****p < 0.00001$ after Bonferroni correction.

	HTL	RFMD	N_0S_0	N_0S_π	BMLD
RFMD	0.52*	1			
	0.53*				
N_0S_0	0.49	0.68****	1		
	0.53*	0.76*****			
N_0S_π	0.69****	0.65***	0.61**	1	
	0.45	0.58**	0.67****		
BMLD	−0.58**	−0.39	−0.14	−0.84*****	1
	−0.28	−0.24	−0.15	−0.80*****	

Table 3. Spearman's correlation coefficients for the BILD, age, PTA4, PTALF, and psychoacoustic data (top cell entries: 0.5 kHz; bottom cell entries: 1 kHz). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, *****$p < 0.00001$ after Bonferroni correction.

	Age	PTA4	PTALF	RFMD	N_0S_0	N_0S_π	BMLD
BILD	-0.38	-0.29	$-0.45*$	$-0.53**$ -0.25	$-0.46*$ -0.28	$-0.72*****$ $-0.59***$	$0.59***$ $0.52**$

Because the N_0S_π threshold at 500 Hz could predict the BILD effectively (Sec. 3.3), it constitutes a suitable (and time-efficient) candidate for this.

The moderate correlations between the RFMD and HTL data (Table 2) suggest that the RFMD measure captures additional supra-threshold abilities. The fact that there was an influence of BILD status but not audiometric asymmetry on the RFMD thresholds (Fig. 1) also supports this. The strong correlations between the RFMD and binaural detection thresholds (Table 2) are consistent with the view that monaural phase sensitivity facilitates binaural processing abilities (e.g., Strelcyk and Dau, 2009). Interestingly, however, the RFMD thresholds and BMLDs were not correlated (Table 2) and contributed separately to the BILD prediction (Sec. 3.3), suggesting that both monaural and binaural factors play a role for binaural squelch abilities. In contrast, cognitive factors were unrelated to BILD performance, consistent with previous findings (Santurette and Dau, 2012).

Together, these results provide handles for characterizing, modeling, and compensating individual speech-in-noise deficits, and research is underway to address these issues.

Acknowledgments

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