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Frequency Following Responses to Tone Glides: Effects of Age and Hearing Loss

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Abstract

Purpose Speech is characterized by dynamic acoustic cues that must be encoded by the auditory periphery, auditory nerve, and brainstem before they can be represented in the auditory cortex. The fidelity of these cues in the brainstem can be assessed with the frequency-following response (FFR). Data obtained from older adults—with normal or impaired hearing—were compared with previous results obtained from normal-hearing younger adults to evaluate the effects of age and hearing loss on the fidelity of FFRs to tone glides.

Method A signal detection approach was used to model a threshold criterion to distinguish the FFR from baseline neural activity. The response strength and temporal coherence of the FFR to tone glides varying in direction (rising or falling) and extent (1/3, 2/3, or 1 octave) were assessed by signal-to-noise ratio (SNR) and stimulus–response correlation coefficient (SRCC) in older adults with normal hearing and with hearing loss.

Results Significant group mean differences in both SNR and SRCC were noted—with poorer responses more frequently observed with increased age and hearing loss—but with considerable response variability among individuals within each group and substantial overlap among group distributions.

Conclusion The overall distribution of FFRs across listeners and stimulus conditions suggests that observed group differences associated with age and hearing loss are influenced by a decreased likelihood of older and hearing-impaired individuals having a detectable FFR response and by lower average FFR fidelity among those older and hearing-impaired individuals who do have a detectable response.

Keywords Frequency-following response · Aging · Hearing impairment · Glides · Montage

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Introduction

For dynamic acoustic cues like those in speech to be represented at the cortical level, they must first be more or less faithfully encoded in the auditory periphery, auditory nerve, and brainstem. The frequency-following response (FFR) can be used to characterize the brainstem-level coding of auditory stimuli. Stimulus factors (e.g., frequency), methodological considerations (e.g., electrode montage), and participant characteristics (e.g., age or hearing loss) can all affect the recorded FFR.

Previously, Billings and colleagues [1] used tone glides to investigate the brainstem encoding of dynamic frequency change for young adults with normal hearing. The dynamic frequency changes of speech can be roughly modeled as tone glides that vary in instantaneous frequency over time by increasing or decreasing the frequency extent (i.e., Hz or octaves traversed) for glides of fixed duration. Because the strength of the FFR is partially dependent on the frequency content of the stimulus—response amplitudes and temporal coherence decline with increasing frequency [2, 3]—to minimize the potential influence of absolute frequency differences, comparisons among glides that differ in frequency extent must have the same overall average frequency.

Aging generally results in decreased FFR amplitude and degraded phase coherence for both tonal stimuli [4, 5] and speech-like stimuli [6, 7]. These aging effects occur even when older individuals have normal audiometric thresholds [4, 6–9]. However, there is evidence that the neural degradation that results from hearing impairment is larger than for aging alone [10, 11]. A common finding is that hearing loss affects the proportional representation of the envelope and fine structure of speech in the neural response (e.g., [11, 12]): for people with hearing loss, the proportion of the total response attributable to envelope encoding tends to be greater than for people with normal hearing thresholds, whereas fine-structure representation tends to be proportionally diminished.

A potentially important factor to consider across FFR studies with statistically significant group-level FFR differences, and when determining the effect sizes of age and hearing thresholds, may be the decreased likelihood of finding a "valid," "present," or "detectable" response in people who are older or have elevated hearing thresholds. Because data are routinely excluded from individuals with responses deemed to be abnormal, noisy, small, or absent (e.g., [7, 8, 12–18]), the members of some participant groups (e.g., older listeners with hearing loss) are more likely than others to be removed from group-level analyses. In this context, decisions about which data points to exclude, if any, may affect group-level statistics and distribution patterns unequally across groups.

Employing a data-exclusion threshold may increase or decrease the likelihood of observing a statistically significant group difference depending on the relative impact of two interconnected side-effects: (1) raising the overall mean for groups with excluded data (which may decrease group differences and thereby increase the *p*-value) and (2) reducing within-group variance (which, all else being equal, would tend to lower the *p*-value). Therefore, it is important to consider within-group FFR variability, especially in terms of its potential impact on the apparent presence or statistical significance of between-group differences (or lack thereof).

In a previous study [1], we addressed the effects of stimulus properties and recording montage on two FFR metrics (signal-to-noise ratio and stimulus–response correlation coefficient) in a group of young listeners with normal hearing (YNH). Generally, we found that the FFR could portray differences in neural activity in response to tone glides differing in frequency extent and direction. In the current study, two additional participant groups were tested—older listeners with and without hearing loss (OHI and ONH, respectively)—to address the influence that age-related declines in neural synchrony, loss of peripheral hearing sensitivity, or both may have on the FFR for tone glides. In addition, we explored an objective criterion for FFR detection and examined how its use for the exclusion of data points affected group means and variance in the current sample.

Method

Participants

Thirty adults—three groups of ten each—participated in this study. Group assignment was based on age and hearing status: younger listeners with normal hearing (YNH; 7 female, 3 male, aged 24–33 years, mean = 28.1, SD = 3.6), older listeners with normal hearing (ONH; 5 female, 5 male, aged 51–66 years, mean = 59.7, SD = 5.3), and older listeners with hearing impairment (OHI; 3 female, 7 male, aged 54–78 years, mean = 66.5, SD = 7.4). Group-level data for the YNH participants have been reported previously [1]. Participants with normal hearing had pure-tone thresholds $\leq$ 20 dB HL in the test ear at all octave frequencies 250–4000 Hz. Thresholds of the participants with hearing loss were bilaterally symmetric (no differences greater than 20 dB) and between 25 and 70 dB HL at octave frequencies 250–4000 Hz. Mean audiometric thresholds in the test ear for the three participant groups are shown in Fig. 1. No participants reported taking sleep-inducing or mood-altering medications. All were paid for their participation and provided informed consent. The research was conducted with the approval of the Institutional Review Board of the VA Portland Health Care System.

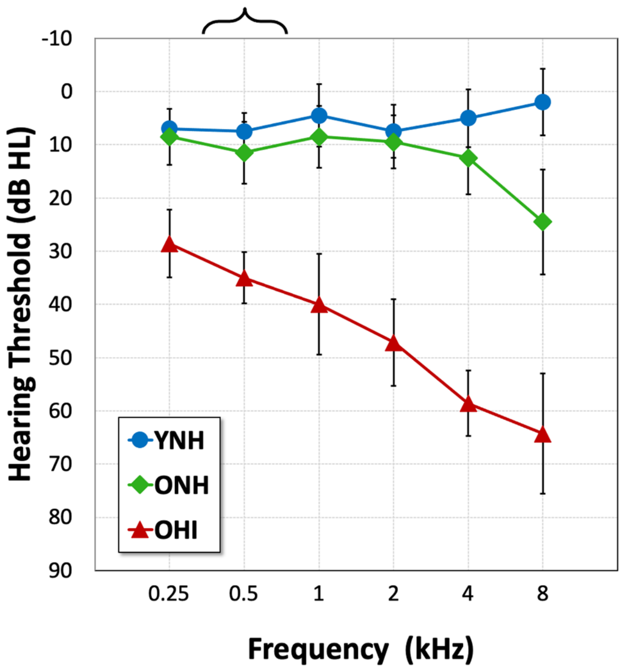


Fig. 1 Average audiograms for the three listener groups. Errors bars indicate ± 1 SD. A bracket along the top edge indicates the maximum frequency extent of the tone glides

Stimuli

Stimuli were six-tone glides that varied in glide direction (rising or falling in frequency) and extent of frequency change (1/3, 2/3, or 1 octave). The frequency extents of all six stimuli were centered around 500 Hz on a log2 (octave) scale, resulting in starting and ending frequencies that varied depending on the extent of frequency change as shown in Fig. 2. The glides were 120 ms in duration with 5-ms cosine on- and off-ramps.

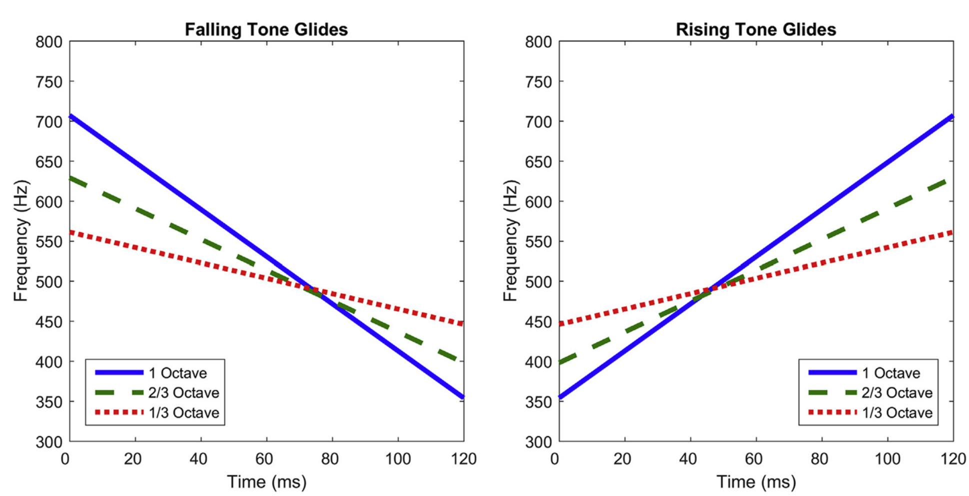
Data Acquisition and Processing

Testing was completed in a single 4-h session, which included informed consent, audiometric testing, and FFR data collection. The FFR was recorded in a sound-attenuating, electrically shielded booth. Participants were reclined in a comfortable position and instructed to lie still and quiet; sleeping was encouraged. The six glide conditions were presented in random order, each consisting of 3000 alternating-polarity sweeps with an interstimulus interval that varied randomly between three different durations (146, 163, and 180 ms, offset to onset). Stimuli were presented unilaterally at 80 dB SPL using Stim2 software and digital-to-analog conversion hardware (Compumedics Neuroscan, Charlotte, NC) and routed through an ER-3A insert earphone (Etymotic Research, Elk Grove Village, IL) treated with mu-metal magnetic shielding and double-length tubing. The left ear was selected as the test ear unless the right ear had a lower pure-tone average (0.5, 1, and 2 kHz); seven participants were tested in the right ear for this reason (2 ONH, and 5 OHI).

FFRs were recorded from disposable snap-on Ag/AgCl electrodes (Neuroline 720, Ambu USA, Columbia, MD) at a sampling rate of 20 kHz and an online filter passband of 100–3000 Hz using SynAmps RT amplifiers and Scan Acquire 4.5 software (Compumedics Neuroscan, Charlotte, NC). Recording electrodes were positioned at Cz (vertex), C7 (7th cervical vertebra), M1 (left mastoid), and Fz (halfway between Cz and the nasion), with the reference electrode at M2 (right mastoid), and the ground electrode at FPz (forehead). Data were re-referenced for analysis using a vertical montage (Cz to C7) and a horizontal montage (M1 to M2) as described in Billings et al. [1].

Processing of the continuous electroencephalogram into the FFR followed the protocol described in Billings et al. [1]. Epochs extending from − 40 to 240 ms re: stimulus onset were baseline-corrected such that the mean amplitude of

Fig. 2 Schematic of the six tone-glide conditions. Used with permission from Billings et al. [1]



the pre-stimulus interval was equal to zero. All epochs containing at least one instantaneous amplitude whose absolute value exceeded 30 μV were rejected. To obtain the FFR, an equal number of accepted sweeps were averaged separately for each polarity, and then the difference between the two polarity-based averages was divided by two. The FFR was subsequently filtered using a 401-tap digital FIR filter with a passband of 300–800 Hz, created in MATLAB (see Billings et al. [1] for additional details). After filtering, the FFR was time-aligned with the stimulus using the cross-correlation-based estimate. The lag was allowed to range between 2 and 22 ms, which encompasses all physiologically feasible values for brainstem generator sites ([19] physiological delay 0–20 ms, plus 2 ms to account for our ER-3A tube delay). Calculation of the lag was completed for each participant in each condition and subsequently subtracted from the original timestamps to isolate the portion of the neural response that aligned best with the evoking stimuli.

Response Characterization

Following Billings et al. [1], responses were analyzed in three adjacent, non-overlapping time windows relative to the estimated onset of the electrophysiological response to the stimulus: 0–40 ms, 40–80 ms, and 80–120 ms. In each window, the FFR was quantified in two ways: (1) response strength, measured as the signal-to-noise-ratio (SNR) of the response, and (2) temporal coherence between the stimulus and response, measured as the stimulus-to-response correlation coefficient (SRCC). In each time window, the SNR was calculated as the ratio of the peak magnitude of the discrete Fourier transform (DFT) of the response in a ± 25 Hz range around the stimulus frequency to the average DFT magnitude of the pre-stimulus baseline (− 40–0 ms relative to stimulus onset) in the same ± 25 Hz range. The SNR was then scaled to decibels by taking 20 times the base-10 logarithm of this ratio. The SRCC was defined as the absolute value of the covariance between the stimulus and response, normalized to a 0–1 scale by dividing by the product of their standard deviations.

FFR Threshold Criteria

A signal-detection approach was used to model the threshold for detecting the “true” presence of the FFR. For each stimulus condition, the distributions of the SNR and the SRCC were modeled based on the activity recorded during the 40-ms silent pre-stimulus interval (stimulus *Absent*), and on the average of the activity recorded during the three 40-ms analysis windows (stimulus *Present*). Simulated data sampled from the *Present* and *Absent* distributions were then used to train a classifier model. The classifier was trained on simulated data rather than the raw empirical data to minimize the degree of overfitting the model to observed data. The procedure was completed separately for the horizontal and vertical montages. We initially considered the SNR and the SRCC values separately and in conjunction as potential model parameters. However, exploratory analyses suggested that SRCC on its own provided a better separation between the *Present* and *Absent* distributions than did the SNR, and that including the SNR provided no meaningful improvement to the model based on SRCC alone (additional details available at https://github.com/mrmolis). Consequently, threshold criteria were based only on SRCC.

Present and *Absent* SRCC beta distributions were fit using pooled responses from all three participant groups. To account for possible dependence between the *Present* SRCCs and their corresponding *Absent* baseline SRCCs, we fit a *t* copula to a joint distribution of *Present* and *Absent* window pairs. Prior to fitting the *t* copula, each of the two SRCC distributions was separately subjected to a probability-integral transform—a cumulative distribution function (CDF) transform—which allowed both marginal distributions to be modeled as uniform. Next, 100,000 *Present* and *Absent* data pairs were simulated by randomly sampling from the *t* copula. The paired data points were decoupled and converted into SRCC values using the inverse CDFs of the two beta distributions estimated previously.

The simulated SRCC data were then used to fit a logistic regression model expressing the estimated probability that a given SRCC value was drawn from the *Present* distribution rather than the *Absent* distribution. The output of the logistic regression model was used to generate receiver operating characteristic (ROC) curves that described the rate of true positives against the rate of false positives across the full range of SRCC values from the simulated data. The detection criterion for the presence or absence of a response for each recording montage was defined as the SRCC value that minimized the Euclidean distance between the ROC curve and the point representing 100% detection accuracy (0,1). This process produced a threshold SRCC criterion of 0.218 for the vertical montage (hit rate: 0.88, false positive rate: 0.08) and 0.222 for the horizontal montage (hit rate: 0.89, false positive rate: 0.06). The potential consequences of excluding data points that fall below these detection thresholds are addressed in the “Discussion” section.

Results

Grand-average waveforms for each of the three participant groups in response to the 2/3-octave falling and rising conditions in each of the two analysis montages are shown in Fig. 3.

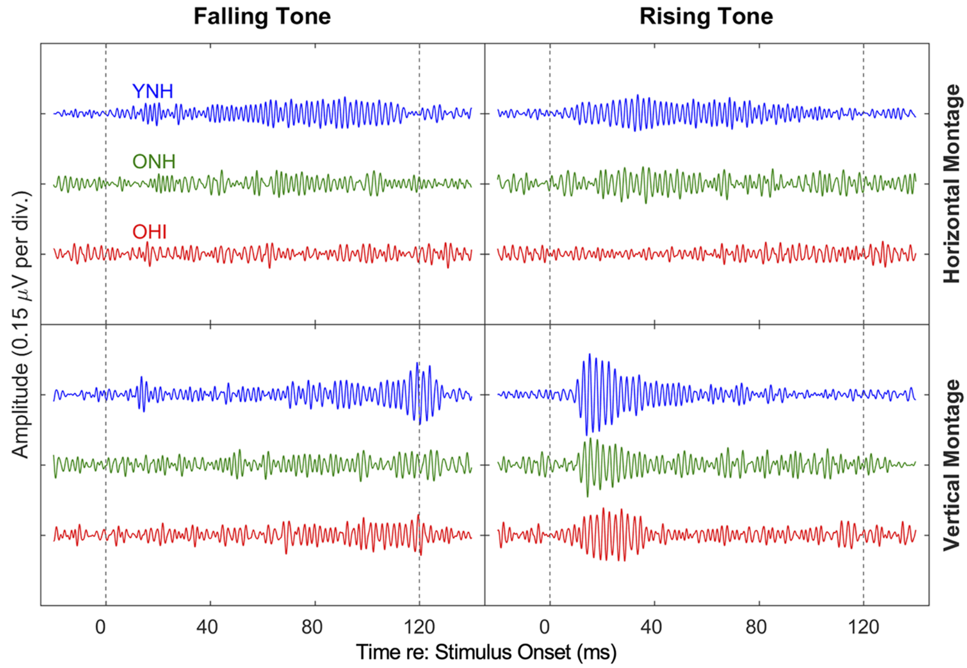


Fig. 3 Grand-average waveforms for YNH (blue), ONH (green), and OHI (red) groups in response to falling (left) and rising (right) 2/3-octave tone glides recorded with a horizontal electrode montage (top) or a vertical montage (bottom). Vertical dashed lines indicate stimulus onset and offset

Data from all 30 participants were included in the analyses. Two separate four-way repeated-measures analyses of variance (RM-ANOVAs), conducted using SPSS v27, were completed with the factors of window (first, second, and third), direction (rising and falling), extent (1/3, 2/3, and 1 octave), and montage (vertical and horizontal) as within-subjects independent variables, with participant group (YNH, ONH, and OHI) as the sole between-subjects variable, and with SNR and SRCC as dependent variables. Greenhouse–Geisser corrections [20] were applied to the degrees of freedom in cases where the assumption of sphericity was rejected by Mauchly's test [21]. Data from all participants are analyzed below—values falling below the FFR threshold criterion were not excluded in this analysis. Additional details of the statistical analysis, including the effect of applying the threshold criterion, as well as the code used for data processing and analyses are available at https://github.com/mrmolis; de-identified data are available upon request.

Within-Subject Effects

The results of the RM-ANOVAs are shown in Table 1. The main effects found to be statistically significant were those of window, extent, and montage for both SNR and SRCC; the main effect of direction was not found to be statistically significant for either dependent variable. Two significant two-way interactions were observed for both SNR and SRCC: direction × window and montage × window. Additionally, there was a significant direction × montage × window interaction for both SNR and SRCC. Significant higher-order interactions were observed for slope × direction × montage only for the SNR and for slope × direction × window and extent × direction × montage × window for the SRCC alone.

This portion of the analysis is analogous to the RM-ANOVA reported in Billings et al. [1] that was based on data from the 10 YNH participants alone. Figure 4 shows SNR and SRCC for data pooled across all participants in this study. Figure 4 can be compared with Fig. 5 in Billings et al. to evaluate the consequences of including older listeners with and without hearing loss in estimates of average response. For the most part, the pattern of interactions among the variables is the same as those reported previously. In general, the vertical montage was more sensitive to changes in stimulus frequency than the horizontal montage, regardless of glide direction. The SRCC was relatively unaffected by glide direction, whereas the magnitude of the SNR was mediated by an onset effect; low frequencies occurring at stimulus onset (i.e., rising tones) produced a larger response amplitude than low frequencies occurring at stimulus offset (i.e., falling tones).

Between-Group Effects

Figure 5 shows the distribution of SNR (top) and SRCC (bottom) values by listener group for all frequency extents and glide directions for both recording montages. Each point in the distribution represents a separate 40-ms analysis window for a given condition in an individual participant; horizontal lines across each distribution indicate the mean of all points for each participant group. For both measures and both montages, the order of the group means was the

Table 1 Results of four-way repeated-measure ANOVAs for the two response measures. Main effects and interactions are listed in the left-hand column, with the associated statistical values for the SNR and SRCC in the middle and right columns, respectively. Bolded *p*-values indicate statistical significance at an alpha level of 0.05. Italics indicate instances where Greenhouse–Geisser corrections were applied to adjust for nonsphericity

Effect	Measure					
	SNR			SRCC		
	df	*F*	*p*	*df*	*F*	*p*
Extent	2, 54	4.53	**0.015**	2, 54	17.99	**0.000**
Direction	1, 27	3.28	0.082	1, 27	0.23	0.633
Montage	1, 27	6.88	**0.014**	1, 27	7.08	**0.013**
Window	2, 54	9.22	**0.000**	2, 54	7.40	**0.001**
Extent × direction	2, 54	0.90	0.411	2, 54	0.95	0.394
Extent × montage	2, 54	0.74	0.480	1.4, 38.6	0.70	*0.458*
Extent × window	4, 108	1.02	0.402	2.8, 85.0	0.53	*0.651*
Direction × montage	1, 27	3.95	0.057	1, 27	2.57	0.120
Direction × window	1.4, 38.6	10.56	***0.001***	1.2, 32.4	78.60	***0.000***
Montage × window	2, 54	6.56	**0.003**	1.7, 44.7	5.85	***0.008***
Extent × direction × montage	2, 54	3.27	**0.045**	2, 54	0.72	0.491
Extent × direction × window	3.1, 84.9	0.69	*0.568*	4, 108	14.42	**0.000**
Extent × montage × window	4, 108	1.84	0.127	4, 108	2.14	0.081
Direction × montage × window	2, 54	5.93	**0.005**	1.6, 48.6	17.74	***0.000***
Extent × direction × montage × window	4, 108	1.36	0.252	4, 108	3.62	**0.008**

same (YNH > ONH > OHI). However, it should be noted that the response distributions were very broad for each group, with considerable overlap between groups for both SNR and SRCC in both montages.

The main effect of the group was found to be statistically significant for both the SNR ($F(2, 27) = 5.49$, $p = 0.010$) and the SRCC ($F(2, 27) = 6.94$, $p = 0.004$). Bonferroni-corrected post hoc tests revealed that the difference between the YNH group and the OHI group was statistically significant for both the SNR ($p = 0.008$) and SRCC ($p = 0.003$) measures, but the differences between the ONH group and the other groups were not statistically significant for either the SNR (vs. YNH, $p = 0.169$; vs. OHI, $p = 0.620$) or the SRCC (vs. YNH, $p = 0.225$; vs. OHI, $p = 0.216$). A table of the main effect of the between-subject variable (Group) and its interactions with the within-subject variables is available at https://github.com/mrmolis.

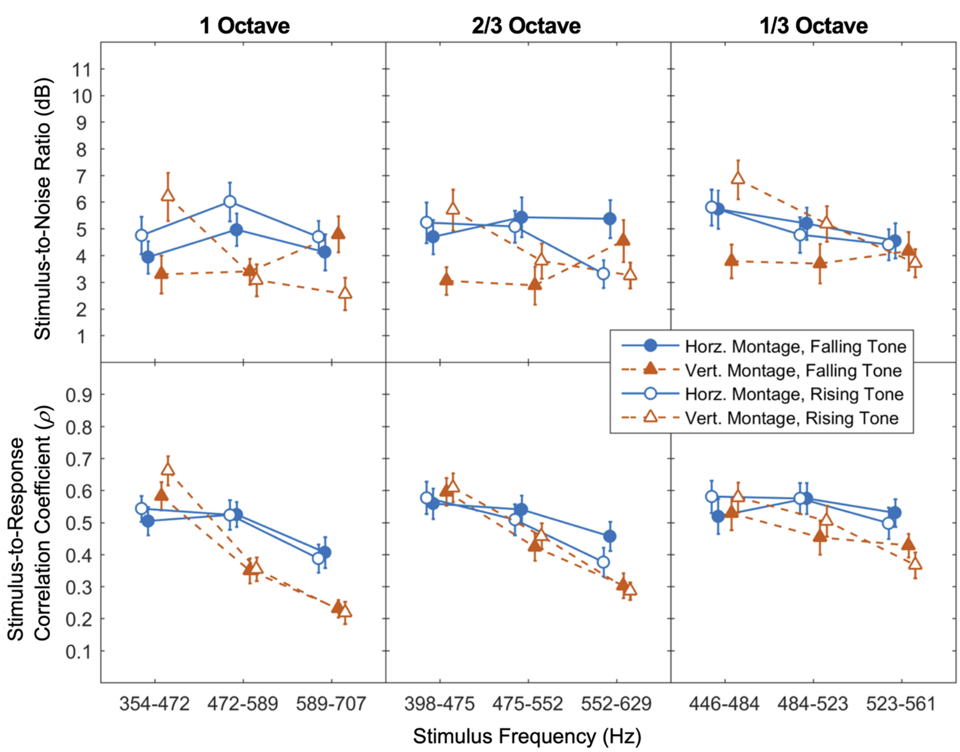


Fig. 4 SNR (top row) and SRCC (bottom row) by signal frequency for the three glide extents, with montage and glide direction as parameters. The effects of direction (rising: open symbols; falling: solid symbols) and montage (horizontal: triangles; vertical: circles) are shown for each extent (columns). SRCCs recorded with a vertical montage (bottom row, orange triangles) demonstrate greater frequency dependence than SRCCs recorded with a horizontal montage (bottom row, blue circles)

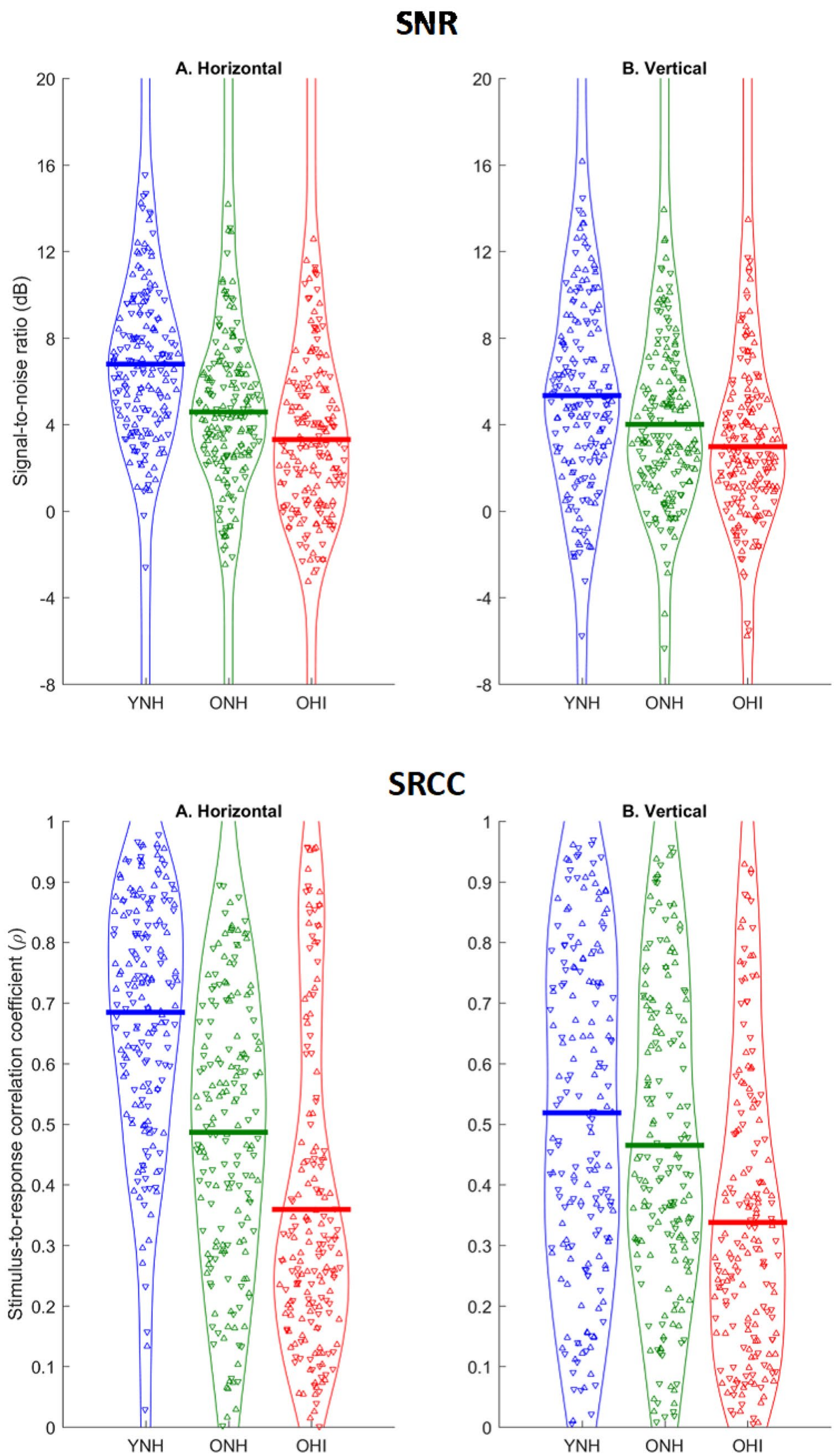


Fig. 5 The distribution of SNRs (top) and SRCCs (bottom) for the horizontal (left) and vertical (right) electrode montages plotted for all three glide extents for each group (left to right: YNH, blue; ONH, green; OHI, red). Rising tone glides are depicted with upward pointing triangles and falling glides with downward triangles. The width of the distributions represents the relative density of data points at a given SRCC or SNR value; thick horizontal bars represent the distribution means

None of the interactions between the group and the stimulus-based variables were found to be statistically significant. However, two interactions related to the measurement-based variable of electrode montage were found to be statistically significant: group × montage for the SRCC ($F(2, 27) = 3.38$, $p = 0.049$) and group × window × montage for the SNR ($F(4, 54) = 3.59$, $p = 0.011$). These interactions appear in Fig. 5 as larger mean differences in the SRCC and SNR across electrode montage for the YNH listeners than for the other groups. Post hoc two-tailed *t*-tests, adjusted for multiple comparisons, indicated the difference between montages was statistically significant for the YNH group, $t(323.85)$, $p < 0.001$, but not for the ONH or OHI groups. The differences between the YNH and ONH groups were statistically significant for the horizontal montage, $t(350.41)$, $p < 0.001$, as were differences between the ONH and OHI groups for both the horizontal and vertical montages, $t(352.45)$, $p < 0.001$ and $t(356.09)$, $p < 0.001$, respectively.

Individual Variability

Figure 6 shows SRCC values for each listener averaged across the three analysis windows for each frequency extent and glide direction. The left and right panels show responses collected with horizontal and vertical montages, respectively. The dashed line in each panel indicates the threshold value based on the classifier model described in the "FFR threshold criteria" section—responses that fall below the threshold cannot be reliably differentiated from neural activity recorded during the pre-stimulus baseline. Two OHI participants (OHI5 and OHI7) were noted to have exceptionally good responses, particularly in the horizontal montage. Table 2 shows, for each listener group by montage, the number of SRCC values out of 60 (10 listeners × 2 directions × 3 windows) that fell above or below the threshold criterion. The number of values falling below the threshold was greatest for the OHI group, compared with relatively few values falling below the threshold for the YNH and ONH groups.

Table 2 Number of SRCC values falling above or belove the threshold criterion for each listener group by montage

Group	Thresholds re: criterion	Montage			
		Vertical		Horizontal	
		Above	*Below*	*Above*	*Below*
YNH		59	1	60	0
ONH		57	3	59	1
OHI		46	14	44	16

Discussion

Previously, we demonstrated that differences in the rate of frequency change among tone glides are portrayed in the FFRs of younger adults (24–33 years) with normal hearing

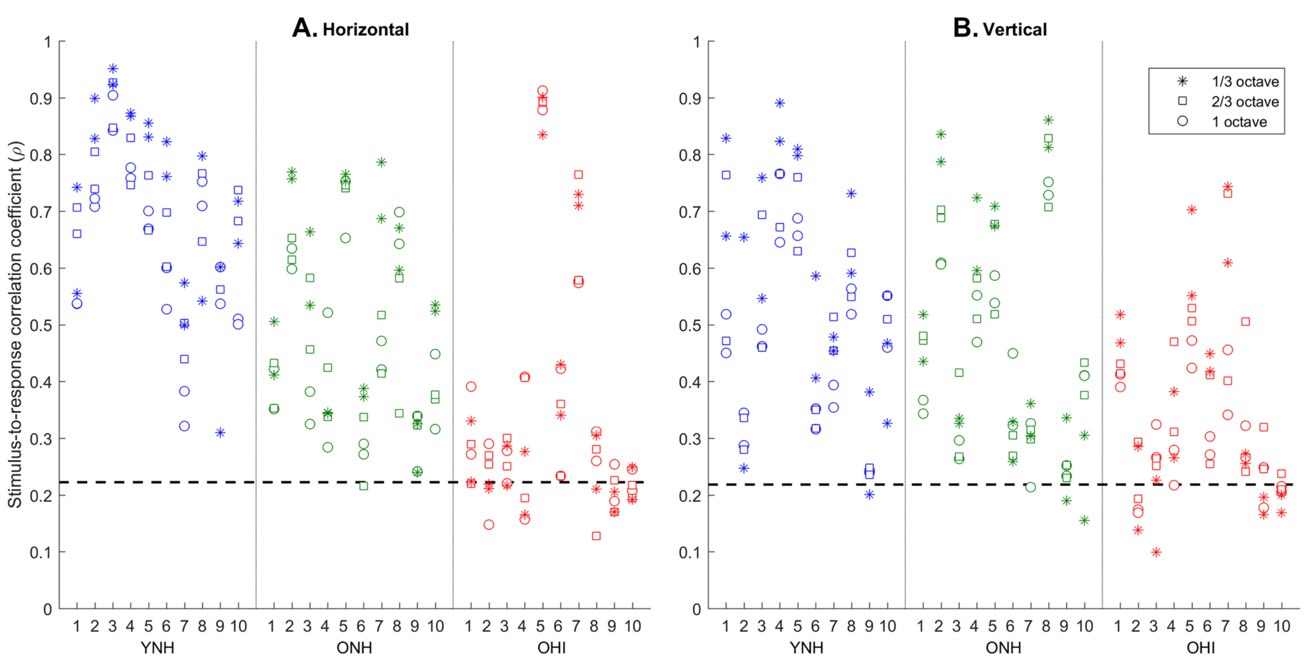


Fig. 6 Average SRCC values by a listener for each frequency extent and glide direction for the horizontal (left) and vertical (right) electrode montages. Listeners are arrayed from left to right within each group according to age. Dashed lines indicate the threshold criterion value based on the classifier model

[1]. The current study evaluated the effects of age and hearing loss on the neural transmission of dynamic acoustic signals in older listeners (51–78 years) with and without hearing loss and sought to determine if the pattern of responses to tone glides observed for ONH and OHI listeners was similar to that of the YNH listeners.

Group

The current results suggest that both age and hearing impairment affect the morphology of the FFR to a changing stimulus at the group level. This effect was reflected in both the SNR and SRCC measures. Figure 5 shows that, on average, YNH listeners showed the strongest responses, and OHI listeners showed the weakest responses, with the ONH listeners falling in between. A comparison of Fig. 4 in the present work with Fig. 5 from Billings et al. [1] shows that the overall patterns of responses have not changed with the addition of data from the older groups. The overall pattern of responses due to changing extent and direction of the tone glides remains similar—smaller extents produced stronger responses and there was no overall effect of glide direction.

The reduction in FFR strength observed with increased age [4, 5, 7, 22] could reflect an age-related decline in neural synchrony. Aging has been associated with cochlear hair cell loss [23], decrease in synchronization [24], and prolonged neural refractory periods [25], all of which could lead to problems with encoding dynamic frequency changes (even for low frequencies around 500 Hz). Neuroanatomical changes in the auditory pathways and age-related declines in GABA inhibition could also affect the ability to phase lock to changing frequency in older listeners [26], sometimes even in the absence of substantially increased hearing thresholds [27]. These changes may also extend to the inferior colliculus and auditory cortex [28, 29] and affect the encoding of rapidly changing frequency information. The current data also indicate that hearing impairment is associated with even further degradation of neural encoding—at least at the level of the brainstem—as evidenced by weaker responses that are more likely to be buried in the noise floor of the recording.

Individual Differences

Overall differences in group means are apparent in Fig. 6: on average listener group membership corresponds to the overall quality of FFR outcome measures. Furthermore, the likelihood of absent responses increases with age and hearing loss (especially hearing loss). Although it seems clear that, on average, age and hearing loss are associated with reduced strength of the FFR to dynamic stimuli, it is similarly clear that other individual factors also influence the observed response and may do so differentially for different stimulus conditions. Substantial overlap of SRCC values among groups and the wide variation in SRCC values within listeners of every group—although on average the YNH listeners had greater values, some younger listeners had SRCC values that were below those recorded for listeners in the ONH or OHI groups. Similarly, some older participants had values that were better than most younger participants. For example, OHI5 and OHI7 were noted to have exceptionally good responses with the horizontal montage. OHI5 was 60 years old at the time of testing with a PTA of 35 dB HL, and OHI7 was 54 years old with a PTA of 30 dB HL. Compared to the OHI group's mean age (66.5 years) and PTA (38.7 dB HL), these two OHI participants were among the youngest and best hearing in their group. However, another OHI participant OHI8 (age: 61 years; PTA: 31.7 dB HL) with similar age and hearing levels showed much poorer responses. Further study is necessary to determine the factors that may determine the exceptions to the general group trends present in these data.

Electrode Montage

Similar to Billings et al. [1], we observed a significant effect of electrode montage, such that responses were more robust on average for recordings made with a horizontal montage, and the overall fidelity of the response in the vertical montage was more sensitive to the effect of frequency. Previous literature indicates that responses recorded with a horizontal montage are generated at lower-level sites and more directly reflect the effects of peripheral encoding, whereas responses recorded with a vertical montage originate from higher-level sites to reveal the contributions of more central processing [8, 30].

Differences between the responses of the younger group and either of the older groups are most visible in Fig. 5 in the measures recorded with the horizontal montage. The mean differences among the groups are smaller for the vertical montage. The responses obtained with the vertical montage include potential contributions from more central generators and represent a more integrated version of the response from sites at various levels of the auditory system. Overall, this pattern suggests greater peripheral integrity in the younger listeners and weaker peripheral encoding in the older listeners, even for those with relatively low auditory thresholds. This interpretation is further supported by the findings of Märcher-Rørsted et al. [31], which provide evidence for cochlear neural degeneration (synaptopathy, inner hair cell loss, etc.) as a major, or perhaps even primary, contributor to the weaker FFRs seen in older listeners. Their computational modeling of the auditory nerve suggests that peripheral neural degeneration is sufficient on its own to produce notable reductions in the phase-locked response of the remaining functional fibers. These are the same fibers that feed into the auditory brainstem, so reductions in brainstem-level responses may also be the result of forward propagation from the periphery.

FFR Detection Criterion

An objective SRCC-based threshold criterion was derived to classify the quality of individual responses. To mitigate the overfitting of the classifier to the observed sample, the threshold criterion was determined based on a model of the data rather than from the raw data itself.

As shown in Table 2, among the OHI listeners, 23% of responses in the vertical montage and 27% in the horizontal montage fell below this threshold. Among the ONH listeners, only 5% of responses from the vertical and 2% from the horizontal montages fell below the threshold. Across the YNH group, only 1 response from the vertical montage fell below the threshold. For this data set, applying a threshold criterion would remove about a quarter of the data points from the OHI listeners from the analysis but would exclude only a handful of data points from the YNH and ONH groups.

It is noteworthy that excluding these responses did not qualitatively change the patterns of results seen in Figs. 3 or 4 (comparison figures available at https://github.com/mrmolis). Group effects (rather than extent, direction, etc.) were more likely to be affected for these data given the different amounts of exclusion as a function of the group. Based on this observation, researchers should keep in mind the potential impact of excluding data or subjects when the exclusion rate differs across groups.

Conclusions

This study extended our previous evaluation of the neural coding of dynamic spectral changes in tonal stimuli in young adults with normal hearing to include older listeners with and without hearing loss. Neural coding at the auditory nerve and brainstem levels—quantified by the SNR and SRCC—was assessed with both vertical and horizontal electrode montages. Although we observed overall reductions in the strength of the FFR to tone glides in both groups of older participants for all conditions, the overall pattern of results for these groups matched those previously observed in younger adults.

Analyses revealed that most of the systematic variation according to stimulus properties was already captured in the original YNH data [1]. Similar effects of the stimulus-related parameters like window, frequency extent, direction, and their interactions on both measures were observed across all groups tested in this study. In contrast to the YNH findings, the effect of recording montage was not found to be significant for either of the older groups.

Although average response fidelity varied across groups, the differences between the younger and older groups were most pronounced in the horizontal montage. This pattern suggests that overall group differences in FFR fidelity originate at lower levels of the auditory system, as suggested by Märcher-Rørsted et al. [31].

It appears that the likelihood of obtaining a poor response from an individual listener increases with both age and hearing loss, with hearing status being associated with larger differences than age. However, given the occurrence of good and poor FFRs within both groups of older listeners—both with and without hearing loss—there are doubtless individual factors in addition to age and hearing loss that influence the observed response.

Overall, our results further confirm the FFR's suitability to evaluate neural coding of acoustic stimuli whose spectra change over time. This study employed relatively simple stimuli to approximate the quickly changing frequency information present in speech. Recent work using stimuli possessing even more speech-like features has shown that stimulus complexity affects the FFR [32]. Future research will apply the methods developed here to more complex speech-like stimuli.

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Declarations

Conflict of Interest The authors declare no competing interests.

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