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Research paper

Using individual differences to assess modulation-processing mechanisms and age effects

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ABSTRACT

This study used a correlational approach to clarify the mechanisms involved in modulation coding. Amplitude-modulation (AM) and frequency-modulation (FM) detection thresholds (AMDTs and FMDTs, respectively) were assessed for 70 normal-hearing listeners. In order to increase between-listeners variability in peripheral coding, participants with a wide range of age (20–70 years) were included. AMDTs and FMDTs were measured at a 5-Hz rate, using a 500-Hz sinusoidal carrier. FMDTs were also measured in the presence of an interfering AM to discourage the use of temporal-envelope cues. The results showed that AMDTs were significantly correlated with FMDTs, but not with FMDTs measured with interfering AM. FMDTs with and without interfering AM were significantly correlated with each other. This pattern of correlation proved to be robust, providing additional evidence that for low carrier frequencies, (i) low-rate AM and FM detection is based on a common code using temporal-envelope cues and (ii) low-rate FM detection is based on an additional code using cues distinct from temporal-envelope. The analyses also showed that age was correlated with FMDTs only. However, no significant difference was found when comparing the various correlations with age. Hence, the effects of age on modulation sensitivity remain unclear.

1. Introduction

Over the last decades, a large number of psychophysical studies have shown that amplitude-modulation (AM) and frequency-modulation (FM) cues play a crucial role in the identification of speech in quiet and in the presence of interfering sound sources such as noise or competing speech (*e.g.*, Shannon et al., 1995; Zeng et al., 2005; for a review, see Shamma and Lorenzi, 2013).

It is commonly assumed that the ability to detect AM relies on monitoring dynamic changes in excitation-pattern cues, that is, temporal-envelope cues (Viemeister, 1979; Dau et al., 1997a,b) encoded *via* fluctuations in the mean discharge rate of auditory-nerve fibers. Several studies have investigated whether the ability to detect FM is based on the same underlying mechanism as AM (*i.e.*, temporal-envelope cues). Zwicker (1952, 1956, 1970) put forth an 'excitation-pattern model' for FM detection, whereby the changes in frequency are perceived by monitoring changes in excitation level - that is, temporal-envelope cues - at one or multiple places of the excitation pattern. This mechanism is often referred to as 'FM-to-AM conversion' because frequency-dependent attenuation of the FM caused by cochlear filters results in AM (Maiwald, 1976a,b; Saberi and Hafter, 1995). However, a number of studies have suggested that the excitation-pattern model of FM detection provides an incomplete description of FM-detection capacities for normal-hearing listeners. These studies indicate that changes over time in the pattern of neural phase-locking to temporal-fine-structure (TFS) cues in the auditory-nerve fibers may be used to perceive FM, at least for low FM rates (≤5–10 Hz) and low carrier frequencies (≤1–4 kHz; *e.g.*, Demany and Semal, 1986, 1989; Moore and Sek, 1994, 1995, 1996; Moore and Skrodzka, 2002; Paraouty et al., 2016; Wallaert et al., 2016). These studies also pointed out that TFS cues cannot be used to detect FM with modulation rates above about 5–10 Hz as

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the mechanism using phase-locking information is 'sluggish'. Nevertheless, the respective roles of TFS and temporal-envelope information in FM perception is still a matter of debate (Ernst and Moore, 2010; Sheft et al., 2012; Ives et al., 2013; Otsuka et al., 2014, 2016; Whiteford and Oxenham, 2015; Kortlang et al., 2016; Paraouty et al., 2016; Wallaert et al., 2016). Clarifying the mechanisms involved in FM detection is required given the recent demonstrations that FM sensitivity is a strong predictor of speech intelligibility (e.g., Ruggles et al., 2011; Johannesen et al., 2016).

In the above studies, the investigation of modulation-processing mechanisms was generally achieved using either systematic manipulations of the AM and FM stimuli and/or group designs exploring the effects of age and hearing loss on AM and FM detection. In recent years, the correlational approach has been increasingly used to study these mechanisms (*e.g.*, Strelcyk and Dau, 2009; Ruggles et al., 2011; Bharadwaj et al., 2015; Whiteford and Oxenham, 2015). In the study of Whiteford and Oxenham (2015), AM and FM detection thresholds were measured for a large cohort of young normal-hearing listeners (number of participants, N = 100). They showed that AM and FM detection thresholds were strongly correlated with each other and found no evidence of stronger correlations between measures thought to reflect the use of neural phase-locking to TFS cues or between measures thought to reflect the use of excitation-pattern (rate-place) cues. One possible explanation suggested by the authors was that the variability in peripheral coding for young, normal-hearing listeners was too small to have a large influence on modulation-detection thresholds. They recommended the investigation of large samples of listeners of different ages in order to increase the variability in peripheral coding between the listeners, and consequently, outweigh other factors contributing to individual differences in modulation-detection performance. The rationale of the present study follows this recommendation.

It is important to note that age would not only increase the between-listeners variability, but it might also impact AM and FM sensitivity, possibly to a different extent. Indeed, a number of psychophysical results suggest that aging is associated with a decline in the capacity to detect and discriminate AM and FM cues in both low and high audio-frequency regions (*e.g.*, He et al., 2007, 2008; Grose and Mamo, 2012; Sheft et al., 2012; Füllgrabe et al., 2015; Kortlang et al., 2016; Wallaert et al., 2016; for a review, see Moore, 2014). For AM detection, detrimental effects of age were reported by He et al. (2008; N = 16), Füllgrabe et al. (2015; N = 30) and Wallaert et al. (2016; N = 29) for AM rates between 2 and 20 Hz, using either low (500 Hz) or high (4000 Hz) sine-tone carriers or broadband noise carriers. For FM detection, detrimental effects of age were reported by He et al. (2007; N = 20) for a carrier frequency of 500 Hz and 4000 Hz and an FM rate of 5 Hz, by Grose and Mamo (2012; N = 36) for a carrier frequency roved between 460 and 540 Hz and an FM rate of 2 Hz, and by Wallaert et al. (2016; N = 29) for a carrier frequency of 500 Hz and an FM rate of 2 Hz when measuring FM detection in the presence of an AM masker. A detrimental effect of age was also reported by Kortlang et al. (2016; N = 12) for the detection of random-FM (1–4 Hz) detection in noise when using a carrier frequency of 500 Hz. However, inconsistent with these repeated findings, Takahashi and Bacon (1992; N = 40) as well as Schoof and Rosen (2014; N = 38) reported no significant effects of age on the detection of AM applied to a noise carrier for AM rates ranging between 2 and 1024 Hz. Paraouty et al. (2016; N = 20) reported no significant age effects for the detection of AM applied to a 500-Hz sine-tone carrier for an AM rate of 5 Hz. Moreover, Schoof and Rosen (2014; N = 38) reported no significant age effects for the detection of a 2-Hz FM applied to a 1000-Hz carrier. This review indicates that the effects of age on modulation sensitivity are still unclear. However, some of the studies cited above (e.g., Takahashi and Bacon, 1992; Sheft et al., 2012; Wallaert et al., 2016; see also Whiteford and Oxenham, 2015) clearly indicate that elderly listeners with normal-hearing show more variability in AM and FM detection and discrimination tasks compared to younger listeners with normal-hearing. This further motivates the inclusion of listeners of different ages in order to increase the variability in peripheral coding.

The main goal of the present study was to clarify the type(s) of cues used by listeners for AM and FM detection using individual differences. The secondary goal was to investigate further the effects of age on AM and FM detection. To achieve this, a large cohort of 70 normal-hearing listeners aged between 20 and 70 years were tested on three modulation-detection tasks: (i) an AM detection task, (ii) an FM detection task, and (iii) an FM detection task using FM stimuli presented together with an uninformative 'interfering' AM at the same rate as the FM in order to discourage the use of temporal-envelope cues resulting from FM-to-AM conversion at the output of cochlear filters. Detection thresholds were measured for sine AM and FM at a modulation rate of 5 Hz, using a 500-Hz sinusoidal carrier. These parameters were chosen as they should allow the use of both sensory cues (temporal-envelope and TFS cues) for the detection of AM and/or FM (*e.g.*, Moore and Sek, 1996; Paraouty et al., 2016). The following hypotheses were made: if FM detection is based on a rate-place code, then FM detection thresholds measured with and without interfering AM should be correlated with each other and they should also be correlated with the AM detection thresholds. On the other hand, if FM detection is also based on a phase-locking code, then FM detection thresholds measured with and without interfering AM should be correlated with each other but only FM detection thresholds measured without interfering AM should be correlated with AM detection thresholds. All participants had an absolute threshold lower than or equal to 20 dB hearing-level (HL) at 500 Hz, and were therefore clinically defined as having 'normal hearing' at that audio frequency (Goodman, 1965). An additional measure of frequency selectivity at 500 Hz based on the notched-noise masking technique was included to investigate between-listeners differences in auditory filtering. It was reasoned that poorer frequency selectivity at the tested carrier frequency would yield reduced FM-to-AM conversion, and thus, poorer ability to detect FM on the basis of temporal-envelope cues.

2. Method

2.1. Listeners

All listeners had normal (≤20 dB HL) audiometric thresholds for octave frequencies between 125 and 3000 Hz, except for three older listeners who had normal thresholds up to 2000 Hz only. The listeners were aged between 20 and 70 years old (mean = 42 yr, standard deviation (SD) = 16) and had no history of cognitive impairment or psychiatric disorders. All listeners were fully informed about the goal of the study and provided written consent before their participation. The study was approved by the French Regional Ethics Committee (N° IRB: 20143200001072). Listeners had no former experience with such experimental conditions and no training before the tests. However, if a listener had difficulties in understanding the instructions or in performing the task, a single practice run was given. There were no significant difference between the left and right audiometric thresholds at 500 Hz for all listeners ([$t(69) = 0.00$; $p = 1.00$]), hence the mean audiometric threshold for each listener at 500 Hz was calculated. This mean audiometric threshold was taken as an estimate of absolute