Auditory temporal processing deficits in older listeners: From a review to a future view of Presbycusis

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Numerous behavioural studies support the hypothesis that there are age-related auditory temporal processing deficits. The effects of age on some psychoacoustic and speech tasks implicate a loss of synchrony or periodicity coding, while other results point to losses in gap and duration coding, or poor use of envelope cues. Performance on psychoacoustic tests of auditory temporal processing has been related to performance on speech tests. This paper reviews the evidence for age-related differences in performance to address two questions: Does aging affect auditory temporal processing at one or more levels, and how are these age-related differences related to the processing of speech? Future directions for research are proposed to address the extent to which different types of auditory temporal processing deficits are inter-related. Future directions for practice are proposed to address the need to develop a new approach to the assessment and rehabilitation of sub-types of presbycusis. Differentiating neural presbycusis from other sub-types may clarify the bases of individual differences in temporal processing and their consequences to speech understanding.

INTRODUCTION

A wealth of evidence has accumulated concerning the possible connection between auditory temporal processing deficits and speech perception in older adults. The present paper will review these findings with a view to developing new approaches to audiologic assessment and rehabilitation of older adults that are tailored to sub-types of presbycusis. To this end, two specific questions will be addressed: Does aging affect auditory temporal processing at one or more levels, and how are these age-related differences related to the processing of speech?

EFFECT OF AGE ON AUDITORY AND SPEECH PROCESSING

It is important for audiologists to differentiate amongst levels of auditory temporal processing for both diagnostic and rehabilitative purposes (Phillips, 1995). From a diagnostic perspective, the pattern of perceptual deficits in auditory temporal processing may provide information about pathology. A review of physiological findings is

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beyond the scope of the present paper, but it is well-known that different sites in the auditory pathway are specialized for coding specific temporal features that play a role in speech processing, such as monaural and interaural phase, onsets and offsets, and durations, as well as rhythms and temporal patterns. Furthermore, evidence from physiological research points to age-related declines in temporal processing, with degeneration at multiple sites in the auditory system (Frisina *et al.*, 2001). From a rehabilitative perspective, the pattern of deficits may affect speech perception, with specific consequences for communication function and intervention options.

Temporal cues relevant to speech processing have been described at three main levels (Greenberg, 1996): sub-segmental (phonetic), segmental (phonemic), and supra-segmental (syllabic and lexico-syntactic). Sub-segmental fine structure cues include periodicity cues based on the fundamental frequency and harmonic structure of the voice. Some types of segmental information are provided by local gap and duration cues in the envelope which contribute to phoneme identification (e.g., presence of a stop consonant, voice onset time). Supra-segmental cues, such as amplitude fluctuations in the region of 3-20 Hz, convey prosodic information related to the rate and rhythm of speech, and these cues serve lexical and syntactic processing. Each level has been investigated in older adults using behavioural psychoacoustic and speech perception measures (Table 1). Enough evidence has been amassed that it seems worthwhile to begin to consider unifying explanations.

Cue Type	Role in Speech	Experimental Measures	
		Psychoacoustic	Speech
Periodicity (synchrony; phase)	Voice (quality, identity, clarity, segregation	Frequency DL MDL FM modulation High-level intensity DL	F_0 DL Speech MLD Identification of concurrent vowels jittered speech
Gaps/durations (onsets/offsets)	Phonemic contrasts (stops, VOT)	Gap detection Duration discrimination	Discrimination of phonemes, words
Envelope (modulation)	Prosody (rate, rhytm, stress)	AM modulation	Intelligibility of noise-vocoded, compressed speech

Table 1: Three main levels of temporal auditory and speech processing.

Older adults often have more trouble than younger adults in understanding speech in noise. Age-related differences in temporal processing have been studied extensively because such differences seem likely to explain age-related differences in speech understanding that are not readily explained by differences in audiometric thresholds (Pichora-Fuller and Souza, 2003). Over the last two decades, annual research on temporal processing and aging has almost doubled (Table 2). Effects of age have been confirmed at each level of temporal processing relevant to speech processing. Nevertheless, older individuals exhibit various patterns and degrees of deficit, with some performing equivalently to younger listeners, and with the degree of deficit varying with stimulus and testing conditions. This emerging picture of heterogeneity in the experimental samples of older adults raises questions regarding the clinical significance of temporal processing abilities in sub-types of presbycusis. First we will highlight findings pertaining to each of the three main levels of temporal processing relevant to speech processing, and then we will consider the implications of the findings for clinical practice and research.

	1987-1991	1992-1996	1997-2001	2002-2006	2007 (to August)
Annual Articles	66	86.2	105.2	116.6	109

Table 2: The annual number of publications on aging and temporal processing in six journals: Ear and Hearing, Hearing Research, IJA (before 2002 Audiology, British J. of Audiology, Scandinavian Audiology), JASA, JAAA (starting 1990), JSLHR (before 1997 JSHR).

Periodicity

Periodicity, or synchrony coding, based on the phase-locked response of the auditory system to low-frequency periodic signals, enables the listener to use the fundamental frequency and harmonic structure of sounds to follow or identify the voice of a talker, or to judge the tonality of notes played on a musical instrument such as a piano. The frequency difference limen (DL) is the most common monaural psychoacoustic measure that would reflect a deficit in temporal processing at this level. Because the frequency DL is thought to depend on phase-locking at low frequencies, deficits in periodicity coding could explain why age-related increases in frequency difference limens (DL) are greater for low frequencies than for high frequencies (e.g., Abel *et al.*, 1990). This explanation has also been given for the finding that age-related differences in the detection of FM modulation are larger at low frequencies than at high frequencies (He *et al.*, 2007). Recently, we have argued that age-related differences in intensity DLs for high-level tones in noise may also be attributed to a deficit in periodicity coding (MacDonald *et al.*, 2007). Furthermore, loss of synchrony might contribute to age-related declines in detection of a mistuned harmonic (Alain *et al.*, 2001), or identification of concurrent vowels (e.g., Snyder and Alain, 2005; Vongpaisal and Pichora-Fuller, 2007). Binaurally, age-related changes in masking-level differences (MLD) have been observed for both non-speech and speech signals (Grose, 1996), and the pattern of age-related differences in MLDs has been attributed to an age-related increase in temporal jitter or reduced synchrony coding (Pichora-Fuller and Schneider, 1992). In addition, disruptions in periodicity coding may account for age-related differences, as well as reductions in the performance in younger adults when signals are temporally jittered, on measures of both speech intelligibility in noise (Pichora-Fuller *et al.*, 2007), and judgements of musical tonality (Minghella *et al.*, in press).

Gaps and Durations

Gap detection threshold, the smallest gap that a listener can detect in a stimulus, is the most common psychoacoustic measure of temporal processing. Older adults with good audiograms do not detect gaps until they are significantly longer than those detected by younger adults, but gap detection thresholds are not significantly correlated with audiometric thresholds (e.g., Schneider *et al.*, 1994; Snell and Frisina, 2000). Furthermore, age-related differences in gap detection thresholds are unaffected by some markers properties, such as envelope shape and intensity, so long as the marker levels are not near absolute threshold (Schneider *et al.*, 1998). Indeed, studies not concerned with the effect of age indicate that gap detection threshold is not correlated with degree of audiometric loss (Florentine and Buus, 1984), or measures of frequency selectivity (Grose *et al.*, 1989). We have learned that age-related differences are more pronounced when the sound markers surrounding the gap are shorter than 10 ms (Schneider and Hamstra, 1999), and when the location of the gap is near to the onset or offset of the signal (He *et al.*, 1999). Thus, age-related differences have been found when gaps must be detected between acoustically simple 'within-channel' markers, with the effect of age being exacerbated when the temporal characteristics of the markers are altered, but not when their intensity or frequency-specificity is altered.

Various dimensions of dissimilarity between the markers heard before and after the gap increase the difficulty of detecting a gap. The effects of these stimulus dimensions on gap detection seem to be additive (Taylor *et al.*, 1999), and may require higher-level processing (Pichora-Fuller *et al.*, 2006; Grose *et al.*, 2007). In 'within-channel' conditions (spectrally identical markers), the perceptual operation is thought to involve relatively simple processing of activity in the neural channel representing the stimulus. However, in 'between-channel' conditions (spectral differences between markers), a number of factors may be involved: a relative timing operation between different neural regions (Phillips *et al.*, 1997), a second process reflecting the comparisons of components across frequency channels (Viemeister and Plack, 1993), or multiple within-channel decisions (Heinz *et al.*, 1996). Importantly, speech processing likely relies more on 'between-channel' than "within-channel" processes, and age-related differences may involve one or both types of processes.

The effect of age on gap detection is exacerbated when more complex stimuli are used, as illustrated in studies examining gap discrimination thresholds when the frequency of the leading marker was fixed and the frequency of the lagging marker was varied (Lister *et al.*, 2002), and when synthetic speech stimuli with spectrally dynamic markers were compared to those with spectrally stable markers (Lister and Tarver, 2004). In a study investigating the pattern of age-related differences in gap detection for both non-speech and speech markers that were either spectrally symmetrical ('within-channel') or spectrally asymmetrical ('between-channel'), we confirmed that gap detection thresholds were larger for both age groups when the markers were spectrally asymmetrical, and that age-related differences were also more pronounced in the 'between-channel' conditions than in the 'within-channel' conditions, especially for non-speech markers (Pichora-Fuller *et al.*, 2006).

There is also abundant research on age-related differences in duration discrimination ability. This evidence converges with the findings for gap detection on three key points. First, age-related differences in duration discrimination are not significantly correlated with audiometric thresholds (e.g., Fitzgibbons *et al.*, 2007). Second, age-related differences in ability to discriminate the duration of markers or the intervals between markers are more readily observed when the reference signal is shorter (20 msec) than when it is longer (200 msec) (Abel *et al.*, 1990; Fitzgibbons *et al.*, 2007). Third, age-related differences in duration discrimination can be exacerbated by increasing stimulus or task complexity (Fitzgibbons and Gordon-Salant, 2001). Similar findings using speech markers underscore the relevance of duration discrimination for the perception of phonemic contrasts serving word discrimination (Gordon-Salant *et al.*, 2006). As with gap detection, different mechanisms may contribute to age-related deficits in duration discrimination depending on marker properties. Impaired coding of rapid onsets and offsets seems likely to be involved in deficits seen when brief markers are used, whereas higher-level auditory processing involving a central timing mechanism may be involved in the age-related differences observed for longer duration and more complex stimuli (Fitzgibbons *et al.*, 2007).

Envelope

At the segmental level, gaps and duration cues provide temporal information about some phonemic contrasts, in particular those relying on consonant manner distinctions (e.g., Pichora-Fuller *et al.*, 2006; Gordon-Salant *et al.*, 2006). The amplitude modulations in the time-waveform can be thought of as a sequence of gaps and durations that provide temporal information pertaining to the supra-segmental or prosodic level of speech processing required for lexico-syntactic analyses (Fitzgibbons and Gordon-Salant, 2001; Purcell *et al.*, 2004; Fitzgibbons *et al.*, 2007). In quiet, envelope cues are sufficient to enable listeners with various degrees of hearing loss to identify words when the fine structure of the signal is obliterated by noise-vocoding (Turner *et al.*, 1995). Psychoacoustically, sensitivity to envelope fluctuations or modulations can be determined by varying the depth of modulation until it can no longer be detected, with appropriate controls on the intensity differences between modulated and unmodulated stimuli (Viemeister and Plack, 1993). Significant effects of age have been found on measures of modulation detection, and these behavioural results are correlated with electrophysiological envelope following responses, suggesting the involvement of both brainstem and cortical subsystems (Purcell *et al.*, 2004). Age-related differences in coding envelope cues are suggested by studies of time-compressed speech (e.g., Versfeld and Dreschler, 2002), gated words (e.g., Wingfield *et al.*, 2000), and noise-vocoded bisyllables (Souza and Boike, 2006) and words presented in a carrier phrase (Sheldon *et al.*, 2007). Thus, deficits in temporal processing based on envelope cues to supra-segmental speech information also figure in age-related differences in temporal processing. However, it is noteworthy that, although age-related differences in the speech understanding are well documented, older adults benefit more than younger adults from enriched prosodic information to understand time-compressed speech (e.g., Wingfield *et al.*, 1992).

FUTURE DIRECTIONS FOR ASSESSMENT AND REHABILITATION

Despite the strong evidence of the effect of age on measures of each of the three levels of temporal processing related to speech processing, it is important to recognize that there is a wide range of psychoacoustic and speech perception abilities, even among older listeners with good hearing thresholds. Most studies have used small group research designs with a younger control group compared to an older group that is selected or matched to the younger group, at least on audiometric criteria (Pichora-Fuller and Souza, 2003). The main analyses conducted for most studies have focused on group differences; however, many reports have noted that there are a handful of members of the older group who perform just as well as the younger group.

To examine the distribution of abilities within age groups, data was pooled from four studies in which gap detection was measured using brief 2-kHz tone-pip markers shaped with a Gaussian envelope with a standard deviation of 0.5 ms (Schneider *et al.*, 1994; Schneider *et al.*, 1998; Schneider and Hamstra, 1999; Haubert and Pichora-Fuller, 1999). The mean gap threshold is 3.2 ms (SD=1.3) for 62 younger adults (mean age=23.3, SD=2.5 years) and 6.1 ms (SD=3.6) for 60 older adults (mean age=70.0, SD=4.3 years). Importantly, some older individuals achieved gap detection thresholds equivalent to those of younger listeners, but individual differences were not correlated with the degree of audiometric threshold elevation at 4 kHz (Figure 1).

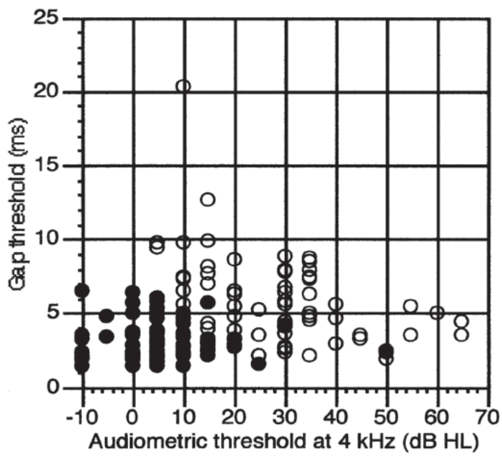

Fig. 1: Gap detection thresholds with 2-kHz markers shaped with a Gaussian envelope with a standard deviation of .5 ms. Data are pooled from four studies (Schneider *et al.*, 1994; Schneider *et al.*, 1998; Schneider and Hamstra, 1999; Haubert and Pichora-Fuller, 1999). Filled circles represent younger individuals and open circles represent older individuals.

Other studies have also reported that a small number of older adults performed as well as the younger group on temporal processing measures other than gap detection (e.g., Purcell *et al.*, 2004; MacDonald *et al.*, 2007). It is not known whether the same older individuals would perform equally well across different experiments, although research into individual differences could shed light on important relationships amongst different measures of temporal processing. It will be important for future research to explore the extent to which different types of temporal processing deficits are independent or related.

The greater variability in older groups on measures of temporal processing prompts questions about the reasons for this heterogeneity. Some research conducted on larger samples has used a correlational approach to examine age-related differences in the contribution to speech understanding of temporal processing abilities compared to other kinds of auditory processing abilities (e.g., van Rooij and Plomp, 1992). Correlations between psychoacoustic and speech measures have been difficult to establish (Phillips *et al.*, 2000; Snell and Frisina, 2000). Poor speech perception does not seem to coincide with temporal or spectral resolution abilities on simple tasks, but there are correlations between psychoacoustic measures of temporal processing and speech perception in noise or reverberation in studies including listeners ranging in age and degree of audiometric hearing loss (Gordon-Salant and Fitzgibbons, 1993).

Whether small group designs or correlational approaches were used, age has been the primary variable of interest. Studies often control for other auditory factors such as degree of audiometric loss and for non-auditory factors such as first language when speech materials are used (Pichora-Fuller and Souza, 2003). Nevertheless, some of the variability observed amongst older listeners, including the recurring observation that a minority have no apparent deficits, may be a consequence of the non-unitary nature of presbycusis. The focus on age as the main variable, and the selection of older participants with relatively good audiograms, may have inadvertently resulted in a characterization of predominantly only one type of presbycusis.

The classification of sub-types of presbycusis has been refined over four decades. Extensive animal research has culminated in a delineation of three sub-types truly associated with biological aging (Mills *et al.*, 2006), but these are not differentiated clinically. Two sub-types involve inner ear damage with high-frequency loss: one involves outer hair cell damage, and the other involves stria vascularis damage and reduced endocochlear potentials. A third involves damage to the auditory nerve, possibly without high-frequency loss, and there may be degeneration higher in the auditory system (Frisina *et al.*, 2001). As well, audiometric loss in many older adults is caused by environmental factors (e.g., noise, ototoxicity) rather than by age per se. To control for confounds between age and hearing loss indexed by audiometric thresholds, older adults with clinically abnormal audiograms below 4 kHz have often been excluded from laboratory studies. What has been learned about the temporal aspects of auditory aging may be more about neural presbycusis than about other sub-types.

In the general population, as well as those with one or more sub-types of presbycusis, there will be some with preserved normal hearing. The prevalence of the sub-types of presbycusis is unknown. Just as the demographic profile of auditory neuropathy in children has emerged recently (Rance, 2005), future research should clarify the prevalence of neural presbycusis. Indeed, the differential diagnosis of hearing loss attributable to outer hair cell or strial pathology is an active research topic (e.g., Mills, 2006). The most useful clinical tools for such differential diagnosis will probably be a battery of otoacoustic emissions and auditory brainstem response tests, as well as new tests of higher levels of temporal processing adapted for clinical purposes (e.g., Purcell *et al.*, 2004). Better diagnosis of the sub-types should reduce the apparent hetereogeneity in older groups. If the relationship between sub-types of presbycusis and behavioural temporal and speech processing measures is clarified, then in turn, these refinements in assessment will be tremendously useful in planning rehabilitation that can be tailored more specifically to the abilities and potential of older adults.

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