The relationship between temporal and spectral processing of sound and self-reported hearing difficulty in older adults with sensori-neural hearing loss

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Impairments to the temporal and spectral processing of sound contribute to difficulties in understanding speech, and likely contribute to the large variability in hearing aid outcomes of older adults with sensori-neural hearing loss (SNHL). We measured sensitivity to temporal fine structure (TFS), gap detection thresholds, and masked thresholds for frequency resolution in 80 older adults with bilateral symmetrical SNHL. Performance on the three psychoacoustic tests was not strongly correlated, and estimates of temporal and frequency resolution were not associated with patient self reports of hearing difficulty. However, listeners with good sensitivity to TFS were found to experience significantly greater confidence in their abilities on the spatial hearing and sound quality self-report scenarios than those listeners with poor sensitivity to TFS. These results indicate that the structures and mechanisms underlying temporal and spectral processing are independent, and that sensitivity to TFS is likely to contribute to a patient's experience of his/her hearing difficulties.

INTRODUCTION

Older adults with sensori-neural hearing loss (SNHL) exhibit difficulties understanding speech in noise which cannot be completely resolved with provision of amplification (i.e. hearing aids). Research on normal and hard-of-hearing populations suggest that reduced capability to resolve spectral and temporal information in sounds may account for some of the variability in speech perception, and subjective measures of successful hearing aid provision. In particular, reduced frequency resolution (i.e, broader auditory filters) is thought to be a major cause of the difficulties encountered by adults with SNHL in understanding speech in noisy situations (Glasberg and Moore, 1990; Hopkins and Moore, 2007; Strelcyk and Dau, 2009). Listeners with SNHL have larger gap detection thresholds (i.e., poorer temporal resolution) than normally-hearing listeners (Kishon-Rabin *et al*., 2009; Tyler *et al*., 1982; Pichora-Fuller and MacDonald, 2007). Reduced sensitivity to temporal fine structure (TFS) is thought to be another contributing factor to poor speech perception (Hopkins and Moore, 2007, 2010, 2011; Moore, 1985; Strelcyk and Dau, 2009). However, the relationship between these psychoacoustic capabilities, self-reports, age and hearing loss remains unclear.

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Strelcyk and Dau (2009) tested the relationship between frequency resolution and temporal fine structure at 750 Hz, and speech reception in modulated noise or two-talker in hearing impaired listeners. Their results showed that hearing impaired listeners had broader auditory filters, were less sensitive to TFS and had poorer speech reception thresholds than normal hearing listeners. No associations were found between measures of TFS and frequency resolution, suggesting that these two psychoacoustic capabilities are affected by impairments to different underlying structures or mechanisms. Sensitivity to TFS did not correlate with speech reception performance in modulated noise, but did for speech presented against a two-talker background. However, the data was not adjusted for age differences between populations. Hopkins and Moore (2011) tested sensitivity to TFS (at 250, 500 and 750 Hz), frequency resolution (at 500 Hz, 1 kHz, and 2 kHz) and speech reception in steady and modulated noise in 23 adults with mild to moderate hearing loss and two control groups (young vs. old) with normal hearing. Their results supported those of Strelcyk and Dau (2009) as measures of sensitivity to TFS did not correlate with frequency resolution or speech reception in noise. These data also suggested that insensitivity to TFS could not be solely explained by a broadening of auditory filters. Older adults with and without hearing loss were less sensitive to TFS information than the younger group, suggesting that age *per se*, independently of hearing thresholds, could affect sensitivity to TFS.

This report forms part of a larger study on hearing aid outcomes. The purpose of this report was to explore the associations between sensitivity to TFS, temporal resolution, and frequency resolution in a group of older adults with SNHL. In particular, we wanted to determine the impact of these abilities on patient self-reports of listening difficultly: the Glasgow Hearing Aid Benefit Profile part one (GHABP; Gatehouse, 1999) and the Speech, Spatial and Qualities questionnaire (SSQ; Gatehouse and Noble, 2004).

METHODS

Participants

The recruitment of participants was made via leaflets distributed to patients attending audiological services in Nottingham for a hearing assessment. Ethical approval for this study was obtained from the Derbyshire Research Ethics Committee.

All participants that enrolled in the study met the following selection criteria: (a) followed GP direct-referral route to audiology, (b) 50+ years of age, (c) mild-to-moderate bilaterally symmetrical sensori-neural hearing loss, (d) had not previously worn a hearing aid, (e) normal or corrected-to-normal vision.

Hearing thresholds were measured by audiologists according to BSA guidelines in a double-walled, sound proof booth at octave frequencies between 250 Hz and 8 kHz, using a Siemens Unity 1 or 2 audiometer with TDH39 headphones.

Equipment and stimuli

Signals used in the measurement of thresholds for temporal fine structure, temporal resolution and frequency resolution were digitally generated using a PC and an external sound card (ECHO Gina 3D), at a sampling rate of 44100 Hz and presented via Sennheiser HD-25 headphones. Listeners were tested in a double-walled sound-attenuating booth.

Temporal Fine Structure

The TFS-LF (low frequency) method employed in this study was developed by Hopkins and Moore (2010) to be tested at low frequencies in normal and hard-of-hearing listeners. Stimuli were presented using a two-interval two-alternative forced choice (2I-2AFC) task. Each interval contained four 500 Hz pure tones in either a *AAAA* sequence or a *ABAB* sequence. In *AAAA* interval, all the tones were presented diotically. In the *ABAB* interval, the first and third tones were diotic whilst the 2^{nd} and 4^{th} tones were presented with an interaural phase difference ($\Delta\varnothing$). A two-up, one-down adaptive procedure was used to vary $\Delta\varnothing$. At the beginning of a run $\Delta\varnothing$ was set to a maximum value of 180°.Thresholds were calculated by calculating the geometric mean of $\Delta\varnothing$ at the last six turn points which corresponded to the 71% correct point. However, the adaptive procedure terminated early if this maximum value was reached twice before the second turn point, or at all after the second turn point. In this situation, the program reverted to a non-adaptive procedure in which a further forty trials were presented with $\Delta\varnothing$ fixed at its maximum value and a percentage correct score was calculated.

Gap Detection

Temporal resolution was measured using a gap detection paradigm adapted from Kishon-Rabin *et al*. (2009). Stimuli were noises that had been low-pass filtered at 1 kHz. The stimulus in the standard interval was continuous for 1600 ms. The stimulus in the test interval comprised of an 800 ms noise signal, followed by a variable silent gap and a trailing noise signal that, together with the silent gap was 800 ms in duration. Participants were asked to identify which interval contained the test stimulus. Thresholds for gap detection were measured using an adaptive 2I-2AFC task. The initial gap was 60 ms, and the maximum gap value was set to 100 ms. The inter-stimulus interval was 700 ms. Stimuli were presented 15 dB above average hearing thresholds across 6 frequencies (250 Hz to 8 kHz) to ensure audibility.

Frequency resolution

The equivalent rectangular bandwidth (ERB) of auditory filters at 2 kHz was estimated using the notch-noise method by Patterson (1976). This frequency was chosen because as it is important for speech intelligibility. The detection threshold of a pure-tone signal (probe tone) presented in continuous masking noise was determined as a function of the width of a band-stop region (notch) centred on the signal frequency. Thresholds were determined using a 2I-2AFC adaptive procedure. Participants were instructed to judge which interval contained the 2 kHz probe tone.

The masker levels at thresholds for four notch widths were used to derive the ERB of the auditory filter. The threshold of a 2 kHz probe tone was determined for a number of flat spectrum noises that differed only in the width of a symmetric spectral notch centred on the signal frequency. Four notch widths were used (200, 400 and 600 Hz). The probe tone was pulsed repeatedly on and off (20 ms raised-cosine ramps, 120 ms steady duration and 50 ms interval between pulses). Masked thresholds were assessed for probe tones presented 10 dB SPL above individual 2 kHz pure-tone hearing thresholds.

Self-reports

In order to ascertain the degree of difficulty experienced in a range of un-aided listening scenarios, all participants completed the first part of the GHABP and the SSQ. Part one of the GHABP asks participants to rate themselves using a 5-point ordinal scale on two dimensions: initial disability and handicap. Higher ratings on each of these dimensions indicate greater levels of difficulty or handicap. The SSQ asks participants to rate their abilities in speech understanding, spatial hearing, and the appreciation of sound quality using a 10-point ordinal scale. Higher ratings on the SSQ indicate greater levels of ability (i.e., least difficulty).

RESULTS

Participant characteristics

The sample comprised of 46 men and 34 women. The average age of the men was 71.8 (SD = 7.6; range, 51 to 85). The average age for women was 73.2 (SD = 7.4; range 51 to 84). Hearing thresholds for men and women were very similar at low and mid frequencies, however at 4 kHz women had significantly better hearing than men (df = 79; F = 11.03; $p = 0.001$), which is consistent with the patterns reported in the literature (e.g., Cox *et al*., 2007; Jerger *et al*., 1993).

Three participants dropped out of the study before completing the psychoacoustic tests.

Associations between variables were determined with non-parametric correlation coefficient Spearman's rho. Sensitivity to TFS was not found to be associated with measures of temporal resolution, frequency resolution, age or hearing loss. Frequency resolution at 2 kHz was found to be correlated with degree of hearing loss at 2 kHz (left ear r = 0.48, $p < 0.001$; right ear r = 0.51, $p < 0.001$). Moderate but significant correlations were found between measures of temporal and frequency resolution at the left ear (r = 0.26; $p = 0.03$).

Sensitivity to temporal fine structure

49 participants (61.3%) completed the TFS task using the adaptive procedure while 26 participants (32.5%) completed the task when discriminating tones with a fixed

maximum phase shift of 180° (i.e., non-adaptive procedure). Two participants could not perform the TFS task at all because they could not hear any differences between the intervals. Values of the detectability index, d', were calculated for all listeners. (see Figure 1). For listeners who completed the non-adaptive procedure version of the test the mean d' values was 0.6 (sd = 0.88, range -0.2 to 3.6). For those listeners who completed the adaptive procedure the mean d' was 4.03 (sd = 3.04, range 1.2 to 17).

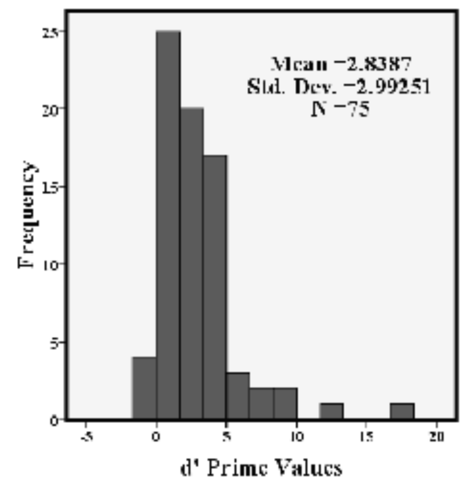

Fig. 1: Distribution of *d*' prime derived from the TFS task.

Temporal resolution

Gap detection thresholds were measured in right and left ears separately. Average threshold for right ear was 11.42 ms (SD = 16.57; range 2.8 to 83.5 ms) and average threshold for left ear was 9.62 ms (SD = 13.63; range 2.8 to 75.80 ms). Thresholds did not differ statistically between ears (df = 1; F = 0.53; $p = 0.5$). Data from one outlier participant was excluded from the analysis.

Listeners identified as being part of the adaptive TFS group had smaller gap detection thresholds (mean = 8.65 ms) than the listeners that reverted to the non-adaptive TFS procedure (mean = 13.15 ms). Differences between gap detection thresholds in the two groups, however, were not significant (F = 3.34; $p = 0.07$). Gap detection did not deteriorate as a function of age or hearing loss.

Frequency resolution

Masked thresholds of a pulse tone at four notch widths were used to derive the ERB of the auditory filter at 2 kHz for the right (mean = 0.36; SD = 0.025) and left ear (mean = 0.42; SD 0.24). A two-sample t-test showed no significant differences in frequency resolution between the ears.

There were no significant differences in frequency resolution between the adaptive and non-adaptive TFS procedure groups (F = 0.01; $p = 0.94$).

Self-reports

Initial disability and handicap scores of the GHABP were strongly correlated with one another (r = 0.8, $p < 0001$), but did not correlate with any of the psychoacoustic test measures, age or degree of hearing loss.

The three sub-scales of the SSQ (speech, space and sound quality) were strongly and positively correlated with one another ($r \geq 0.7$, $p < 0.001$), and were moderately and negatively associated with the initial disability and handicap dimensions of the GHABP (average $r \geq -0.3$, $p < 0.001$). This suggests that the two questionnaires tap into roughly the same factors.

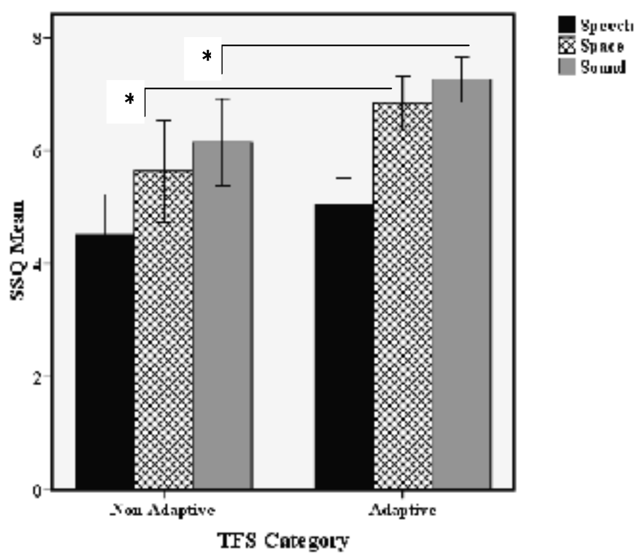

Fig. 2: 95% confidence interval plot of SSQ mean scores on Speech, Space and Sound dimensions plotted as a function of TFS category. (*) $p < 0.01$

Participants with good sensitivity to TFS reported less difficulties in the spatial [F = 7.23 (1, 73), $p < 0.01$], and sound [F = 8.39 (1, 73), $p < 0.01$] dimensions of the SSQ than those participants with poorer sensitivity to TFS (i.e., non-adaptive group). No differences were observed between TFS groups in the Speech dimension. All three dimensions of the SSQ were significantly associated with degree of hearing loss at the poorer ear (average $r \geq -.3$, $p > 0.001$).

CONCLUSIONS

This study measured binaural sensitivity to TFS at 500 Hz, temporal resolution and frequency resolution at 2 kHz in a group of 80 older adults with SNHL. We also assessed self-report scores of initial disability and handicap speech understanding, spatial processing and appreciation of sound quality.

The TFS test employed in this study was able to categorise listeners into two groups, those able to complete the task following the adaptive procedure and those that were able to complete the task following the non-adaptive procedure. We found that a large number of participants (32.5%) had particularly poor sensitivity to TFS and were unable to complete the adaptive procedure. This group reported more difficulties in spatial hearing and sound quality on the SSQ questionnaire. Listeners with good sensitivity to TFS tended to have better temporal resolution when compared to the non-adaptive group.

Our results suggest that those with poorer frequency resolution do not necessary have impaired sensitivity to TFS as no differences were observed between TFS groups and frequency resolution at 2 kHz. Because our tests assessed different frequencies (500 Hz and 2 kHz), we are limited in the strength of this argument. Previous studies, however, have reported the absence of significant correlations between measures of sensitivity to TFS and frequency resolution measured at the same test frequency (Hopkins and Moore, 2007, 2010, 2011; Strelcyk and Dau, 2009).

The results of this study, lend support to the argument that sensitivity to TFS, frequency resolution and temporal resolution are independent aspects of auditory processing. These results suggest that sensitivity to TFS contributes to a patient's personal experience of their hearing difficulties and it will likely play a role in explaining the large variability in hearing aid outcomes. We are currently investigating the impact of these impairments on aided and unaided speech reception and self-reported hearing-aid outcomes.

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Speech intelligibility as a function of time compression, age, word position, and signal-to-noise ratio

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Among other parameters, speech intelligibility depends on the rate of speech. Therefore, variation of time compression might be useful for adjusting the threshold of 50% intelligibility in speech in noise tests at fixed positive signal-to-noise ratios (SNRs). Speech rate can be modified with uniform and non-uniform algorithms. Uniform algorithms delete equally spaced segments, while non-uniform algorithms first characterize the structure of the speech and then increase the speech rate dependent on the classification. Referring to studies using fast speech, age effects have to be taken into account. To investigate fast speech in a German speech intelligibility test, sentences speeded to different time compressions were presented at different SNRs and intelligibility measurements were conducted with young and elderly normal-hearing listeners. The outcomes were used to calculate SNR-dependent discrimination functions. The results showed increasing SNRs for 50% intelligibility with increasing time compression. As expected, young listeners reached higher intelligibility than elderly listeners at equal time compressions and SNRs for 50% intelligibility were shifted to lower values. Additionally, increasing the speech rate affected word intelligibility in dependence on the words' position within the sentences. These differences in intelligibility led to shallower slopes of the discrimination functions and could possibly constrain the accuracy of the test.

INTRODUCTION

In natural environments, speech often occurs together with interfering signals, which affect intelligibility. This situation is reproduced in clinical tests measuring speech intelligibility in background noise, when speech or noise is adapted in level until the threshold of 50% intelligibility (speech recognition threshold, SRT) is reached (e.g., HINT, Nilsson, 1994; OLSA, Wagener *et al*., 1999). Not only interfering signals influence intelligibility, but also speaker's speech rate. Previous studies documented, as expected, a decreasing performance with increasing speech rate (e.g., Adams and Moore, 2009). Following the example of Versfeld and Dreschler (2002), who adjusted the speech rate to reach the SRT in quiet, it could also be possible to measure the SRT by varying the speech rate at fixed signal-to-noise ratios (SNRs) in

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