Mutual Information Analysis of Neural Representations of Speech in Noise in the Aging Midbrain

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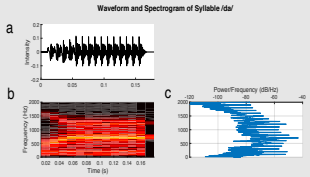
Introduction

- When two people talk at the same time, a young healthy listener does not have trouble attending to only one speaker. However, the ability to understand speech in challenging conditions deteriorates with aging, even for older adults with clinically normal audiograms. Deficits in the central auditory system, including midbrain, may underlie this difficulty.
- In response to hearing a synthesized syllable /da/, the auditory midbrain synchronizes to frequencies present in the syllable, known as frequency following response (FFR).[1] We analyzed (Shannon) Information contained in the FFR in different noise conditions, recorded by electroencephalography (EEG).
- Evidence shows deficits in the amount of information received in the aging midbrain across noise conditions, and the older adults receive more information in meaningless noise condition than in meaningful noise.[2]

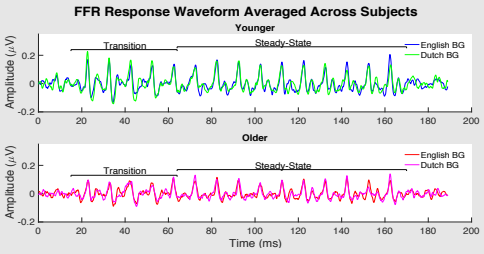
Methods

Sound stimulus



- The foreground sound stimulus is a 170-ms /da/, synthesized at a 20-kHz sampling rate[3], and is presented 2000 times in both polarities.
- For conditions with a noise background, the background is a story narrated by a female speaker in either English ("meaningful") or Dutch ("meaningless").
- The background speech segment is 1-min long and are repeated continuously one after another.
- The background speech is mixed at SNR levels of 3 dB, 0 dB, -3 dB and -6 dB.
- The FFR is recorded with EEG at sampling frequency 16,384 Hz.

Subjects. 17 younger adults (age: 18-27) and 15 older adults (age: 61-73) with clinically normal hearing.



Mutual Information. Since the foreground syllable is presented in opposite polarities for consecutive trials, a new trial is obtained by averaging two neighboring trials in order to rule out feedthrough artifacts. As a result, 1,000 effective trials with polarity compensation are used for further analysis.

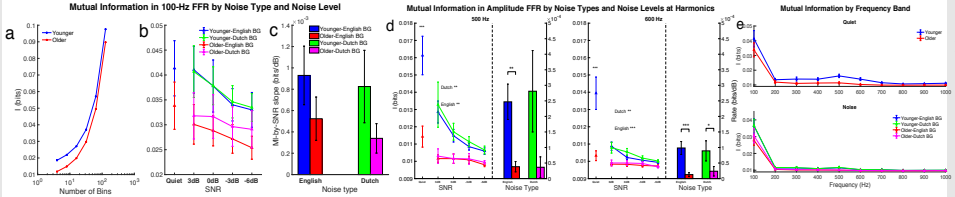
- Trials are band-passed into frequency bands centered at harmonics of 100 Hz.
- Responses of each trial are separated into transition region (15-64 ms) and stead-state region (64-170 ms).
- Mutual information between stimulus and response is estimated by

$$I(X;Y) = H(Y) - H(Y|X) = -\sum_{i=1}^{N} p(Y=i)\log p(Y=i) + \frac{1}{T}\sum_{t=1}^{T}\sum_{i=1}^{N} p(Y=i|X=x_t)\log p(Y=i|X=x_t)$$

- Here, X and Y are random variables denoting stimulus and response, respectively. The probability distribution of Y is estimated by binning response samples from all trials, and the conditional probability of Y given X is estimated by binning response from all trials at one single time point. The distribution of X is assumed uniform.

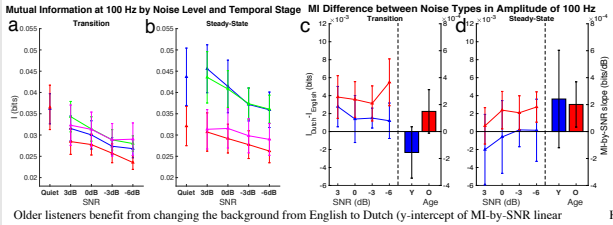
Results

1 Information in FFR *amplitude* by noise level and frequency



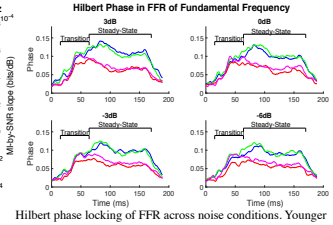
Mutual information between stimulus and FFR *amplitude* at 100 Hz, by bin number, noise type and SNR (age group and noise content denoted by color). **(a)** The number of bins used has no interactions with factors of age ($F_{(5,17122)} = 0.06$, $p = 0.9976$). **(b)** Information carried in FFR amplitude of older listeners (red & magenta) appears lower than younger (blue & green). **(c)** Slope of information decrease appears less severe for older. At 100 Hz, though, none of these differences are significant. **(d, e)** Differences between groups become significant in higher frequency bands. For example, at 500 Hz $p = 0.003$ and at 600 Hz $p = 0.003$ (one-tailed *t*-test with FDR correction of y-intercept of MI-by-SNR linear regression) with English background. The decreasing slope of MI-by-SNR for younger is significantly larger than for older at 500 Hz (English background) and at 600 Hz (both noise types).

2 Noise type influence on amplitude



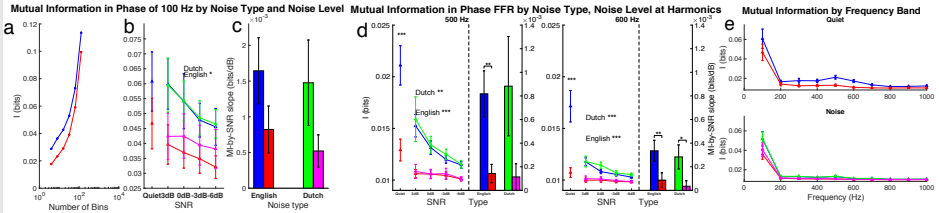
Older listeners benefit from changing the background from English to Dutch (y-intercept of MI-by-SNR linear regression) during the transition stage (p=0.046). Younger listeners do not show such a benefit.

3 Hilbert phase locking of FFR



Hilbert phase locking of FFR across noise conditions. Younger adults have stronger phase locking than older, for all conditions.

4 Information in FFR *phase* by noise and frequency



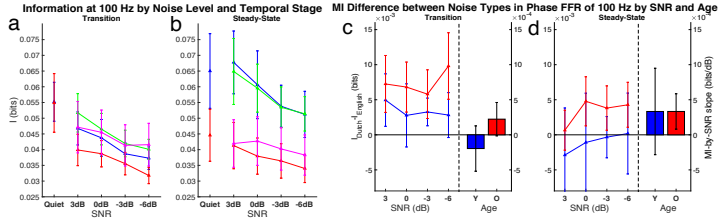
Mutual information between stimulus and FFR ***phase*** by bin number, noise type and SNR at 100 Hz, by bin number, noise type and SNR (age group and noise content denoted by color). **(a)** The number of bins used has no interactions with factors of age ($F_{(5,17122)} = 0.5$, $p = 0.7758$). **(b)** Information carried in FFR phase for English background in older listeners (red) is significantly lower than younger (blue). **(c)** Slope of information decrease appears smaller for older listeners younger but is not significant. Differences between groups are significant in higher frequency bands. For example, at 500 Hz $p = 0.002$ and at 600 Hz $p = 0.002$ (one-tailed *t*-test with FDR correction of y-intercept of MI-by-SNR linear regression) with English background. The decreasing slope of MI-by-SNR for younger is significantly larger than for older at 500 Hz (English background) and at 600 Hz (both noise types).

5 Noise type influence on phase

Hilbert phase. The Hilbert phase is computed by first taking Hilbert transform of the signal as imaginary part and then computing the angle of the complex, i.e.,

$$H(t) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(\tau)}{t-\tau}d\tau$$

$$\theta(t) = \angle\frac{H(t)}{x(t)}$$



Similar to the case for amplitude, older listeners' phase-based information benefits from changing the background from English to Dutch (y-intercept of MI-by-SNR linear regression) (p=0.039). Younger listeners do not show such a benefit.

Conclusions

1. The older midbrain carries *less information in both amplitude and phase* of FFR, across all frequency bands in speech-in-noise conditions, than younger.
2. The older midbrain benefits from *switching background noise from meaningful to meaningless* in the *most challenging noise* conditions.
3. Information carried by the younger midbrain *decreases faster than the older* as a function of decreasing SNR, especially in higher frequency bands. The older midbrain's ability to extract information decays more slowly with SNR.
4. The FFR of both groups exhibits a low-pass character. The *older midbrain reaches its limit at a lower frequency*, retaining only a low-level information-extraction ability for higher frequencies.

Future work

1. Older adults have *larger* response in auditory cortex to speech in noise[2][4], while the relation between midbrain deficit and loss of inhibition in cortical response remains unknown. Mutual information analysis may help in solving this.
2. The compensation for midbrain deficit in the older auditory pathway occurs either along the information flow from midbrain to cortex or in cortex from top-down mechanism. Future work will identify where the compensation happens.

Acknowledgments

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References

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