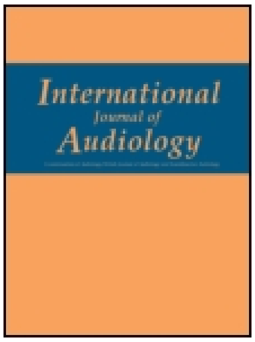

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Original Article

The effects of age on temporal fine structure sensitivity in monaural and binaural conditions

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Abstract

Objective: To extend the study of Hopkins and Moore (2011) by examining the effect of age in the medium age range on sensitivity to temporal fine structure (TFS), which is assumed to be represented in the patterns of phase locking in the auditory nerve. *Design:* Monaural TFS sensitivity was assessed using the TFS1 test (Moore & Sek, 2009) at centre frequencies of 850 and 2000 Hz, and binaural TFS sensitivity was assessed using the TFS-LF test (Hopkins & Moore, 2010a) at centre frequencies of 500 and 850 Hz, using a sensation level of 30 dB. *Study sample:* Thirty-five newly recruited normal-hearing subjects (thresholds better than 20 dB HL from 250 to 6000 Hz) were tested. Their ages ranged from 22 to 61 years. *Results:* There was a significant correlation between age and TFS sensitivity at all frequencies for both TFS tests. For the single centre frequency (850 Hz) that was used for both tests, scores for the two tests were modestly but significantly correlated. *Conclusions:* Sensitivity to TFS decreases with increasing age. The monaural and binaural TFS tests appear to reflect at least somewhat distinct auditory processes.

Key Words: Temporal fine structure; aging; binaural hearing

Significant increases in longevity have led to an increase in interest about the impact of aging on the auditory system. It is well known that older people have difficulty in understanding speech in challenging listening conditions (Bergman, 1971). However, it is difficult to determine the extent to which this is due mainly to problems in relatively peripheral sensory processing (van Rooij & Plomp, 1990, 1992), to decline in the functioning of the central auditory system (Martin & Jerger, 2005), or to changes in cognition and attention (Harris et al, 2010). Aging may affect the auditory system in several different ways even in the absence of peripheral hearing loss as measured by the audiogram.

Several studies have compared the performance of young and older listeners with normal (or near-normal) hearing sensitivity for a range of temporal processing tasks (Pichora-Fuller & Schneider, 1991; Schneider et al, 1994; Strouse et al, 1998; Dubno et al, 2008; Harris et al, 2010). The results suggest that older people perform more poorly than younger people on most measures of temporal resolution. This paper is especially concerned with the idea that older people have reduced sensitivity to the temporal fine structure (TFS) of sounds, as reflected in the patterns of phase locking in the auditory nerve (Pichora-Fuller & Schneider, 1991; 1992). This can result in reduced sensitivity to interaural phase differences (IPD) (Grose & Mamo, 2010; Hopkins & Moore, 2011; Moore et al, 2012) and reduced binaural masking level differences (Pichora-Fuller & Schneider, 1991; 1992; Strouse et al, 1998) in older people. Consistent with this, cortical auditory evoked potentials (CAEP) produced by IPD cues decline with increasing age (Ross et al, 2007). The decline was apparent even for a middle-aged group (mean age = 50.8 years) and the effect was more pronounced for an older age group.

One of the simplest and most direct ways of measuring sensitivity to TFS is to measure the ability to detect a change in the IPD of binaurally presented sinusoidal tones (Nilsson & Liden, 1976; Rosenhall, 1992; Hopkins & Moore, 2010a). The test developed by Hopkins and Moore (2010a), called the TFS-LF test, was intended to be fast and easy to use for research studies with a large number of participants or in clinical practice. It can be performed reliably by young subjects with normal hearing. However, since the test necessarily involves binaural processing, it is unclear whether poor performance on the TFS-LF test reflects a deficit in peripheral processing of TFS or a deficit in the ability to combine TFS information across ears. Also, since sensitivity to IPD is lost for frequencies above 1500 Hz even for people with normal hearing (Moore, 2012), the TFS-LF test cannot be used to assess sensitivity to TFS at medium and high frequencies.

Recently, a monaural test of sensitivity to TFS has been described that can be used to assess sensitivity to TFS at medium and high frequencies (Moore & Sek, 2009). The test is called the TFS1 test. Subjects are required to discriminate a harmonic complex tone with fundamental frequency F0 from a 'frequency-shifted' tone, in which all components are shifted upwards by the same amount in Hertz, ΔF.

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Abbreviations

ERB_N	Equivalent rectangular bandwidth of the auditory filter
F0	Fundamental frequency
IPD	Interaural phase difference
SD	Standard deviation
SL	Sensation level
TEN	Threshold equalizing noise
TFS	Temporal fine structure
TFS1	Test for measuring monaural TFS sensitivity
TFS-LF	Test for measuring binaural TFS sensitivity

The harmonic and frequency-shifted tones have the same envelope repetition rate but different TFS. The tones are passed through a fixed band-pass filter to minimize differences in spectral envelope. For people who are sensitive to TFS, the frequency shift is heard as a change in pitch (Schouten et al, 1962; Moore & Moore, 2003). Moore and Sek (2009) showed that the TFS1 test could be performed reliably by normal-hearing subjects with a range of ages for F0s of 100, 200, and 400 Hz, when the bandpass filter was centred on the 11th component, which corresponded to filter centre frequencies of 1100, 2200, and 4400 Hz. An F0 of 50 Hz was also used, but many of the normal-hearing subjects could not perform the task for this F0. Moore and Sek (2009) showed that performance on the TFS1 test improved little with practice, and that the sensation level (SL) at which the tones were presented had little effect on performance.

Several studies have shown that performance on the TFS1 test, or closely related tests, is adversely affected by sensorineural hearing loss (Moore et al, 2006; Hopkins & Moore, 2007, 2010b, 2011). In most of those studies, the hearing-impaired subjects were older than the comparison group of normal-hearing subjects, making it difficult to separate the effects of hearing loss and age. However, Hopkins and Moore (2011) included a group of six older subjects (aged 63–69 years) with audiograms within the normal range (audiometric thresholds of 20 dB HL or better at octave frequencies between 250 and 8000 Hz). They used a battery of tests including both the TFS-LF test and a variation of the TFS1 test. The older group with normal hearing performed significantly more poorly than the younger group with normal hearing for both TFS tests. For the single test frequency at which both tests were performed (750 Hz), the results were significantly but modestly correlated across the two tests, suggesting that performance of the tests may be partly influenced by different factors.

This study is an extension of the study of Hopkins and Moore (2011). We included a larger subject group than them (35 versus 16), and we used subjects with a range of ages between 22 and 61 years, rather than using two separate groups, young (20–35 years) and older (63–69 years). Note that none of the subjects in the study of Hopkins and Moore were included in the present study. Both the TFS-LF and TFS1 tests were used. This allowed us to establish more clearly how performance on the two tests changes with age. One of the test frequencies (850 Hz) was chosen since both tests could be performed at this frequency. This provided the possibility of replicating the finding of Hopkins and Moore (2011) that scores for the two tests are modestly correlated. We used a slightly higher centre frequency than Hopkins and Moore (2011) to reduce the proportion of subjects who could not reliably perform the TFS1 test; as noted above, this test becomes more difficult for low centre frequencies.

Method

Subjects

Thirty-five subjects, aged between 22 and 61 years, were tested. Sixteen were male and 19 were female, and the distribution of ages was similar for the two genders. All subjects were screened to have audiometric thresholds better than 20 dB HL at 250, 500, 1000, 2000, 4000, and 6000 Hz, for both ears. None reported any history of illnesses, treatments, or accidents that might have affected their hearing. Two of the male subjects played a musical instrument non-professionally. Thirteen subjects were not native speakers of English, and the remainder were. The study was approved by the University College London Ethics Committee.

Equipment

Audiometry was conducted using a Grason-Stadler GSI-61 Clinical Audiometer and TDH39 supra-aural headphones. The TFS1 and TFS-LF tests were conducted using a Dell laptop computer with a Sound Blaster Audigy sound card and Sennheiser HD600 supra-aural headphones. The tests were carried out in a sound-attenuating booth. The equipment was calibrated using a Hewlett-Packard 3561A Dynamic Signal Analyser and a Knowles KB0062 KEMAR manikin.

Sequence of testing

A screening (pass/fail) audiogram was measured for each ear at 250, 500, 1000, 2000, 4000, and 6000 Hz. Only subjects with audiometric thresholds better than 20 dB HL at all frequencies for both ears were included.

The TFS-LF test was conducted using frequencies of 500 and 850 Hz. The TFS1 test was conducted using centre frequencies of 850 and 2000 Hz; for this test only the ear with the better audiometric threshold at 850 Hz was tested. Absolute thresholds in dB SPL for the test frequencies of 500, 850, and 2000 Hz were determined using an adaptive two-interval forced-choice procedure, which is described below. Stimuli for the TFS tests were presented at a sensation level of 30 dB, based on the absolute thresholds measured using the forced-choice procedure. Next, the TFS1 test was carried out using a centre frequency of 2000 Hz (see below for details of the test procedure). Practice runs were conducted until the scores for two consecutive runs were within 20% of each other. The geometric mean for these two runs was taken as the TFS1 score at 2000 Hz. Then, the centre frequency was set to 850 Hz and two runs were conducted. This process was repeated for the TFS-LF test, for which practice was given for a test frequency of 500 Hz, and then testing was conducted for a frequency of 850 Hz.

Measurement of absolute thresholds

Absolute thresholds were measured using a forced-choice method for the test frequencies of 500, 850, and 2000 Hz. Subjects were required to choose which of two intervals, marked by flashing boxes on a computer screen, contained a tone. At the start of a run, the level of the tone was set to 30 dB SPL, which was clearly audible for all listeners at all of the frequencies that were used. Following two correct responses, the level of the tone was decreased by k and following one incorrect response the level of the tone was increased by k. Before the first turn point, k was equal to 6 dB, between the first and second turn points, k was equal to 4 dB, and subsequently k was equal to 2 dB. The run was terminated after eight turn points, and the threshold for the run was taken to be the mean level of the tone at the last six turn points. A single threshold estimate was obtained for each centre frequency.

Stimuli for the TFS1 test

The TFS1 test (Moore & Sek, 2009) uses a two-interval, two-alternative force choice task. Subjects were required to discriminate a harmonic complex tone (H) with fundamental frequency F0 from a second tone in which all the components were shifted upwards by ΔF Hz, resulting in an inharmonic tone (I). Each interval contained four successive 200-ms tones (including 20-ms onset and offset ramps), separated by 100 ms. One interval contained four H tones, giving the pattern HHHH. The other interval contained alternating H and I tones, giving the pattern HIHI. The subject had to choose the interval in which they heard a fluctuation in pitch.

To reduce cues due to differences in the excitation patterns of the H and I tones, the stimuli were passed through a bandpass filter centred at 9F0. The filter had a central flat region with a width equal to F0. The skirts of the filter fell off at a rate of 30 dB/octave. The filter minimized differences in the spectral envelope of the harmonic and inharmonic complexes. The value of F0 was 94 Hz for the centre frequency of 850 Hz and 222 Hz for the centre frequency of 2000 Hz.

A threshold equalizing noise (TEN) (Moore et al, 2000) extending from 50 to 11 050 Hz was used to mask combination tones and to limit the audibility of components falling on the lower side of the bandpass filter. The TEN started 300 ms before the first tone burst and ended 300 ms after the last tone burst. The TEN level was specified as the level in a 1-$\mathrm{ERB_N}$ wide band centred at 1000 Hz, where $\mathrm{ERB_N}$ stands for the average value of equivalent rectangular bandwidth of the auditory filter at moderate sound levels for listeners with normal hearing (Glasberg & Moore, 1990). The level of the TEN was set 15 dB below the overall level of the complex tone.

Stimuli for TFS-LF test

The TFS-LF test (Hopkins & Moore, 2010a) is also based on a two-interval, two-alternative forced choice task. Each interval contained four successive tone bursts of the same frequency, *f*, each 400 ms long with 50-ms onset and offset ramps. There was a 20-ms gap between tones within an interval, and a 200-ms gap between intervals. All of the tones in one interval were in-phase at the two ears. In the other interval, the first and third tones were in-phase at the two ears, but the second and fourth tones had an interaural phase difference (IPD) of $\Delta\phi$ in the TFS only (the envelopes of the tones were synchronous in the two ears). The subject was asked to indicate the interval in which the tones appeared to move within the head.

Procedure for the TFS1 and TFS-LF tests

For both tests, a two-down one-up adaptive procedure (Levitt, 1971) was used, and visual feedback (Correct/ Incorrect) was given after each trial, via the computer screen. After two successive correct responses, the value of ΔF or $\Delta\varphi$ was divided by a factor, *k*. After one incorrect response, the value of ΔF or $\Delta\varphi$ was multiplied by *k*. Before the first turn point, *k* was set to 1.25^3. Between the first and second turn points, *k* was 1.25^2, and beyond the second turn point, *k* was equal to 1.25. An adaptive track ended after eight turn points. The threshold, corresponding to 71% correct responses, was calculated as the geometric mean of the values of ΔF or $\Delta\varphi$ at the last six turn points.

The maximum value of ΔF was set to 0.5F0 Hz; this corresponds to the value at which the H and I tones are most different. Similarly, the maximum value of $\Delta\varphi$ was set to 180°; this corresponds to the value of $\Delta\varphi$ at which lateralization is most extreme. If the limit was reached twice before the second turn point or any time after the second turn point, the adaptive procedure ended and forty further trials were presented with ΔF or $\Delta\varphi$ fixed at the maximum value. When the adaptive procedure was not completed for the first run of a given condition, it was also always not completed for the second run, indicating consistently poor performance. This happened for eight subjects for the TFS1 test at the centre frequency of 850 Hz and for five subjects for the TFS-LF test for the centre frequency of 850 Hz. Of these subjects, there were four who did not complete the adaptive procedure for both the TFS1 test and the TFS-LF test. The adaptive procedure was completed by all subjects for the centre frequency of 2000 Hz for the TFS1 test and the centre frequency of 500 Hz for the TFS-LF test.

For cases where the adaptive procedure was not completed, the percentage correct score for the forty trials was converted to a value of the detectability index, d′, using standard tables (Hacker & Ratcliff, 1979). For the TFS1 test at 850 Hz, the resulting d′ values (with ages of the subjects in parentheses) were 0.0 (31), −0.21 (48), 0.60 (49), 0.19 (52), 0.19 (53), 0.66 (54), −0.18 (57), and −0.21 (61). For the TFS-LF test at 850 Hz, the d′ values were 1.0 (52), 0.10 (52), 0.54 (53), 0.10 (54), and 0.24 (57). Values of d′ in the range −0.5 to + 0.5 are not significantly different from what would be expected by chance ($d' = 0$) based on a binomial test.

To allow d′ scores obtained in this manner to be compared to those for the adaptive procedure, linear extrapolation was used to calculate the value of ΔF or $\Delta\varphi$ that would yield 71% correct responses for a two-alternative forced choice task (corresponding to $d' = 0.78$). It was assumed that d′ would be zero for ΔF or $\Delta\varphi = 0$, and that d′ was proportional to ΔF or $\Delta\varphi$. The extrapolation was applied only to d′ values > 0.5, which probably indicate above-chance performance. Note that these extrapolated values are not meaningful, as performance would not improve if ΔF were larger than 0.5F0 or $\Delta\varphi$ were larger than 180°. The extrapolation was used solely to allow all data to be expressed on a common scale; large values of ΔF or $\Delta\varphi$ indicate poor performance. When the dΔ value was < 0.5, the extrapolated value of ΔF was set to 0.75F0 (the value that would occur for a d′ value $= 0.52$). This happened for six subjects for the centre frequency of 850 Hz. When the extrapolated value of $\Delta\varphi$ was larger than 270°, it was limited to 270° (the value that would occur for a d′ value $= 0.52$). This happened for three subjects for the centre frequency of 850 Hz. It should be noted that the correlations reported below were not markedly changed when different limits were applied (for example when the maximum value of ΔF was set to any value in the range 0.6F0 to 0.9F0, or when the maximum value of $\Delta\varphi$ was set to any value in the range 200 to 324°). In particular, none of the correlations reported as significant in what follows became non-significant when the extrapolation limits were altered within these ranges.

Results

Initially, we assessed the repeatability of the results and whether there was evidence for learning effects. For a given test and centre frequency, this was done by dividing the threshold for the first test by that for the second test, and averaging the resulting ratio across all subjects who were able to complete the adaptive procedure. For the TFS1 test at 2000 Hz, the mean ratio was 1.03, indicating minimal learning. The standard deviation (SD) of the ratio was 0.18, indicating reasonably good consistency across repetitions. For the TFS1 test at 850 Hz, the mean ratio was 1.09, indicating a small learning effect, and the SD was 0.38, indicating somewhat less good repeatability. The poorer repeatability here was mainly caused by the results for two subjects who improved by more than a factor of two from test 1 to test 2. For the TFS-LF test at 500 Hz, the mean ratio was 1.02, indicating minimal learning. The SD was 0.22, indicating reasonably good consistency across repetitions. For the TFS-LF test at 850 Hz, the mean ratio was 1.04, indicating minimal learning. The SD was 0.17, indicating reasonably good consistency across repetitions.

An initial analysis indicated that there was no consistent effect of the gender of the subject. Hence, in what follows, the data are collapsed across genders. A logarithmic transformation was applied to the threshold values of ΔF and $\Delta\varphi$ as this resulted in the data being more normally distributed. Correlations with variables such as age were calculated for both the linear (lin) and logarithmic (log) values.

Figure 1 is a scatter plot of results for the TFS1 test and results for the TFS-LF test for the test frequency of 850 Hz that was used for both tests. There was a moderate correlation between the two ($r = 0.48$, $p < 0.01$ for log values and $r = 0.49$, $p < 0.01$ for linear values). This is close to the correlation of 0.45 (for linear values) reported by Hopkins and Moore (2011) for the combined results across all groups tested by them (young and older normally-hearing subjects and older hearing-impaired subjects). The moderate correlation suggests that the two tests are measuring partly different abilities. In particular, as noted in the introduction, the TFS-LF test requires binaural processing, whereas the TFS1 test does not. In Figure 1 and subsequent figures, the filled circles show results for the two musically trained subjects. As can be seen, their performance was better than average for both tasks.

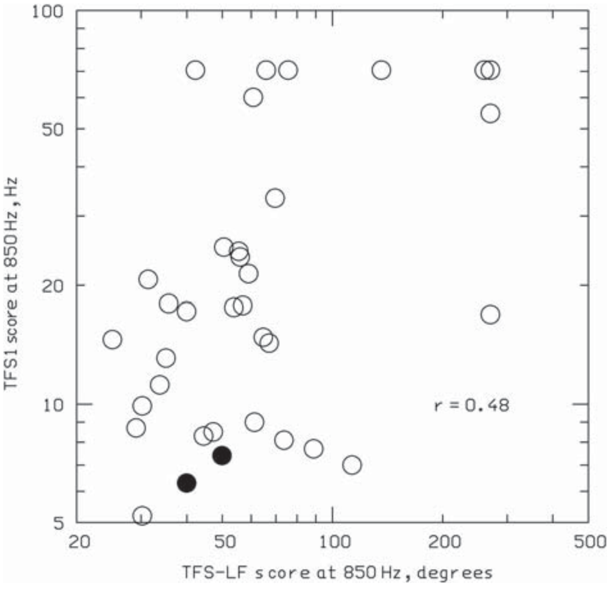

Figure 1. Scatter plot of scores for the TFS1 test against scores for the TFS-LF test (both on a logarithmic scale), for the frequency of 850 Hz. TFS1 scores based on extrapolation were limited to 70.5 Hz, and TFS-LF scores based on extrapolation were limited to 270° (see text for details). In this and subsequent figures, filled symbols show results for the two subjects with musical training.

TFS1 scores at 850 Hz were correlated with absolute thresholds at 850 Hz ($r = 0.61$, $p < 0.001$ for log values and $r = 0.67$, $p < 0.001$ for lin values), even though audiometric thresholds were within the normal range. TFS1 scores at 850 Hz were also correlated with age ($r = 0.66$, $p < 0.001$ for log values and $r = 0.69$, $p < 0.001$ for lin values). Figure 2 shows a scatter plot of results for the TFS1 test at 850 Hz and age. TFS1 scores at 2000 Hz were only weakly correlated with absolute thresholds at 2000 Hz ($r = 0.40$, $p < 0.02$ for log values and $r = 0.39$, $p < 0.02$ for lin values). TFS1 scores at 2000 Hz were correlated with age ($r = 0.55$, $p < 0.002$ for log values and $r = 0.57$, $p < 0.001$ for lin values). Figure 3 shows a scatter plot of results for the TFS1 test at 2000 Hz and age. For both test frequencies, the two musically trained subjects (filled symbols) scored unusually well for their age. The correlations of TFS1 scores with age would be higher if results for these subjects were excluded. Note that, although the correlations illustrated in Figures 2 and 3 are highly significant, there was nevertheless considerable scatter in the results; at a given age, the scores could cover a wide range.

Since eight of the TFS1 scores in Figure 2 were based on extrapolated (and/or limited) values, an additional analysis was conducted to assess whether there was an effect of age on performance on the TFS1 test at 850 Hz. The subjects were divided into two groups, one of 18 subjects aged 34 years or less, and one of 17 subjects aged 36 years or more. For the first group, only one subject failed to complete the adaptive procedure, while for the second group seven subjects failed. Based on a chi-square test, the difference in proportions across groups is significant ($p < 0.02$). This confirms that performance on the TFS1 test declines with increasing age.

TFS-LF scores at 500 Hz were weakly correlated with age ($r = 0.37$, $p < 0.02$ for log values and $r = 0.41$, $p < 0.02$ for lin values), and were not significantly correlated with absolute threshold ($r = 0.11$, $p > 0.05$ for log values and $r = 0.05$, $p > 0.05$ for lin values). Figure 4 shows a scatter plot of results for the TFS-LF test at 500 Hz and age. TFS-LF scores at 850 Hz were more strongly

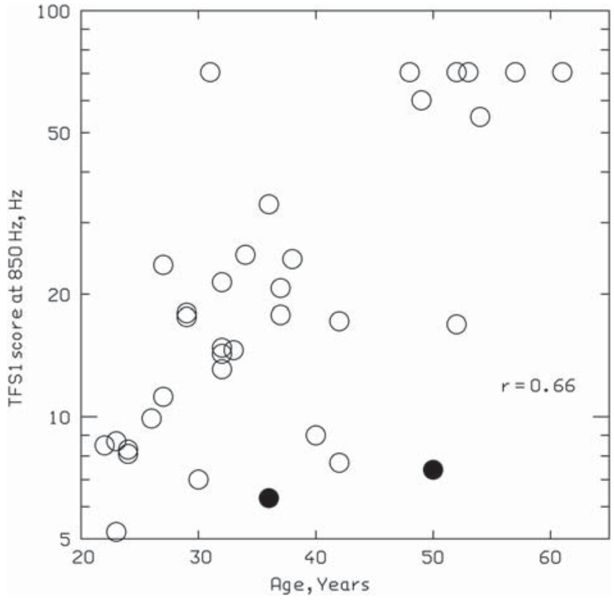

Figure 2. Scatter plot of scores for the TFS1 test (log scale) at 850 Hz against age.

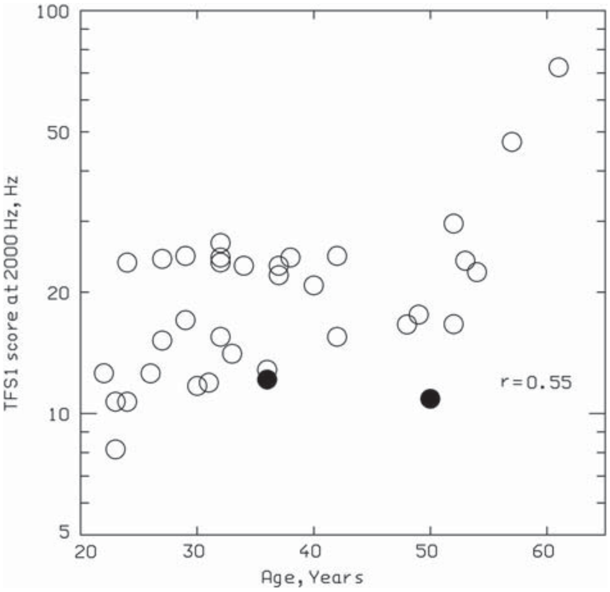

Figure 3. Scatter plot of scores for the TFS1 test (log scale) at 2000 Hz against age.

correlated with age ($r = 0.65$, $p < 0.001$ for log values and $r = 0.64$, $p < 0.001$ for lin values) and again were not significantly correlated with absolute threshold ($r = 0.27$, $p > 0.05$ for log values and $r = 0.26$, $p > 0.05$ for lin values). Figure 5 shows a scatter plot of results for the TFS-LF test at 850 Hz and age. Assuming that the absolute threshold primarily reflects the functioning of the cochlea, this pattern of results suggests that the decrease in performance of the TFS-LF test with increasing age does not reflect a degradation in peripheral processing, but reflects deterioration in more central processes. At 850 Hz, the two musically trained subjects scored unusually well for their age, but this was only the case for one of those subjects at 500 Hz.

Discussion

A main aim of this study was to assess how scores on the TFS1 and TFS-LF tests changed with age for subjects in the medium age range (22–61 years) and with normal audiometric thresholds for frequencies up to 6000 Hz. The results showed that scores for all of the TFS tests were correlated with age. Thus sensitivity to TFS worsened with increasing age over the medium age range.

A second main aim of this study was to assess the extent of the correlation between scores for the TFS1 and TFS-LF tests when both were applied at the same centre frequency, 850 Hz, for subjects with audiometrically normal hearing. There was a modest but significant correlation between the scores. A similar modest correlation was found by Hopkins and Moore (2011) for a different group of subjects, although they included the results for older subjects with hearing loss. Overall, the results suggest that the two tests measure partly different abilities. In particular, as noted in the introduction, the TFS-LF test requires binaural processing, whereas the TFS1 test does not. Consistent with this general line of argument, the scores for the TFS1 test were significantly correlated with absolute thresholds (more so at 850 than at 2000 Hz), whereas the results for the TFS-LF test were not significantly correlated with absolute thresholds, for either test frequency. The data show that the binaural processing of TFS can be impaired when absolute thresholds are not elevated.

The TFS1 task was generally easier at 2000 than at 850 Hz. Geometric mean thresholds were 18.6 Hz at 2000 Hz (corresponding to 0.093F0) and 18.8 Hz at 850 Hz (corresponding to 0.2F0). Based on a matched-samples, *t*-test, the difference in the values of $\Delta F/F0$ at threshold was statistically significant ($p < 0.001$). Eight subjects failed to complete the adaptive procedure at 850 Hz, but all completed the procedure at 2000 Hz. This is consistent with previous results showing that performance on the TFS1 task, expressed as the threshold value of ΔF divided by F0, tends to worsen with decreasing F0 (Moore & Sek, 2009; Moore et al, 2009). It is also consistent with the results of previous studies showing that F0 discrimination of complex tones with unresolved harmonics worsens at low F0s (White & Plack, 2003). A possible explanation for this effect is that

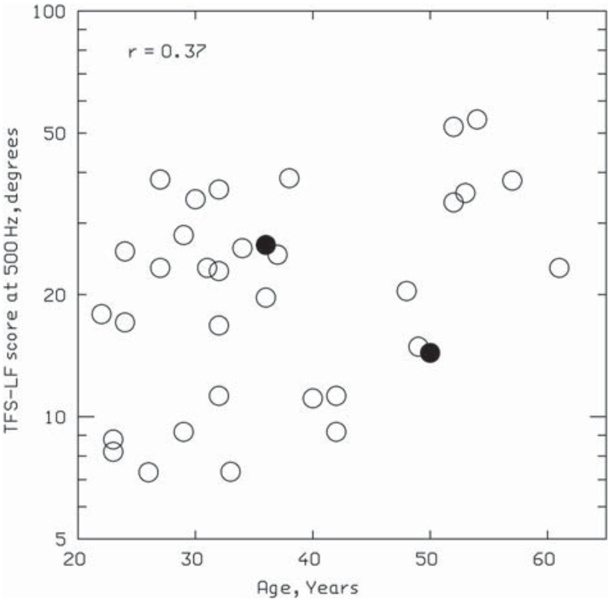

Figure 4. Scatter plot of scores for the TFS-LF test (log scale) at 500 Hz against age.

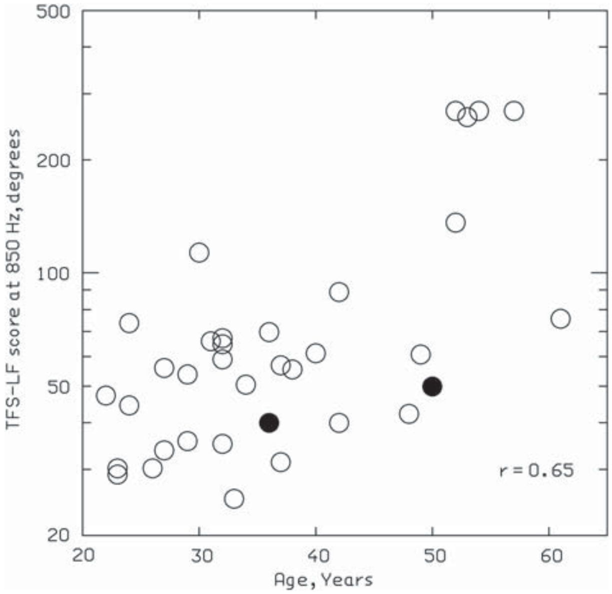

Figure 5. Scatter plot of scores for the TFS-LF test (log scale) at 850 Hz against age.

the auditory system has difficulty in measuring very long inter-spike intervals (de Cheveigné & Pressnitzer, 2006; Moore & Sek, 2009; Moore et al, 2009; Moore & Glasberg, 2010).

For the TFS-LF task, the geometric mean score at 500 Hz (20.1°) was better than the geometric mean score at 850 Hz (61.9°). Based on a matched-samples *t*-test, the difference in the mean thresholds was statistically significant ($p < 0.001$). Five subjects failed to complete the adaptive procedure at 850 Hz, but none failed at 500 Hz. This pattern of results is consistent with the general trend for IPD discrimination to be best around 500 Hz and to worsen as the frequency is increased above 750 Hz; generally, IPD discrimination becomes impossible for frequencies above 1500 Hz, a limit that presumably reflects limitations in binaural processing rather than in phase locking per se (Grantham, 1995; Moore, 2012).

The scores for both the TFS1 and the TFS-LF tests were significantly correlated with age, consistent with previous studies showing that sensitivity to TFS, and especially sensitivity to binaural TFS cues, worsens with increasing age. Our results show that this happens progressively over the age range 22 to 61 years, consistent with the electrophysiological results of Ross et al (2007). The highest correlations with age were found for the frequency for which the tasks were most difficult (850 Hz for both the TFS1 and TFS-LF tests).

The poor performance of some of the older subjects on the TFS tests does not seem to reflect an inability to perform forced-choice tasks, as the subjects had little difficulty in performing the forced-choice task used to measure absolute thresholds. Also, some subjects performed well on one of the tasks (e.g. the TFS1 task) but performed poorly on the TFS-LF task, even though the tasks had very similar structures. Nevertheless, it is possible that performance on the tasks was influenced by cognitive abilities. Also, the two subjects with musical training tended to perform better than would be typical for their age, especially for the TFS1 task, which involves pitch perception. It is not clear whether this better performance reflects superior representation and/or processing of TFS, or whether it reflects a better ability to discriminate sounds based on minimal sensory evidence. This requires further study.

Poor performance on the TFS tasks may have implications for performance in everyday listening situations. For example, performance on the TFS1 test is correlated with the ability to understand a target talker in a background talker or in a modulated noise (Hopkins & Moore, 2010b, 2011), and performance on the TFS-LF test is correlated with the ability to understand speech in spatially complex environments (Neher et al, 2012). The results for the two tests might be useful in predicting when a person will have special difficulty listening in such environments.

Conclusions

Performance on two tasks assessing sensitivity to TFS was measured for a group of 35 subjects whose audiometric thresholds were within the normal range and who had ages in the range 22 to 61 years. The main findings (based on correlations of the log values) were:

1. Scores on the TFS1 task, which is a monaural test of the ability to use TFS, were significantly correlated with age. The correlations were $r = 0.66$ at 850 Hz and 0.55 at 2000 Hz.
2. Scores on the TFS1 task were correlated with the absolute threshold at the test frequency. The correlations were $r = 0.61$ at 850 Hz and $r = 0.40$ at 2000 Hz.
3. Scores on the TFS-LF task, which is a test of the ability to compare TFS information across the two ears, were significantly correlated with age. The correlations were $r = 0.65$ at 850 Hz and $r = 0.37$ at 500 Hz.
4. Scores on the TFS-LF task were not significantly correlated with the absolute threshold at the test frequency.
5. Scores for the single test frequency at which both tasks were performed were modestly but significantly correlated ($r = 0.48$). Thus, while the two tasks appear to measure partly related abilities, there must be factors that affect performance on the two tasks differently. This may reflect the fact that the TFS-LF test requires binaural processing.

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References

Bergman M. 1971. Hearing and aging. *Audiology*, 10, 164–171.

de Cheveigné A. & Pressnitzer D. 2006. The case of the missing delay lines: Synthetic delays obtained by cross-channel phase interaction. *J Acoust Soc Am*, 119, 3908–3918.

Dubno J.R., Ahlstrom J.B. & Horwitz A.R. 2008. Binaural advantage for younger and older adults with normal hearing. *J Speech Lang Hear Res*, 51, 539–556.

Glasberg B.R. & Moore B.C.J. 1990. Derivation of auditory filter shapes from notched-noise data. *Hear Res*, 47, 103–138.

Grantham D.W. 1995. Spatial hearing and related phenomena. In: B.C.J. Moore (ed.) *Hearing*, New York: Academic, pp. 297–345.

Grose J.H. & Mamo S.K. 2010. Processing of temporal fine structure as a function of age. *Ear Hear*, 31, 755–760.

Hacker M.J. & Ratcliff R. 1979. A revised table of d' for M-alternative forced choice. *Percept Psychophys*, 26, 168–170.

Harris K.C., Eckert M.A., Ahlstrom J.B. & Dubno J.R. 2010. Age-related differences in gap detection: Effects of task difficulty and cognitive ability. *Hear Res*, 264, 21–29.

Hopkins K. & Moore B.C.J. 2007. Moderate cochlear hearing loss leads to a reduced ability to use temporal fine structure information. *J Acoust Soc Am*, 122, 1055–1068.

Hopkins K. & Moore B.C.J. 2010a. Development of a fast method for measuring sensitivity to temporal fine structure information at low frequencies. *Int J Audiol*, 49, 940–946.

Hopkins K. & Moore B.C.J. 2010b. The importance of temporal fine structure information in speech at different spectral regions for normal-hearing and hearing-impaired subjects. *J Acoust Soc Am*, 127, 1595–1608.

Hopkins K. & Moore B.C.J. 2011. The effects of age and cochlear hearing loss on temporal fine structure sensitivity, frequency selectivity, and speech reception in noise. *J Acoust Soc Am*, 130, 334–349.

Levitt H. 1971. Transformed up-down methods in psychoacoustics. *J Acoust Soc Am*, 49, 467–477.

Martin J.S. & Jerger J.F. 2005. Some effects of aging on central auditory processing. *J Rehabil Res Dev*, 42, 25–44.

Moore B.C.J. 2012. *An Introduction to the Psychology of Hearing, 6th ed.* Bingley, UK: Emerald.

Moore B.C.J. & Glasberg B.R. 2010. The role of temporal fine structure in harmonic segregation through mistuning. *J Acoust Soc Am*, 127, 5–8.

Moore B.C.J., Glasberg B.R. & Hopkins K. 2006. Frequency discrimination of complex tones by hearing-impaired subjects: Evidence for loss of ability to use temporal fine structure information. *Hear Res*, 222, 16–27.

Moore B.C.J., Glasberg B.R., Stoev M., Füllgrabe C. & Hopkins K. 2012. The influence of age and high-frequency hearing loss on sensitivity to temporal fine structure at low frequencies. *J Acoust Soc Am*, 131, 1003–1006.

Moore B.C.J., Hopkins K. & Cuthbertson S.J. 2009. Discrimination of complex tones with unresolved components using temporal fine structure information. *J Acoust Soc Am*, 125, 3214–3222.

Moore B.C.J., Huss M., Vickers D.A., Glasberg B.R. & Alcántara J.I. 2000. A test for the diagnosis of dead regions in the cochlea. *Br J Audiol*, 34, 205–224.

Moore B.C.J. & Sek A. 2009. Development of a fast method for determining sensitivity to temporal fine structure. *Int J Audiol*, 48, 161–171.

Moore G.A. & Moore B.C.J. 2003. Perception of the low pitch of frequency-shifted complexes. *J Acoust Soc Am*, 113, 977–985.

Neher T., Lunner T., Hopkins K. & Moore B.C.J. 2012. Binaural temporal fine structure sensitivity, cognitive function, and spatial speech recognition of hearing-impaired listeners. *J Acoust Soc Am*, 131, 2561–2564.

Nilsson R. & Liden G. 1976. Sound localization with phase audiometry. *Acta Otolaryngol*, 81, 291–299.

Pichora-Fuller M.K. & Schneider B.A. 1991. Masking-level differences in the elderly: A comparison of antiphasic and time-delay dichotic conditions. *J Speech Hear Res*, 34, 1410–1422.

Pichora-Fuller M.K. & Schneider B.A. 1992. The effect of interaural delay of the masker on masking-level differences in young and old subjects. *J Acoust Soc Am*, 91, 2129–2135.

Rosenhall U. 1992. Phase audiometry in neuroaudiological practice. *Acta Otolaryngol*, 112, 429–434.

Ross B., Fujioka T., Tremblay K.L. & Picton T.W. 2007. Aging in binaural hearing begins in mid-life: Evidence from cortical auditory-evoked responses to changes in interaural phase. *J Neurosci*, 27, 11172–11178.

Schneider B.A., Pichora-Fuller M.K., Kowalchuk D. & Lamb M. 1994. Gap detection and the precedence effect in young and old adults. *J Acoust Soc Am*, 95, 980–991.

Schouten J.F., Ritsma R.J. & Cardozo B.L. 1962. Pitch of the residue. *J Acoust Soc Am*, 34, 1418–1424.

Strouse A., Ashmead D.H., Ohde R.N. & Grantham D.W. 1998. Temporal processing in the aging auditory system. *J Acoust Soc Am*, 104, 2385–2399.

van Rooij J.C.G.M. & Plomp R. 1990. Auditive and cognitive factors in speech perception by elderly listeners, II: Multivariate analyses. *J Acoust Soc Am*, 88, 2611–2624.

van Rooij J.C.G.M. & Plomp R. 1992. Auditive and cognitive factors in speech perception by elderly listeners, III. Additional data and final discussion. *J Acoust Soc Am*, 91, 1028–1033.

White L.J. & Plack C.J. 2003. Factors affecting the duration effect in pitch perception for unresolved complex tones. *J Acoust Soc Am*, 114, 3309–3316.