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Large cross-sectional study of presbycusis reveals rapid progressive decline in auditory temporal acuity

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ABSTRACT

The auditory system relies on extraordinarily precise timing cues for the accurate perception of speech, music, and object identification. Epidemiological research has documented the age-related progressive decline in hearing sensitivity that is known to be a major health concern for the elderly. Although smaller investigations indicate that auditory temporal processing also declines with age, such measures have not been included in larger studies. Temporal gap detection thresholds (TGDTs; an index of auditory temporal resolution) measured in 1071 listeners (aged 18–98 years) were shown to decline at a minimum rate of 1.05 ms (15%) per decade. Age was a significant predictor of TGDT when controlling for audibility (partial correlation) and when restricting analyses to persons with normal-hearing sensitivity ($n = 434$). The TGDTs were significantly better for males (3.5 ms; 51%) than females when averaged across the life span. These results highlight the need for indices of temporal processing in diagnostics, as treatment targets, and as factors in models of aging.

1. Introduction

The auditory system is distinguished from other sensory systems by its remarkable speed, temporal precision, and the preservation of precise temporal coding at multiple levels within the central nervous system. Like other sensory systems and the central nervous system in general, the speed and precision of processing undergoes a progressive decline with advancing age (Eckert, 2011; Thompson et al., 2014). Given linkage between auditory temporal processing and speech perception (Gordon-Salant and Fitzgibbons, 1993; Snell et al., 2002; Tyler et al., 1982), pitch perception (de Boer, 1976), and voice identification and separation (Rosen, 1992; Snyder and Alain, 2005), it is likely that declines in temporal processing contribute to the debilitating consequences of age-related hearing loss (presbycusis) including social isolation, general decline in health, and increased risk of dementia (Lin et al., 2013). Reduced audibility (characterized clinically by elevated pure-tone thresholds) and reduced temporal processing (typically measured only in the laboratory) are 2 principal hallmarks of age-related hearing loss. Both are known to compromise speech intelligibility in the presence of interfering sounds, which in turn is the number one complaint of persons with hearing loss. Owing to their comorbidity, however, the relative contributions of audibility and temporal processing are often difficult to disassociate in older listeners.

Major epidemiological investigations and large laboratory data sets have documented the frequency-specific decline in auditory sensitivity with age (Allen and Eddins, 2010; Brant and Fozard, 1990; Cruickshanks et al., 1998; Gates et al., 1990; Hoffman et al., 2010). The general pattern of results is a gradual loss of sensitivity at very high frequencies in early adulthood and with every passing decade, greater hearing loss that encroaches lower and lower frequency regions. This loss, however, is gender specific, with greater high-frequency loss in males, leading to a sloping audiogram, and greater low-frequency loss in females, leading to a flatter audiometric pattern in women. These changes in sensitivity with age accompany a cascade of corresponding changes in the region of hearing loss including altered loudness perception, loss of tuning or frequency selectivity, and overall reduction in speech intelligibility when background interference is present (Moore, 2007). Analysis of the pure-tone threshold data across multiple investigations indicates that auditory sensitivity declines at a rate of about 8 dB per decade in the 2000–4000 Hz frequency region between the ages of ~50–90 years (Allen and Eddins, 2010; Brant and Fozard, 1990; Cruickshanks et al., 1998; Gates et al., 1990; Hoffman et al., 2010). On this basis, expected changes in intelligibility of conversational speech by decade can be estimated merely on the basis of reduced audibility alone using computational methods such as the speech intelligibly index (ANSI, 2012). Estimates of the average decline in temporal resolution with age, analogous to declines in audibility

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with age, have not been reported but are needed to better capture the nature of presbycusis.

The association of temporal processing deficits and age is ubiquitous, as demonstrated by Humes et al. (2012) in their systematic review of the evidence. They reported that the single most common measure of temporal processing associated with aging is temporal gap detection. The temporal gap detection task measures the smallest detectable silent interval separating preceding and trailing stimulus markers (usually noise or tones) following the method introduced by the elegant study of Plomp (1964). Since that time, the method has been used in laboratory and clinical investigations in a wide range of contexts using behavioral, electrophysiological, and neurophysiological methods. Typical behavioral estimates of temporal gap detection thresholds (TGDTs) for broadband noise in young, normal-hearing adults are between 2 and 3 ms as measured in humans and many animal species (Green, 1971). As the noise bandwidth is reduced, TGDTs tend to increase (are longer) due to a combination of reduced across-channel integration of temporal information and progressive increase in the inherent fluctuations of noise (for a review, see Eddins, 2004, Eddins and Green, 1995).

Studies of auditory temporal processing using a variety of measures, including temporal gap detection, reveal reduced performance with increasing age, leading to the logical question of whether reduced temporal processing in presbycusis is a result of the reduced audibility (i.e., hearing loss) associated with typical aging, changes in peripheral and/or central auditory processing associated with typical aging, or, in the worst case, both reduced audibility and age-related changes in peripheral and/or central auditory processing? Of the 13 TGDT investigations reviewed by Humes et al., several measured audibility and TGDTs in the same persons and used statistical methods such as partial correlation to estimate the relative contribution of age or audibility. Other studies cited in that review measured TGDTs in younger persons with normal audibility and older persons with near-normal audibility (so-called "golden ears") so that across-group comparisons were minimally impacted by audibility differences. Twelve of those 13 studies were considered to have reported TGDTs that were unconfounded by hearing loss. Of those 12, 9 reported a significant effect of age on TGDT, and more recently, others also have found an age effect (John et al., 2012; Palmer and Musiek, 2014), though not all have (Schoof and Rosen, 2014; Shen, 2014). Thus, most but not all evidence from the literature indicates that advancing age, apart from audibility, leads to reduced temporal resolution as indexed by TGDTs.

The present data were collected in the context of the standard intake protocol from a long-running programmatic study of age-related hearing loss and comorbid medical disorders funded by the National Institute on Aging of the National Institutes of Health. The measures considered here include pure-tone thresholds that index audibility and monaural (better ear) TGDTs as a proxy measure of temporal processing. Data are reported for a large subject cohort ($n = 1071$; 462 males) ranging in age from 18 to 98 years. Such a cohort provides the statistical power to identify robust relationships between temporal processing, audibility, age, and gender, and the cross-sectional data provide a prediction of the rate of decline in TGDT with age.

2. Methods

2.1. Subjects

Participants included 1071 adults (462 males) aged 18.0–97.9 years. Inclusion criteria included negative history of head injury, ear disease, ear surgery, or conductive hearing loss. Audiometric data are reported in the Section 3. Participants provided written consent, as approved by university institutional review board and were paid an hourly rate.

2.2. Stimuli

Stimuli were low-pass–filtered (either at 1 kHz or 4 kHz) Gaussian noise bursts presented at 70-dB sound pressure level in the presence of a continuous wide-band noise (low-pass filtered at 10 kHz) presented at 50-dB sound pressure level. Each stimulus consisted of a pregap noise burst 40 ms in duration and a postgap noise burst 110 ms in duration. Individual bursts were shaped with a 1-ms cosine-squared rise-fall window. In the signal interval, a silent gap was introduced. The pregap burst, silent period (signal interval only), and postgap burst were concatenated and the full stimulus was gated with a 10-ms cosine-squared rise-fall window. Stimulus generation and presentation via insert earphones (Etymotic ER-3A) was handled by TDT hardware (Tucker-Davis Technologies) at a sampling rate of either 40,000 Hz (System 2 hardware) or 24,414 Hz (System 3 hardware).

2.3. Procedure

The temporal gap detection task was part of a larger, 3-hour test battery and typically occurred in the second half of that session. Audiometric and temporal gap detection measurements were conducted in a double-walled sound-attenuating chamber. The TGDTs were measured via 2-interval, 2-alternative forced-choice procedure with feedback via an adaptive, 2-down-1-up tracking rule estimating 70.7% correct detection (Levitt, 1971). The initial gap duration was 50 ms. Initial step size was 10 ms, which was reduced to 4 ms after 2 reversals. The maximum possible gap duration was 50 ms, and the minimal possible gap duration was 2 ms. Thresholds were based on the average of two 40-trial blocks, in which the first 2 reversals were discarded. Stimulus presentation and response collection was controlled through custom software (System 2) or TDT SykofizX 2.0 software (System 3).

2.4. Statistical analyses

In the primary analyses, participants were separated into 3 broad age groups: younger (>18 and ≤40 years; 74 males and 69 females), middle-aged (>40 and ≤65 years; 103 males and 197 females), and older (>65; 285 males and 343 females). As these participants were part of a larger study on age-related hearing loss, there is a bias in sample size toward the middle-aged and older groups. Across groups, the mean age was 62.9 years, and the median age was 68.0 years. The overall ratio of males to females was roughly 3:4.

Secondary analyses included a subset of listeners who had pure-tone thresholds less than or equal to 25 dB HL at all octave frequencies from 250 to 4000 Hz, allowing for a comparison of TGDTs as a function of age in groups of persons having clinically normal-hearing thresholds (ANSI, 2010). In addition to controlling for substantial changes in pure-tone threshold with age, this reduced data set had the unplanned advantage of creating more similar sample sizes within the 3 age-groups described previously. This can be explained by the effect of age on hearing sensitivity: for younger listeners, only 2 participants were excluded due to elevated pure-tone thresholds, whereas progressively greater proportions of participants were excluded from the middle-aged and older groups. Because exclusions were inversely proportional to the original sample sizes, the end result was more similar sample sizes in the derived subset. In all, a total of 637 listeners did not meet the pure-tone threshold inclusion criteria, leaving the younger group with