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Research paper

Frequency modulation detection as a measure of temporal processing: Age-related monaural and binaural effects

John H. Grose*, Sara K. Mamo

Dept. Otolaryngology, Head & Neck Surgery, University of North Carolina at Chapel Hill, Chapel Hill, NC 27519, USA

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ABSTRACT

The detection of low-rate frequency modulation (FM) carried by a low-frequency tone has been employed as a means of assessing the fidelity of temporal fine structure coding. Detection of low-rate FM can be made more acute, relative to the monaural case, by the addition of a pure tone to the contralateral ear. This study examined whether FM detection in the 500-Hz region could be further improved by using a binaural stimulation mode where the modulator was antiphasic across the two ears. The study also sought to determine whether these dichotic FM conditions were beneficial in identifying the emergence of a temporal fine structure processing deficiency relatively early in the aging process. Young, mid-aged, and older listeners ($n = 12$ per group) were tested. The results demonstrated better FM acuity in the dichotic task irrespective of listener age. Dichotic FM detection also differentiated between age groups more definitively than diotic detection, especially in terms of distinguishing mid-aged from older listeners. In the group of older listeners, dichotic FM detection was weakly associated with absolute sensitivity to the carrier. In addition, this group failed to show a dichotic benefit in the presence of a marked asymmetry in sensation level across ears. The overall pattern of results suggests that dichotic FM measurements have advantages over monaural measurements for the purposes of assessing age-related temporal processing effects, although a marked asymmetry in absolute thresholds across ears could undermine these advantages.

1. Introduction

Psychophysical assessment of temporal fine structure processing in the auditory system requires a task that can be interpreted in terms of the strength of underlying neural synchrony, or phase locking. One task that has been used in this context is the detection of frequency modulation (FM) at low carrier and modulation frequencies (Lacher-Fougere and Demany, 1998; Moore and Sek, 1996). The notion is that the ability to track the instantaneous frequency of a slowly modulated tone relies more on the temporal pattern (phase locking) of the neural response than on place cues in ears with good phase locking. This task has been used to gauge fine structure coding in focus populations such as listeners with cochlear hearing loss (Buss et al., 2004; Ernst and Moore, 2012a; Moore and Skrodzka, 2002; Strelcyk and Dau, 2009), and older listeners (He et al., 2007). In all of these studies, FM detection was measured using monaural presentation. Binaural tasks have also been used to assess the processing of temporal fine structure. Many of these have involved some measure of sensitivity to interaural time/phase differences as a function of frequency (Grose and Mamo, 2010; Hopkins and Moore, 2010; Lacher-Fougere and Demany, 2005; Moore et al., 2012a).

In terms of gauging the strength of phase locking, it is reasonable to suggest that binaural measures may offer a more sensitive indicator of neural synchrony than monaural measures. The basis for this is that, for measures that reflect the comparison of phase-locked inputs from the two ears, deficits at the binaural level will be greater than deficits at the monaural level. This has been clearly demonstrated by Batra et al. (1997), who showed that the synchronization index of cells in the superior olive to binaural inputs was the product of the synchronization indices to the respective monaural inputs – the monaural indices typically being less than 1.0. Somewhat tempering this viewpoint is the finding of Moore et al. (2012b) who found only a moderate correlation

Abbreviations: FM, frequency modulation; dB SPL, decibel sound pressure level; dB HL, decibel hearing level; dB SL, decibel sensation level; yrs, years; Hz, Hertz; ms, millisecond; 3AFC, three-alternative forced-choice; ANOVA, analysis of variance; NIH NIDCD, National Institutes of Health, National Institute on Deafness and other Communication Disorders.

* Corresponding author. Dept. Otolaryngology, Head & Neck Surgery, University of North Carolina at Chapel Hill, G190 Physicians Office Building, CB#7070, 170 Manning Drive, Chapel Hill, NC 27599-7070. Tel.: +1 919 966 3342; fax: +1 919 966 7941.

E-mail address: jhg@med.unc.edu (J.H. Grose).

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between the results of monaural and binaural psychophysical tests designed to measure sensitivity to temporal fine structure, suggesting that the two tests were measuring partly different abilities. Nevertheless, the argument that binaural measures of fine structure coding might be more sensitive than monaural measures raises the question of whether the sensitivity of the FM detection task can be increased by employing it in a binaural context. Evidence supporting this comes from a study by Witton et al. (2000), who showed that the detection threshold for low-rate FM could be an order of magnitude more acute if a steady tone was presented to the ear contralateral to that receiving the modulated tone. The dichotic advantage was present for FM rates up to about 40–60 Hz, and occurred even for interaural level differences of 40–50 dB. The dichotic stimulus configuration used by Witton et al. (2000), as well as in earlier studies (e.g., Green et al., 1976), results in sinusoidal interaural phase modulation. One purpose of the present study was to determine whether an advantage could be gleaned from using a stimulus configuration that also resulted in dynamic interaural phase modulation, but in which the two ears received antiphasic FM (rather than one ear receiving a steady tone). This configuration effectively doubles the depth of interaural phase modulation.

The interest in binaural FM detection in this study occurs within the context of the effects of advancing age on temporal processing. There is converging psychophysical and electrophysiological evidence that the coding of temporal fine structure declines with age, and independently of hearing loss (Clinard et al., 2010; Grose and Mamo, 2010; Moore et al., 2012a; Ross et al., 2007). This has led to an interest in the development of tests of temporal fine structure processing that can be applied in the clinic (e.g., Hopkins and Moore, 2010, 2011). In addition, there is an interest in the time course of this decline, with a focus on the emergence of temporal processing deficits relatively early in the aging process (Dobreva et al., 2011; Grose and Mamo, 2010; Moore et al., 2012b). The purpose of this study therefore was twofold: (1) to determine whether the dichotic FM configuration tested here is a sensitive measure of temporal processing, particularly with respect to its monaural counterpart; and (2) to determine whether this measure identifies a pre-senescent emergence of temporal fine structure processing deficiency. The corresponding hypotheses were that: (1) dichotic FM detection is more sensitive than monaural FM detection for normal-hearing listeners irrespective of listener age; and (2) older listeners show less benefit from dichotic presentation than younger listeners, and that this effect is evident in middle-age.

2. Method

2.1. Participants

A cohort of 36 listeners participated, 12 in each of three age groups: Younger (19–29 yrs, 7 female), Mid-Aged (43–57 yrs, 6 female), and Older (65–77 yrs, 9 female). All listeners had normal audiometric thresholds ($\leq$20 dB HL) across the octave frequency range 250–4000 Hz, except for three Older listeners whose thresholds at 4000 Hz ranged from 25 to 35 dB HL in at least one ear. There was no interaural threshold asymmetry, with the mean absolute interaural difference across frequencies and listeners being about 4 dB. The averaged audiograms for the three age groups are shown in Fig. 1.

2.2. Stimuli

All stimuli in the FM detection task were 1250 ms in duration, including 25-ms raised cosine rise/fall ramps. The FM waveform was given by

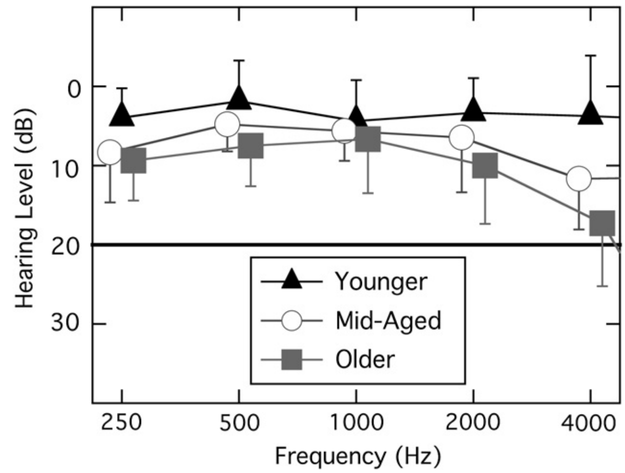

Fig. 1. Mean audiometric thresholds in dB HL for the octave frequencies 250–4000 Hz for the younger (triangles), mid-aged (circles), and older (squares) groups. Error bars show 1 standard deviation.

$$x(t) = A\sin(2\pi f_c t + \beta\sin(2\pi f_m t))$$

where A is the amplitude of the signal, β is the modulation index (i.e., 'FM depth'), f_c is the carrier frequency, and f_m is the modulation frequency. For all conditions, $f_m = 2$ Hz, yielding 2.5 cycles of modulation per stimulus. The starting phase of the modulator was always 0 radians for monaural and diotic presentations, and 0 and π radians when the modulator was out of phase at the two ears. The carrier frequency was randomly roved on a presentation-by-presentation basis across the range 460–540 Hz, with random starting phase. The purpose of the frequency rove was to undermine the ability to use place cues to detect FM since the listener could not establish a reliable 'place anchor' against which to compare frequency shifts within the observation intervals of a forced-choice trial. Stimuli were generated for each presentation at a sampling rate of 25 kHz, and presented at 65 dB SPL through Etymotic Research ER2 insert phones. There were five presentation conditions: (1) monaural left [*Monaural-L*]; (2) monaural right [*Monaural-R*]; (3) binaural presentation of identical tones [*Diotic*]; (4) dichotic presentation wherein a pure tone was presented to the left ear and an FM tone to the right ear [*Dichotic PT/FM*]; (5) dichotic presentation wherein an FM tone was presented to each ear but the modulator phase was inverted between ears [*Dichotic FM/FM*].

In order to obtain a more fine-grained measure of auditory sensitivity at the frequency region of interest to this study, absolute thresholds for a 500-Hz pure tone were also measured. The stimulus for this measurement was 400 ms in duration, including 25-ms raised cosine rise/fall ramps.

2.3. Procedure

FM detection thresholds were measured using a three-alternative forced-choice (3AFC) procedure that incorporated a three-down, one-up stepping rule to converge on the 79.4% correct point. In the two standard intervals, the stimulus was an unmodulated pure tone; in the signal interval (chosen at random), the stimulus was an FM tone. The inter-stimulus interval was 500 ms. The intervals were marked by lights on a response box, and the listener was instructed to select the interval that was different by means of a button press; correct-interval feedback was provided visually following each trial. Following three correct responses in a row, the depth of FM was reduced; following one incorrect