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Measuring Binaural Temporal-Fine-Structure Sensitivity in Hearing-Impaired Listeners, Using the TFS-AF Test

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Abstract

Background: Various methods have been used to measure temporal-fine-structure (TFS) sensitivity in hearing-impaired (HI) listeners. A new method called TFS-adaptive frequency (TFS-AF) test, tracks the highest frequency up to which a person can detect a given interaural phase difference (IPD) in bursts of pure tones. So far, the test was only administered to listeners with normal hearing (NH) or impaired low-frequency hearing. It is currently not known if this test can also be used for listeners with different configurations of hearing losses.

Purpose: To investigate whether the TFS-AF test can also be used on listeners with a larger diversity of hearing losses and what would be the best fixed IPD value to conduct the test.

Research Design: Using a cross-sectional study design, we compared the thresholds of TFS-AF test between the NH and HI listeners at three different IPDs (90°, 60°, and 30°).

Study sample: Thirty NH (mean age = 37.9; range 19–53 years) and thirty HI (mean age = 38.6; range 19–53 years) with different configurations of hearing losses were tested.

Results: The listeners were able to complete the TFS-AF test at larger values of IPD. Average thresholds were lower (i.e., worse) in the HI listeners than in the NH listeners. Threshold did not correlate with the listeners' age in each group.

Conclusion: This test can be used clinically as it provides a graded measure of TFS ability for young to young-old adult listeners with a variety of hearing losses.

Key Words: hearing impaired, temporal-fine-structure processing

Abbreviations: HI = hearing impaired; IPD = interaural phase difference; NH = normal hearing; TFS = temporal fine structure; TFS-AF = temporal-fine-structure–adaptive frequency; SD = standard deviation

INTRODUCTION

The auditory system uses multiple cues to interpret complex acoustic signals. These cues are related to the spectral and temporal aspects of the acoustic signals. The input acoustic signals are filtered into narrow frequency bands by the basilar membrane and transmitted to the auditory nerve. These signals can be considered as a slowly varying temporal envelope superimposed on a rapidly varying temporal fine structure (TFS) (Moore, 2014). TFS information is coded via neural firing to the individual cycles of the TFS. Therefore, phase locking of the action potentials induced by the hair cell is vital in the coding of TFS information (Heil and Peterson, 2015). The phase locking ability of the auditory system becomes weaker for frequencies higher than 4000–5000 Hz (Verschooten and Joris, 2014). Over the last decades, numerous studies have pointed out the importance of TFS cues to sound localization, pitch perception, and spatial separation

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between signal and interfering sounds (Glasberg and Moore, 1990; Smith et al, 2002; Hopkins and Moore, 2009). Perception of the pitch is essential for appreciating music and speech. The perceptions of speech in the presence of interfering sounds are challenging to both normal hearing (NH) and hearing-impaired (HI) listeners. Several studies have investigated the role of TFS cues in the understanding of speech in the presence of background noises in young NH, older NH, and HI listeners with hearing aids. Altogether, the results show that the ability to process TFS information is important in the perception of speech in adverse listening conditions (Strelcyk and Dau, 2009; Füllgrabe et al, 2015; Oberfeld and Klockner-Nowotny, 2016; Lopez-Poveda et al, 2017). Another critical role of TFS cues is to facilitate dip listening. The effective use of TFS cues occurs in situations where the phase locking is precise, and the signal and masker are within the same frequency range (Füllgrabe et al, 2015). Recent studies have shown that the patients with cochlear hearing loss have diminished processing of TFS cues (Hopkins and Moore, 2010; King et al, 2014; Vercammen et al, 2018; for meta-analysis, see Füllgrabe and Moore [2018]). The ability to process TFS information may also be affected by age even in the absence of hearing loss (Füllgrabe et al, 2015). Hence, the understanding of individual differences in the ability to process TFS information might be useful for the selection of signal processing strategies in hearing aids (for a discussion of possible reasons for this can be found in Füllgrabe et al, 2018). There are tests such as masking level difference and frequency discrimination tasks that are available for measuring TFS sensitivity. These tests partially depend on envelope cues also. Moreover, the contribution of the cues varies on the severity of the hearing loss (Mao et al, 2015). Also, data related to the effects of practice and variability across runs is not available. However, these tests are not being used clinically. A clinical test for measuring TFS processing should be fast and easy to administer, score, and perform by all listeners with different ages and degrees of hearing impairment. Füllgrabe and colleagues (Füllgrabe et al, 2017; Füllgrabe and Moore, 2017) evaluated a new method to assess binaural TFS sensitivity, the TFS-adaptive frequency (TFS-AF) test, on young NH listeners and older listeners with low-frequency hearing loss and a variety of hearing losses at higher frequencies. They measured the threshold for detecting the changes in the interaural phase difference (IPD) as a function of frequency. The procedure tracks the highest frequency up to which a person is able to detect a given IPD (e.g., 180°). They evaluated the changes in TFS sensitivity with different phase angles (30°, 45°, 90°, and 135°) in older NH participants. The results showed a reduction (worse) in the threshold for phase angles below 90°. There was no significant difference observed in thresholds when the phase angle was varying between 90° and 180°. They also divided the tests in to three sessions and administered at different days on older NH listeners to check whether the scores are affected by fatigue, loss of interest, or lack of motivation. However, there was no difference in scores. The absence of practice effect is one of the key advantages of the TFS-AF test. Because of the ease of administration and interpretation, this test has an excellent application in assessing TFS and can be incorporated into routine evaluations. In a recently published article by Füllgrabe et al (2018), a large group of older (≥60 years) listeners with normal or near-normal low-frequency hearing but various degrees of high-frequency loss was assessed using the TFS-AF test, adding to the smaller datasets published in Füllgrabe et al (2017) and Füllgrabe and Moore (2017). All the listeners were able to complete the task, and a run was accepted only if the standard deviation (SD) of the last six reversals was ≤0.2. There is a need to explore this test in HI listeners with different sloping high-frequency hearing losses, including elevated thresholds in the low-frequency range.

METHOD

Informed consent was obtained from all the listeners before the study participation. This study was carried out with the approval of the Ethics Committee of the hospital.

Participants

The study was conducted in a hospital located in the southern part of India. The participants (NH and HI) were recruited from the otolaryngology department, Jawaharlal Institute of Postgraduate Medical Education and Research, India. The study participants were divided into two groups. Group 1 consisted of 30 adults (22 males; 8 females) with sensorineural hearing loss. The age of the participants ranged from 19 to 53 years (mean = 38.6; SD = ±9.0 years). Air conduction and bone conduction thresholds were obtained for all listeners. All the listeners in this group had bilateral sensorineural hearing loss and a pure-tone average of 250, 500, 1000, 2000, and 4000 Hz <80 dB HL. The audiogram configuration consisted of flat, low-frequency, and sloping hearing losses of various degrees. Table 1 depicts the thresholds and configuration of hearing losses of the listeners with HI. Group 2 consisted of 30 healthy adult (NH) listeners (22 males; eight females) with the age range between 19 and 53 years (mean = 37.9; SD = ±9.6 years). The NH listeners had audiometric thresholds ≤20 dB HL at octave frequencies from 250 to 8000 Hz in each ear.

Stimulus and Recording Parameters

All the procedures were carried out in a sound-treated room as per the ANSI Standard S3.1-1999 (ANSI,

Table 1. Age, Gender, and Hearing Thresholds of HI Listeners

HI Listeners	Age (years)/ Gender	250 AC	500 AC	1000 AC	2000 AC	4000 AC	8000 AC	250 BC	500 BC	1000 BC	2000 BC	4000 BC	Pure-Tone Average	Configuration
HI 1	19/M	25/30	45/40	70/70	70/70	75/50	70/55	25	40	65	70	50	65/57.5	R-sharply sloping, L-trough
HI 2	21/M	25/30	35/45	60/60	65/80	95/90	95/95	20	35	60	60/75	75NR	63.75/68.75	B/L sharply sloping
HI 3	23/M	10/5	35/25	60/60	95/85	120/105	100/85	5	25	60	80	75NR	77.5/68.75	B/L sharply sloping
HI 4	30/M	35/35	50/50	70/70	75/75	75/70	60/60	20	45	65	70	60	67.5/66.25	B/L sloping
HI 5	31/F	40/45	45/55	55/60	60/65	60/60	55/65	35	45	55	60	50	55/60	B/L flat
HI 6	31/M	45/55	50/55	60/65	75/70	80/75	80/80	35	50	55	70	65	66.2/ 66.2+5	B/L flat
HI 7	31/M	35/30	45/40	45/55	40/45	35/40	20/25	25	40	45	40	30	41.25/45	B/L flat
HI 8	32/F	25/20	30/35	45/40	55/50	30/40	25/20	20	25	40	50	20	40/41.25	B/L flat
HI 9	34/M	15/10	15/15	25/15	55/25	85/60	75/70	5	10	15	55/20	75/50	45/28.75	B/L precipitously sloping
HI 10	34/M	35/40	45/40	50/50	55/55	55/65	55/65	30	40	50	55	55	51.25/52.5	B/L flat
HI 11	35/F	20/15	20/20	30/25	30/25	35/35	30/30	15	20	25	25	30	28.75/26.25	B/L flat
HI 12	35/F	10/15	10/15	20/25	30/30	35/35	20/20	10	10	20	30	35	23.75/26.25	B/L flat
HI 13	36/M	45/40	45/45	40/45	45/45	50/50	50/60	35	45	40	45	40	45/46.25	B/L flat
HI 14	37/F	10/10	15/20	45/50	60/60	65/70	35/70	10	15	40	55	55	46.25/50	B/L precipitously sloping
HI 15	40/M	45/40	45/50	50/55	60/55	65/60	65/60	35	40	50	55	50	55/55	B/L flat
HI 16	40/F	25/20	45/40	50/45	55/50	65/65	65/65	20	35	40	50	55	53.75/50	B/L gradually sloping
HI 17	40/F	15/15	25/20	25/25	35/30	30/30	20/20	15	20	25	30	25	28.75/26.25	B/L flat
HI 18	41/M	10/20	20/40	35/40	40/45	70/65	60/20	10	20	35	40	55	41.25/47.5	B/L gradually sloping
HI 19	41/M	10/10	20/20	25/25	30/25	70/55	65/85	0	15	25	25	50	36.25/31.25	B/L precipitous sloping
HI 20	43/M	10/10	20/25	30/25	45/40	80/70	70/60	10	20	25	40	70	43.75/40	B/L precipitous sloping
HI 21	43/M	35/25	35/25	40/25	60/15	75/45	100/50	20/25	35/20	35/25	60/10	65/30	52.5/27.5	B/L gradually sloping
HI 22	47/M	10/5	20/15	15/20	10/10	70/80	95/90	5	10	15	10	60	28.75/31.25	B/L precipitously sloping
HI 23	47/M	35/20	35/20	45/30	40/35	50/40	50/55	20/30	35/20	40/30	35	40	42.5/31.25	B/L flat
HI 24	48/M	25/30	40/45	60/50	70/65	80/85	75/70	25	40	50	65	70	62.5/61.25	B/L sharply sloping
HI 25	48/M	5/10	10/25	15/25	20/25	70/40	85/45	0	10	15	20	35	28.75/28.75	B/L precipitously sloping
HI 26	48/M	10/15	15/20	15/15	65/60	90/95	100/95	5	10	15	55	75	46.25/47.5	B/L precipitously sloping
HI 27	49/M	20/20	35/30	45/40	45/45	75/45	80/70	10	25	40	45	40	50/40	B/L sharply sloping
HI 28	50/M	20/30	20/25	35/25	35/25	85/100	100/100	15	20	25	25	70	43.75/43.75	B/L precipitously sloping
HI 29	52/F	10/0	25/15	30/30	50/35	70/55	85/80	0	15	30	35	45	43.75/33.75	B/L sharply sloping
HI 30	53/M	25/25	25/25	30/20	40/25	50/35	40/35	15	25	20	25	30	36.25/26.25	B/L flat FF, L-flat
HI_{Mean}	38.6	20/19.8	29.6/29.8	40.3/38.8	50.1/45.3	68/61.6	64.5/60.5						47.1/43.9	

Note: Configuration based on Lloyd and Kaplan (1978).

Table 2. Comparison of TFS-AF Thresholds in Different IPD Conditions between HI and NH Listeners

IPD Condition	Hearing Group	N	Median (Min, Max; Hz)	*P* Value
90	NH	30	1187.1 (693.2, 1579.4)	<0.01
	HI	30	677.8 (64.4, 1694)	
60	NH	30	1071.55 (548.8, 2236)	<0.01
	HI	30	718.6 (65.6, 1331)	
30	NH	30	682.5 (182.7, 1618.1)	<0.01
	HI	30	245.8 (36.4, 1284.7)	

Note: Max = maximum; Min = minimum; N = number of participants; *p* = statistical significance for one-tailed tests.

R2013). Pure-tone audiometry was performed using an Inventis Piano audiometer and supra-aural TDH 39 headphones. Binaural TFS sensitivity was assessed using the TFS-AF test (retrieved from http://hearing.psychol.cam.ac.uk/), run on a laptop computer with an internal sound card (Realtek High Definition Audio). Stimuli were presented via calibrated Sennheiser HD 202 headphones.

Procedure

Hearing sensitivity was measured for all the listeners at the octave frequencies from 250 to 8000 Hz. Then, the TFS-AF test was administered. The stimulus was delivered to both ears at the 30-dB SL. The testing paradigm used a two-interval, two-alternative forced choice procedure. Each trial was composed of two consecutive intervals, separated by 500 msec. Each interval was composed of four consecutive pure tones of the same frequency, separated by 100 msec. Each tone was 400 msec long (including 20-msec raised cosine rise/fall ramps). In one interval, chosen at random, all tones had the same phase (i.e., IPD = 0°), whereas in another interval, the 1st and 3rd tones also had an IPD of 0° but the 2nd and 4th had an IPD that was not 0°. In a previous study carried out by Füllgrabe and Moore (2017), they found that TFS-AF thresholds changed slightly from phase angles varied between 90° and 180° and thresholds markedly decreased (worsened) between 90° and 0° phase angles. In the present study, thresholds were measured at three IPD conditions (30°, 60°, and 90°). The test began at 200 Hz, and the frequency increased and decreased in response to correct and incorrect responses, respectively. When IPD was zero, those participants having good sensitivity to TFS perceived the tones as emanating from the center of the head, and tones that had a non-zero IPD as lateralized within the head toward one ear or the other. The listener's task was to identify the interval in which the tones were moving. Boxes represented the interval on the screen which was labeled as one and two. The feedback was given after each interval by green light for correct responses and red light for incorrect responses. The 71% correct score on psychometric function was computed using an adaptive two-up, one-down stepping rule. The frequency was changing by a factor of 1.4 until the first reversal, then by a factor of 1.2 for the next reversal, and 1.1 after that. For each condition, two to three threshold estimates per run were performed, and the test stopped after eight reversals. The final threshold value of frequency was displayed on the screen depending on the geometric mean of last six reversal value.

RESULTS

The statistical analysis was carried out by using the software SPSS version 22 (IBM Corp., Armonk, NY). One sample Kolmogorov–Smirnov test was used to check for normality of the distributions. The median value of the TFS-AF threshold in Hertz between the two groups as a function of three different phase angles is represented in Table 2. For the HI listeners, the median TFS-AF threshold was 677.85, 718.6, and 245.8 Hz for an IPD of 90°, 60°, and 30°, respectively. For the NH listeners, the median TFS-AF threshold was 1187.1, 1071.55, and 682.5 Hz for an IPD of 90°, 60°, and 30°, respectively. The difference in the median TFS-AF threshold was 509.25, 352.95, and 436.7 Hz

Table 3. Linear Relationship of TFS-AF Threshold and Different IPD Conditions in HI and NH Listeners

IPD Condition	Hearing Group	N	*r*; *p* Value
90	NH	30	−0.011; 0.954
	HI	30	−0.084; 0.659
60	NH	30	−0.157; 0.408
	HI	30	−0.090; 0.635
30	NH	30	0.091; 0.632
	HI	30	−0.297; 0.111

Note: *p* = statistical significance for one-tailed tests; *r* = correlation coefficient.

for an IPD of 90°, 60°, and 30°, respectively. The median value of the TFS-AF thresholds was lower for the HI group than that for the NH listeners. The lowest thresholds observed in the HI group were 64.4, 65.6, and 36.4 Hz for an IPD of 90°, 60°, and 30°, respectively. A Mann–Whitney test was used to compare median TFS-AF thresholds for the two groups in each IPD condition (all $p < 0.01$). In both groups, there was a decline in threshold with decreasing IPD. Spearman's correlation coefficient was used for the analysis of the linear relationship of TFS-AF thresholds at different phase angles and age in HI listeners and NH listeners (Table 3). The TFS-AF thresholds were decreasing with increasing age at 90°, 60°, and 30° phase angles. However, this reduction in thresholds was not statistically significant.

DISCUSSION

Processing of TFS information plays a role in the separation of target from interfering sounds (Stone et al, 2011). Changes in the TFS information may not affect the speech perception in quiet, but this information is crucial in understanding the speech in background noise (Füllgrabe et al, 2015). In the present study, sensitivity to the binaural processing of TFS was measured for young-to-middle–aged HI and NH listeners. The mean age was 37.9 years for the NH group and 38.6 years for the HI group. The results of the present study showed that TFS-AF thresholds of the HI group were lower than that of the NH listeners. There was also a reduction in the threshold for TFS-AF with decreasing phase angles as already shown by Füllgrabe and colleagues (Füllgrabe et al, 2017; Füllgrabe and Moore, 2017). Similar findings have been reported in the literature using similar tests to measure TFS processing in HI listeners (Neher et al, 2012; King et al, 2014). The present study findings are consistent with the findings of Füllgrabe et al (2017); they used the TFS-AF test for measuring TFS in older HI listeners. There are many factors that can contribute to the poor performance of HI listeners in TFS-AF task. One of the factors can be changes in the basilar membrane properties. The impaired cochlea leads to the broadening of the tuning curve of the basilar membrane and shifts the responses of the basilar membrane to complex signals such as speech. The impaired TFS information from the basilar membrane leads to the deficient coding of fine structure information by the nerve (Moore, 2014). The study also examined the effect of age on the processing of TFS information. In their study, Füllgrabe and Moore (2017) observed a significant reduction in TFS-AF threshold with increasing age. The age range of the listeners in their study was 63 to 83 years, with a mean age of 71.5 years. The finding by Füllgrabe and Moore (2017) has recently been confirmed by Füllgrabe et al (2018) (for a meta-analysis of the effects of age and hearing loss, see Füllgrabe and Moore, 2018). In our study, in most conditions (IPD and group), there is almost no change in sensitivity with age. This finding can be supported by the fact that the decline in TFS processing might only start after middle age (Füllgrabe and Moore, 2018).

CONCLUSION

The present study investigated the binaural TFS processing in HI listeners and compared the result with that of NH listeners. TFS-AF is a recently developed test by Füllgrabe and colleagues (Füllgrabe and Moore, 2017; Füllgrabe et al, 2017) for assessing TFS processing. The study evaluated the TFS processing in HI listeners with different configurations of hearing losses. Both HI and NH listeners were able to perform the task. There was a reduction in TFS thresholds in HI listeners compared with the NH counterparts. A decline in performance was noted while decreasing the phase angle despite both groups not differing in age. For each listener, approximately 15 min was sufficient for completing the task. The task was simple and not demanding a high cognitive load. This test provides a graded measure of TFS ability. This test can be used clinically for young to young-old adult listeners with a variety of hearing losses.

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