The effects of age and hearing loss on interaural phase difference discrimination[a)]

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The discrimination of interaural phase differences (IPDs) requires accurate binaural temporal processing and has been used as a measure of sensitivity to temporal envelope and temporal fine structure (TFS). Previous studies found that TFS-IPD discrimination declined with age and with sensorineural hearing loss (SNHL), but age and SNHL have often been confounded. The aim of this study was to determine the independent contributions of age and SNHL to TFS and envelope IPD discrimination by using a sample of adults with a wide range of ages and SNHL. A two-interval, two-alternative forced-choice procedure was used to measure IPD discrimination thresholds for 20-Hz amplitude-modulated tones with carrier frequencies of 250 or 500 Hz when the IPD was in either the stimulus envelope or TFS. There were positive correlations between absolute thresholds and TFS-IPD thresholds, but not envelope-IPD thresholds, when age was accounted for. This supports the idea that SNHL affects TFS processing independently to age. Age was positively correlated with envelope-IPD thresholds at both carrier frequencies and TFS-IPD thresholds at 500 Hz, when absolute thresholds were accounted for. These results suggest that age negatively affects the binaural processing of envelope and TFS at some frequencies independently of SNHL. © *2014 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4838995]

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I. INTRODUCTION

The auditory system can discriminate interaural time differences (ITDs) in the arrival of sounds (Klump and Eady, 1956) or interaural phase differences (IPDs) if the sounds are periodic and on-going (Zwislocki and Feldman, 1956). These cues are used for lateralization and localization (Wightman and Kistler, 1992). Discrimination of ITDs or IPDs has been used as a way of measuring temporal coding ability, because the coding of these cues relies on the accurate synchronization of neural activity to the stimulus waveform (Jeffress, 1948). For low frequency sounds, auditory nerve fibers are most likely to fire at a particular phase of basilar membrane (BM) motion (Tasaki, 1954; Palmer and Russell, 1986), a phenomenon known as phase locking (Rose *et al.*, 1967). Phase locking codes time intervals between corresponding peaks in the pass-band filtered output from the BM, which represent the temporal fine structure (TFS) of the sound. TFS coding is thought to contribute to accurate pitch discrimination (Moore *et al.*, 2006), speech perception (Young and Sachs, 1979) and perceptual segregation of target sounds, such as speech, from complex background sounds (Hopkins and Moore, 2009; Moore, 2012).

Sensorineural hearing loss (SNHL) is associated with poorer performance on tasks that are thought to provide behavioral measures of TFS coding (e.g., Buss *et al.*, 2004; Lacher-Fougère and Demany, 2005; Hopkins and Moore, 2007; Strelcyk and Dau, 2009; Hopkins and Moore, 2011). Early studies (Hawkins and Wightman, 1980; Buus *et al.*, 1984; Smoski and Trahiotis, 1986) found that listeners with SNHL were poorer at lateralization based on ITDs than listeners with normal hearing (NH). However, these ITDs were implemented by delaying the whole waveform to one ear, so deficits may have arisen due to impaired coding of either TFS or slower fluctuations in amplitude caused by the interaction of TFS components (commonly referred to as the envelope) or both. Later research investigated sensitivity to envelope and TFS IPDs separately using amplitude modulated (AM) tones (Lacher-Fougère and Demany, 2005) and sensitivity to TFS-IPDs exclusively using pure tones (Hopkins and Moore, 2011).

Both Lacher-Fougère and Demany (2005) and Hopkins and Moore (2011) reported better TFS-IPD sensitivity for NH listeners than for those with SNHL. Hopkins and Moore (2011) found that the TFS-IPD thresholds of SNHL listeners were between 1.5 and 2 times those of NH listeners, while Lacher-Fougère and Demany (2005) found a 6.5- to 19.7-fold deficit for SNHL listeners. Lacher-Fougère and Demany (2005) found that envelope-IPD thresholds were also greater for SNHL listeners than for NH listeners, but only by 2.9- to 4-fold. Lacher-Fougère and Demany (2005) interpreted the larger deficit in TFS-IPD thresholds than envelope-IPD thresholds as evidence that SNHL specifically affects TFS processing. Lacher-Fougère and Demany (2005) used the same sound pressure level (SPL) for all listeners, so the sensation levels (SL) of the stimuli would be lower for the SNHL listeners than the NH listeners. Buus *et al.* (1984) and Smoski and Trahiotis (1986) showed envelope ITD discrimination was affected by SL while pure-tone ITD discrimination was not, so Lacher-Fougère and Demany (2005) suggested the differing SL may have affected the SNHL listeners' envelope-IPD thresholds more than their TFS-IPD thresholds.

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The deficit in TFS-IPD sensitivity for SNHL listeners reported by Lacher-Fougère and Demany (2005) and Hopkins and Moore (2011) may be partly explained by the higher mean ages in the SNHL listener groups than the NH listener groups. The age ranges were 24 to 45 yr for NH listeners and 42 to 68 yr for SNHL listeners in the study of Lacher-Fougère and Demany (2005), and 20 to 35 yr for NH listeners and 29 to 82 (mean = 62.8) for SNHL listeners in the study of Hopkins and Moore (2011). Age is associated with a decrease in the highest carrier-tone frequency (f_c) at which a 180° IPD in the TFS of binaurally presented AM tones is detectable by listeners with minimal hearing loss (Ross *et al.*, 2007; Grose and Mamo, 2010). Ross *et al.* (2007) suggested that their results were due to a loss of neural synchrony with age, which would degrade the precision of temporal coding. Consistent with this idea, low-frequency pure-tone IPD thresholds increase with age (Grose and Mamo, 2010; Moore *et al.*, 2012a; Moore *et al.*, 2012b) and performance on other measures of temporal coding also declines with age (e.g., Strouse *et al.*, 1998; Purcell *et al.*, 2004). In order to assess the effect of age on temporal coding, Hopkins and Moore (2011) included a second sample of NH listeners, with a similar mean age to the SNHL listeners. The age-matched NH group did not perform significantly differently to the SNHL listeners. While this showed that age can affect TFS IPD discrimination, it was not possible to assess the independent effects of age and hearing loss on IPD discrimination as age and hearing loss were highly correlated.

Hawkins and Wightman (1980) and Smoski and Trahiotis (1986) found poorer ITD sensitivity for SNHL and NH listener groups that were comparable in age. Hawkins and Wightman (1980) used NH and SNHL listeners with mean ages of 25 and 27 yr, respectively, and Smoski and Trahiotis (1986) used NH and SNHL listeners with mean ages of 24 and 36 yr respectively. However, Hawkins and Wightman (1980) only used three NH listeners and eight SNHL listeners and Smoski and Trahiotis (1986) only used two NH listeners and four SNHL listeners. There appears to be at least some non-age-related effect of SNHL on binaural TFS processing.

This paper reports the TFS- and envelope-IPD thresholds for listeners across a wide age range with normal hearing up to moderate SNHL. Partial correlations were used to assess the effects of age and SNHL independently by removing the variability associated with one variable when assessing the other. AM tones were used, like Lacher-Fougère and Demany (2005), to measure TFS and envelope IPD thresholds separately. However, equal SL across listeners was used rather than a fixed SPL to avoid level affecting IPD thresholds (Buus *et al.*, 1984; Smoski and Trahiotis, 1986).

II. METHODOLOGY

A. Listeners

Forty-six listeners were tested. Their ages ranged from 18 to 83 yr and they had either normal hearing or SNHL as confirmed by air- and bone-conduction pure-tone audiometry (AC- and BC-PTA, respectively), tested in accordance with the British Society of Audiology (2011) recommended procedure. Listeners with suspected conductive hearing loss, or asymmetry between ears greater than 15 dB below 1 kHz, were excluded. Table I lists the listeners by ascending age, with each listener's AC-PTA averaged from 2 to 8 kHz in dB hearing level (HL) (PTA_{HF}) given also. PTA_{HF} was used to estimate the influence of high-frequency hearing loss on IPD sensitivity. There was a significant positive correlation between age and PTA_{HF} ($r = 0.439$, $p = 0.002$).

B. Absolute thresholds

Absolute thresholds (ATs) in dB SPL were measured in order to set the level for the IPD discrimination task at 30 dB SL for each listener.

1. Stimuli

The stimuli were pure tones with a 200-ms steady state duration and 20-ms raised-cosine onset and offset ramps. Frequencies of 250 and 500 Hz were used, which corresponded to the f_c of the stimuli used in the IPD sensitivity test (see Sec. II D). ATs were determined separately for each ear.

2. Procedure

A three-interval, three-alternative forced-choice task was used with a two-down, one-up adaptive procedure. The step size was 4 dB until three turn points occurred and decreased to 2 dB for a subsequent eight turn points. The threshold corresponding to 71% correct (Levitt, 1971) was estimated as the arithmetic mean of the stimulus level at the last eight turn points. Two runs were completed for each ear at each frequency and the final threshold was taken to be the mean of the thresholds from these two runs. These mean thresholds are given in Table I. Listener's age and average AT over both $f_c = 250$ and 500 Hz were not significantly correlated ($r = 0.076$, $p = 0.615$). The average AT is plotted against age in Fig. 1.

C. Setting AM tone presentation level

Hopkins and Moore (2010) showed that pure-tone IPD discrimination was independent of level for levels of 30 dB SL or greater. However, for some listeners, presenting the AM tones at 30 dB SL in each ear resulted in a strongly left or right lateralized sound image. To obtain a stimulus level that resulted in a sound image positioned roughly in the center of the listener's head, participants were asked to compare AM tones at 30 dB SL at each ear (Equal SL) and at 30 dB above the average of the left and right AT at the f_c (Equal SPL). Whichever version of the stimulus the listener reported as sounding more centered between the ears was used for the IPD sensitivity test described in Sec. II D. The AM tones were played for 4 s to the listener for both level settings in a random order. Table I lists, at each f_c, whether Equal SL or Equal SPL was used for each listener.

D. IPD sensitivity test

1. Stimuli

Sensitivity to IPDs was measured using AM tones. Carrier tones of $f_c = 250$ Hz and 500 Hz were amplitude

TABLE I. The 46 listeners listed by their age. Absolute thresholds at 250 and 500 Hz (AT250 and AT500, respectively) and mean audiometric threshold between 2 and 8 kHz (PTAHF) are given for left (L) and right (R) ears. Preference for equal SL or equal SPL across ears in IPD stimulus presentation and which ear contained the positive starting phase in IPD discrimination are given for $f_c = 250$ Hz and $f_c = 500$ Hz.

		AT250 (dB SPL)		AT500 (dB SPL)		PTAHF (dB HL)		IPD stimulus presentation		Leading Ear	
Listener	Age (years)	L	R	L	R	L	R	250 Hz	500 Hz	250 Hz	500 Hz
1	18	44.0	41.8	41.1	35.1	46.7	43.3	SPL	SPL	R	R
2	20	15.9	13.3	6.1	10.9	6.7	8.8	SL	SPL	R	R
3	21	29.3	31.8	36.4	39.0	65.0	73.3	SL	SL	L	L
4	21	21.0	32.0	15.6	23.4	8.3	11.7	SL	SPL	L	L
5	21	20.0	17.5	10.4	12.1	−1.7	3.3	SL	SPL	R	R
6	22	19.6	14.6	16.6	9.1	5.0	5.0	SL	SL	R	R
7	23	10.0	14.1	5.8	1.0	8.3	6.7	SPL	SPL	L	R
8	23	16.6	9.9	5.4	3.5	10.0	5.0	SPL	SPL	R	R
9	25	25.4	25.5	28.0	28.6	30.0	23.3	SL	SL	L	L
10	25	14.9	13.5	12.1	10.8	0.0	1.7	SL	SPL	R	R
11	26	5.4	5.8	−1.3	2.6	6.7	5.0	SL	SL	L	L
12	27	6.8	9.6	0.4	3.3	20.0	10.0	SPL	SL	L	L
13	27	45.0	43.1	41.1	36.1	53.3	48.3	SPL	SPL	R	R
14	28	3.6	7.8	−1.4	3.1	3.3	41.3	SL	SL	L	L
15	28	18.6	18.4	14.0	6.9	16.7	5.0	SL	SL	R	R
16	31	36.4	39.4	55.4	55.4	63.3	65.0	SPL	SPL	R	R
17	31	7.1	9.0	6.3	5.3	3.3	1.7	SPL	SPL	L	L
18	38	73.0	71.1	68.3	63.9	46.7	45.0	SL	SPL	R	R
19	40	16.8	24.0	15.4	19.8	15.0	23.3	SPL	SPL	L	L
20	43	36.6	38.6	45.4	47.6	78.3	73.3	SPL	SL	L	L
21	45	13.4	11.9	1.9	1.8	−3.3	5.0	SL	SL	R	R
22	46	40.3	39.4	44.1	41.6	60.0	56.7	SL	SPL	R	R
23	48	39.4	41.5	40.3	37.3	65.0	66.7	SPL	SL	R	R
24	48	12.9	8.6	8.3	1.8	18.3	10.0	SL	SL	R	R
25	52	12.6	24.8	12.6	17.1	33.8	35.0	SL	SL	L	L
26	52	17.9	16.1	13.6	13.4	5.0	8.3	SPL	SL	R	R
27	56	21.6	21.4	13.8	17.9	33.8	28.3	SPL	SL	L	L
28	65	21.5	27.0	19.8	20.8	40.0	18.3	SPL	SPL	L	L
29	65	17.4	18.4	4.5	5.9	57.5	57.5	SL	SL	L	L
30	66	20.1	23.0	20.6	29.9	23.3	31.7	SL	SL	L	L
31	66	20.5	29.8	20.6	22.1	27.5	26.7	SPL	SL	L	L
32	67	12.6	15.3	15.1	14.6	45.0	25.0	SPL	SL	L	R
33	67	63.0	52.4	59.4	51.1	66.7	71.7	SL	SL	R	R
34	68	13.4	12.4	11.4	18.9	45.0	38.3	SL	SPL	R	R
35	69	21.4	21.1	11.6	11.9	36.7	21.7	SL	SL	R	L
36	69	16.0	12.1	12.9	8.3	53.8	27.5	SL	SL	R	R
37	71	7.0	10.3	−0.6	8.4	36.7	31.7	SPL	SPL	L	L
38	72	20.1	21.5	24.0	29.4	47.5	50.0	SPL	SPL	L	R
39	73	27.3	23.6	22.9	18.0	36.3	36.7	SPL	SL	R	R
40	74	14.6	17.1	15.6	17.8	36.7	38.3	SPL	SPL	L	L
41	76	20.4	22.9	20.5	22.9	13.3	16.7	SL	SL	L	L
42	80	14.8	16.5	10.8	10.1	35.0	28.8	SL	SL	L	R
43	81	35.5	36.8	35.8	33.6	61.7	66.7	SL	SL	L	R
44	82	18.5	23.6	8.9	14.6	56.7	53.3	SL	SL	L	L
45	82	62.5	62.0	56.6	56.3	71.7	75.0	SPL	SPL	L	L
46	83	20.1	17.5	19.5	10.4	58.8	55.0	SPL	SPL	R	R

modulated at 20 Hz. The IPD was created in either the TFS or the envelope by introducing a positive starting phase ($\delta°$) in the signal to one ear and a zero starting phase to the other ear. TFS and envelope IPDs are shown schematically in panels A and B of Fig. 2, respectively. Thus, there were four conditions: non-zero IPDs in the TFS at $f_c = 250$ Hz (TFS250), in the TFS at $f_c = 500$ Hz (TFS500), in the envelope at $f_c = 250$ Hz (Env250) and in the envelope at $f_c = 500$ Hz (Env500).

2. Procedure

IPD discrimination thresholds were measured four times for each condition using a procedure based on that described by Hopkins and Moore (2010). A two-interval,

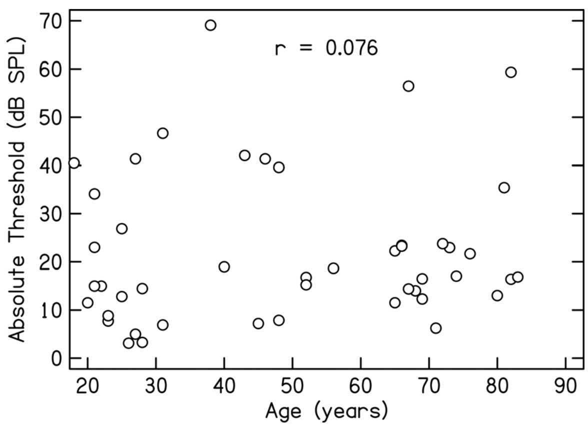

FIG. 1. Listeners' ATs (averaged across 250 and 500 Hz and ears) as a function of their age.

two-alternative forced-choice task was used, with each interval comprising four 500-ms tone bursts (which included 50-ms raised-cosine onset and offset ramps that were synchronous across ears). The tone bursts were separated by 20-ms of silence within each interval and 500-ms of silence between the two intervals. In one interval the four tones all had a zero IPD (AAAA), while in the other interval the second and fourth tones had a non-zero IPD (ABAB). The two intervals were randomly ordered, and listeners were instructed to pick the alternating interval. Panel C of Fig. 2 shows a schematic example of this when the ABAB interval is second. Listeners were advised to focus on lateral position alternation, but that they were free to use any perceptual cue to perform the task. Feedback was given by lights on a screen.

The target IPD ($\delta°$) was initially set to 180° and could not exceed this value. A geometric adaptive two-down, one-up procedure was used. The step size factor was 1.25^2 until three turn points occurred and 1.25 for eight subsequent turn points. The geometric mean of δ at the last eight turn points was taken as the IPD discrimination threshold. As δ was restricted to 180°, this algorithm would estimate a threshold even when performance was purely driven by chance. Therefore, if a listener failed to detect a δ of 180° at any point after the initial three turn points, the adaptive track stopped and 40 further trials with a fixed δ of 180° were presented. This happened 51 times out of 736 runs in total (15 out of 46 listeners). In these cases, a value of d′ was calculated from the percent correct score (Hacker and Ratcliff, 1979). The relation between IPD threshold in degrees and d′ has been shown to be linear (Hafter and Carrier, 1972), so an extrapolated threshold $\delta°$ was derived from the measured d′ and the d′ for 71% correct (0.78) by Eq. (1).

$$\delta(\text{extrapolated}) = \frac{(0.78 \times 180°)}{d'(40 \text{ trials with } \delta = 180°)}. \qquad (1)$$

E. Apparatus

All audio stimuli for absolute and IPD threshold measurement were created in MATLAB 7.6 (The MathWorks, 2008). Sounds were converted from digital to analog at a

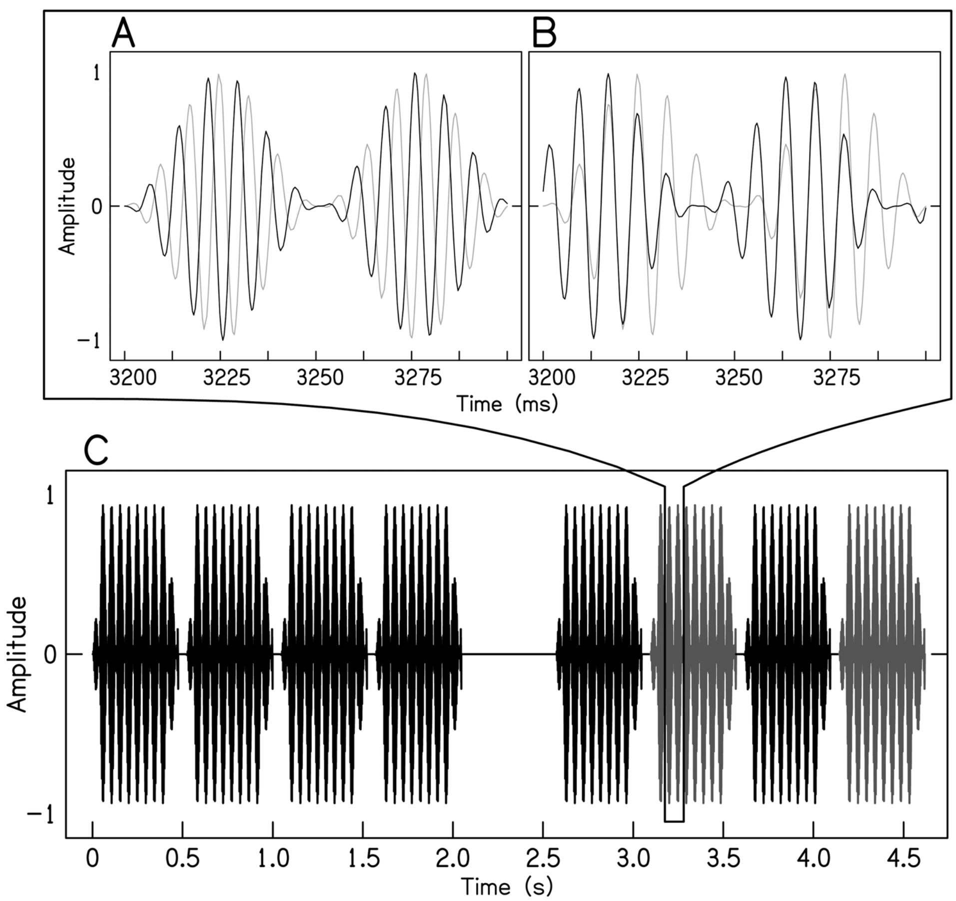

FIG. 2. A schematic diagram of the stimuli and the presentation paradigm. Panels A and B are magnified from Panel C to give an indication of relative time scales. Panel A shows the AM tones for each ear; one (in gray) had a starting phase of 90° in the TFS while the other started at 0°. Presented binaurally, these tones resulted in an IPD in the TFS only—note the synchronous envelopes. Panel B shows the reverse: the gray tone had a starting phase of 60° in the envelope only—note the synchronous zero crossings of the TFS. Panel C shows the presentation paradigm with the target interval (ABAB) second. The gray tone bursts contained the IPD while black tone bursts were diotic.

sample rate of 48 kHz and a 24-bit depth and amplified using a Creative E-MU 0202 USB soundcard. Sounds were played over Sennheiser HD 650 circum-aural headphones. Listeners sat in a double-walled listening booth and made responses via a computer keyboard. Audiometric thresholds were measured using VIASYS GSI-Arrow and Kamplex AC30 audiometers coupled to TDH39P supra-aural headphones and Radioear B-71 bone vibrators.

III. RESULTS

The geometric mean of the four repeated measurements of threshold discrimination was taken as the listener's threshold in each of the four IPD conditions. IPD thresholds are plotted as a function of AT in Fig. 3 and as a function of age in Fig. 4. Some thresholds are plotted as upward pointing arrows at 312°. These reflect performance below 62.5% correct in the constant stimuli method, which cannot be assumed (with 95% confidence) to be above chance. Although d′ would not, in reality, continue to increase for $\delta > 180°$, extrapolated thresholds below 312° probably indicate some ability to detect IPDs. Extrapolated thresholds were limited to 312° for analysis, but cases where extrapolated thresholds exceeded this value should be interpreted as indicating an inability to discriminate the IPDs in those conditions.

IPD thresholds were log-transformed before statistical analysis as this resulted in thresholds that were more normally distributed. Pearson's product–moment correlations (r) were calculated between the IPD thresholds and the listeners' ages with ATs at f_c partialed out, and between the IPD thresholds and the ATs at f_c with age partialed out. Finally, correlations were calculated between IPD thresholds and PTA_{HF}. These correlations and partial correlations are given in Table II. A sequentially rejective Bonferroni correction (Holm, 1979) was applied to the alpha criterion for each correlation to account for the increased familywise error rate due to testing the significance of 14 correlations (the 12 correlations described above and the correlations between age and PTA_{HF} and between age and AT). Only one hypothesis test was affected by this correction. The correlation between Env500 and AT was significant ($p < 0.05$) before correction, but not after ($p > 0.0063$).

With AT partialed out, age was significantly positively correlated with TFS500, Env250, and Env500, but not with TFS250. With age partialed out, AT was significantly positively correlated with TFS250 and TFS500. In contrast, the partial correlations between envelope-IPD thresholds and ATs (controlling for age) were weak and not significant after correction for multiple comparisons. No significant correlations were found between thresholds for the four IPD conditions and PTA_{HF}.

In order to determine whether TFS and envelope processing were affected differently by either age or AT, some of the partial correlations were compared to see whether they were significantly different from each other using Fisher's r to z-score transform. The difference between the z scores was divided by the standard error of the difference between the two z scores and evaluated against the t distribution with $n_1 + n_2 - 4$ degrees of freedom (where n_1 and n_2 equal the sample sizes in the two correlations). The significance of the difference between the age and TFS250 correlation and the age and TFS500 correlation was also tested using this technique. These comparisons were calculated in the

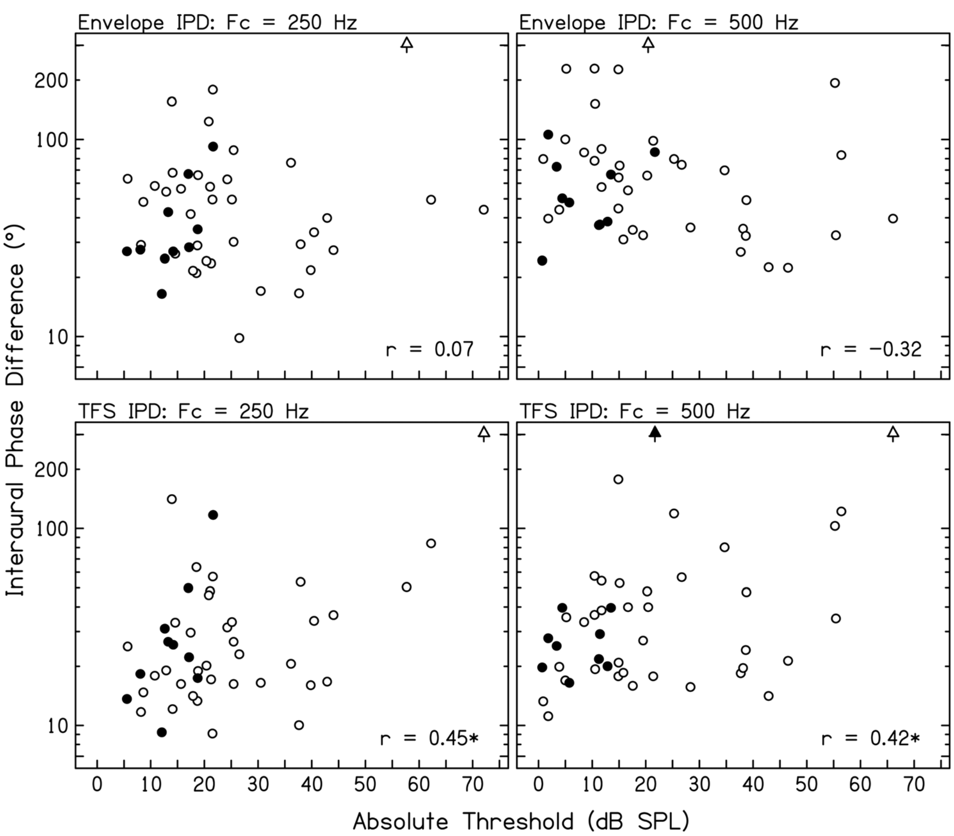

FIG. 3. IPD thresholds as a function of AT averaged across ears (dB SPL). Clinically normal hearing listeners' thresholds are plotted with filled symbols and clinically hearing impaired listeners' thresholds (at any audiometric frequency tested) with open symbols. Upward pointing arrow symbols indicate a case where no IPD threshold could be measured. The top two panels show envelope IPD thresholds and the bottom two show TFS IPD thresholds. Left and right panels show thresholds for $f_c = 250$-Hz and $f_c = 500$-Hz, respectively. Correlation coefficients with age partialed out are given in each panel. Correlations significant ($\alpha = 0.05$) after Holm–Bonferroni correction are shown by asterisks.

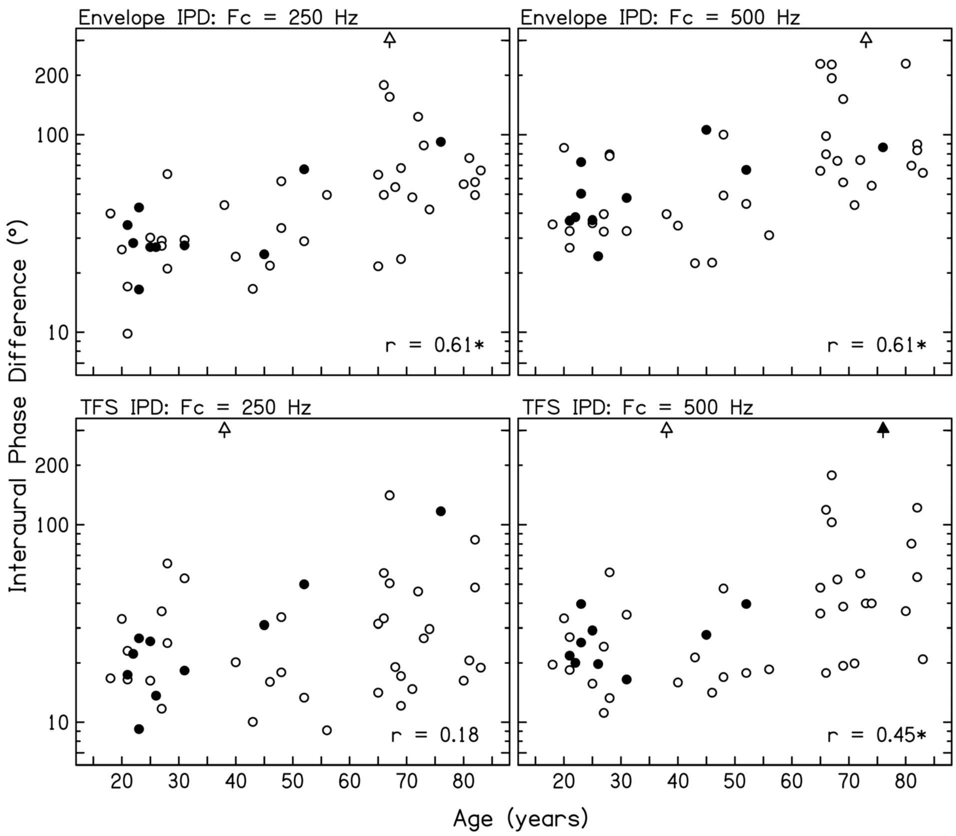

FIG. 4. IPD thresholds as a function of age. Clinically normal-hearing listeners' thresholds are plotted with filled symbols and clinically hearing impaired listeners' thresholds with open symbols. Upward pointing arrow symbols indicate a case where no IPD threshold could be measured. Panels are in the same order as in Fig. 3. Correlation coefficients with AT partialed out are given in each panel. Correlations significant ($\alpha = 0.05$) after Holm–Bonferroni correction are shown by asterisks.

software package Statistica 10 (StatSoft Inc., 2011). Again, a sequentially rejective Bonferroni correction (Holm, 1979) was applied to account for the five comparisons made. The results of these comparisons are given in Table III.

The difference between the partial correlation between AT and TFS500 and the partial correlation between AT and Env500 was significant ($p < 0.001$), but the difference between the partial correlations between TFS250 and Env250 and AT was not significant. The partial correlations between age and TFS500 and between age and Env500 were not significantly different from each other. The partial correlations between age and TFS250 and between age and Env250 were significantly different from each other before correction for multiple comparisons, but not after. The difference between the correlation between TFS500 and age and the correlation between TFS250 and age was also not significant.

IV. DISCUSSION

The results suggest that age and SNHL have negative, but independent, effects on TFS-IPD discrimination. Age was also associated with poorer envelope-IPD discrimination; in contrast, poorer envelope-IPD discrimination was not associated with increasing AT; instead, Env500 performance may have improved very slightly with increasing AT, although this may be a type I error, as the correlation was not significant following correction for multiple comparisons.

A. SNHL and IPD sensitivity

The significant positive correlation between AT and TFS-IPD thresholds supports the idea that SNHL involves a reduction in the quality of, or ability to use, phase-locked information related to TFS (Lacher-Fougère and Demany, 2005; Hopkins and Moore, 2011). The present findings suggest deficits in TFS processing with elevated ATs are independent of age-related changes in TFS processing. There are numerous reasons why this relationship may occur (Moore, 2008; Hopkins and Moore, 2011):

(1) A reduction in the number of auditory nerve fibers can occur after damage to the cochlea (Schuknecht and

TABLE II. The Pearson product–moment correlation coefficients (r) and the probability values (p) for the correlation or partial correlation between listeners' age, ATs and PTA_{HF} and each of the four IPD conditions. Asterisks indicate significant correlations after Holm–Bonferroni correction.

	TFS				Envelope			
	250 Hz		500 Hz		250 Hz		500 Hz	
	r	p	r	p	r	p	r	p
Age (AT partialed out)	0.183	0.228	0.452	0.002*	0.613	<0.001*	0.608	<0.001*
AT at f_c (age partialed out)	0.448	0.002*	0.415	0.005*	0.063	0.679	−0.315	0.035
PTA_{HF}	0.102	0.500	0.221	0.141	0.202	0.179	0.039	0.796

TABLE III. The probability values (p) for the tests of the difference between pairs of partial correlations (after Fisher's z transformation). Each p value refers to the comparison between the correlation on the same line and the correlation on the line above. Asterisks indicate significant correlations after Holm–Bonferroni correction.

Partial Correlation	r	p
Age–TFS250 (controlled for AT)	0.183	
Age–Env250 (controlled for AT)	0.613	0.016
Age–TFS500 (controlled for AT)	0.452	
Age–Env500 (controlled for AT)	0.608	0.314
AT–TFS250 (controlled for Age)	0.448	
AT– Env250 (controlled for Age)	0.063	0.055
AT–TFS500 (controlled for Age)	0.415	
AT– Env500 (controlled for Age)	−0.315	0.001*
Age–TFS500 (controlled for AT)	0.452	
Age– TFS250 (controlled for AT)	0.183	0.165

Woellner, 1955; Spoendlin, 1970), which may lead to reduced phase-locked information and consequently a degraded neural signal (Lopez-Poveda and Barrios, 2013).

(2) An abnormal phase response of the BM (Ruggero, 1994). An abnormal phase response may occur with loss of the nonlinear gain mechanism brought about by damage to the outer hair cells. This could affect comparisons of phase information across adjacent points along the BM that may be used to encode TFS information (Carney *et al.*, 2002).

(3) Changes to the central auditory system, such as a loss of inhibition, might disrupt the decoding of TFS (Moore, 2008).

It has also been suggested that the apparent TFS coding deficit for listeners with SNHL may arise because of the poorer frequency selectivity often associated with cochlear hearing loss. However the current study used stimuli containing only components that would fall within the equivalent rectangular bandwidth of a single normal auditory filter (Glasberg and Moore, 1990). Therefore, it seems unlikely that the relation between raised ATs and poor TFS-IPD thresholds can be explained by poor frequency selectivity.

While Hopkins and Moore (2011), Lacher-Fougère and Demany (2005), and Moore *et al.* (2012a) found listeners with SNHL were poorer than NH listeners at TFS-IPD discrimination, they found no strong evidence of correlation between AT and TFS-IPD threshold at test frequencies of 500 Hz and lower. Hopkins and Moore (2011) and Moore *et al.* (2012a) used pure tones, which, unlike the AM tones used in the current study, would not provide conflicting interaural envelope and TFS cues of a zero and non-zero IPD, respectively. The conflicting cues may impede TFS-IPD discrimination by those with elevated ATs as envelope cues may become dominant over TFS cues with noise-induced hearing loss (Kale and Heinz, 2010). However, Lacher-Fougère and Demany (2005) also did not find a correlation between AT and TFS500 thresholds with stimuli that were similar to those used in the current study (except in level). Rather than due to stimuli, the inconsistency in observed relationship between AT and TFS-IPD thresholds may be due to differences in the nature of the SNHL of the listeners, the extent to which age and AT were correlated or the sample sizes in the different studies.

Reduced sensitivity to TFS IPDs may have important consequences for people with SNHL when they are listening in noisy backgrounds. First, Moore and Glasberg (1987) showed that TFS information is useful for separating target sounds from fluctuating background noises. This appears to extend to more complex hearing abilities such as the intelligibility of speech in background noise (e.g., Füllgrabe *et al.*, 2006; Lorenzi *et al.*, 2006; Hopkins and Moore, 2009; Moore, 2012). Second, the TFS insensitivity observed with SNHL in the current study was demonstrated with IPDs, which are thought to be important for separating sounds from different azimuths (Bronkhorst and Plomp, 1988). Consistent with this, the benefit to speech intelligibility of separating target and masker sentences in azimuth declines with SNHL (Neher *et al.*, 2009) and with TFS-IPD thresholds (Neher *et al.*, 2011). However, Neher *et al.* (2012) found that this correlation was no longer significant when age was accounted for, suggesting that the benefit of azimuthal speech separation and TFS-IPD sensitivity may be affected by a common, age-related cause (Neher *et al.*, 2012).

Lacher-Fougère and Demany (2005) found a deficit in envelope-IPD thresholds for SNHL listeners and a positive correlation between AT and envelope-IPD thresholds. The current study found no deficit in envelope-IPD thresholds associated with ATs. While no significant correlation was found between AT and Env250, the negative correlation between AT and Env500 suggests a trend toward *better* Env500 performance with increasing hearing loss. SNHL listeners may perform better than NH listeners at equal SL because of loudness recruitment, which would effectively magnify perceived envelope fluctuations making them more salient (Moore *et al.*, 1996). However, the negative correlation was not significant when corrected for multiple comparisons. The deficit found by Lacher-Fougère and Demany (2005) may be due to the confound of SNHL and age within the listener groups. The listeners with SNHL in the study of Lacher-Fougère and Demany (2005) might have had poorer envelope IPD thresholds than the NH group because they had a higher mean age. The current study found positive correlations between envelope-IPD thresholds and age, but because listeners with a range of ages and ATs were tested, it was possible to assess the effect of AT at the f_c on envelope-IPD thresholds independently of the effect of age, avoiding this confound.

Lacher-Fougère and Demany (2005) did not view the deficit in envelope IPD thresholds with SNHL as a deficit in envelope processing *per se*, but as a result of NH listeners experiencing a higher SL than the SNHL listeners because stimuli were played at a fixed level (75 dB SPL) for both groups. Lacher-Fougère and Demany (2005) included a control experiment which supported this idea: With 35 dB SPL stimuli, or reduced SL due to the presence of white noise low-pass filtered at 1250 Hz, NH listeners performed worse at envelope-IPD discrimination, but not at TFS-IPD discrimination.

The different relationships of TFS500 and Env500 sensitivity with AT may be explained by a shift in the balance of TFS and envelope coding in ears with SNHL. Kale and Heinz (2010) provided physiological evidence that, rather than showing an absolute reduction in the precision of phase locking, individual nerve fibers phase lock more to stimulus envelope than to stimulus TFS after mild-to-moderate noise-induced hearing loss. The behavioral results in the present study may reflect a change in nerve fibers' phase locking from predominately following the TFS to predominantly following the envelope. Kale and Heinz (2010) suggested that improved envelope coding may not necessarily benefit SNHL listeners in fluctuating background noise as it may magnify the fluctuations perceptually. Increased fluctuation makes gaps in narrow-band noise more difficult to detect (Glasberg and Moore, 1992) and reduces speech intelligibility in fluctuating noise background noise (Moore and Glasberg, 1993).

B. Age and IPD sensitivity

Moderate positive correlations with AT partialed out were found between age and Env250, Env500, and TFS500, but TFS250 was not significantly correlated with age. The correlations of Env250, Env500, and TFS500 with age suggest that aging leads to a more general loss of temporal acuity than SNHL, whereas SNHL appears to result in loss of TFS sensitivity specifically. This general loss of temporal acuity with age may stem from changes in processing speed or accuracy in more central parts of the auditory system; parts where the coding of both the envelope and TFS coded signals are vulnerable. This is consistent with the suggestion by He *et al.* (2008) of a general age-related decline in synchronization of neural responses to both TFS and envelope. He *et al.* (2008) based this suggestion on age-related changes in AM detection as a function of modulation frequency and carrier frequency. Using electrophysiological measures, Ruggles *et al.* (2012) found that the strength of phase-locking to the envelope of the /dah/ syllable was poorer for middle-aged listeners compared to young adults, providing further evidence that age is associated with a decline in the fidelity of temporal coding. Previous research shows that an age-related decrease in the highest modulation rate to which a listener is sensitive (Purcell *et al.*, 2004). Age-related changes in AM detection, and auditory steady-state responses of the brainstem phase-locking to the envelope, are typically less pronounced at modulation rates below 40 Hz (Leigh-Paffenroth and Fowler, 2006; Grose *et al.*, 2009). However, the current study found age-related changes in envelope-IPD thresholds at 20 Hz, suggesting envelope coding can be affected by age even at low modulation rates.

Aging has been associated with reduced temporal resolution as measured by gap detection (Schneider *et al.*, 1994; Strouse *et al.*, 1998) and modulation detection (He *et al.*, 2008), as well as interaural phase discrimination (Grose and Mamo, 2010) and lateralization (Strouse *et al.*, 1998). Aging causes a complex collection of changes in the physiology of mammals, changes that are likely to result in a wide range of deficits in hearing. There are several likely age-related causes of degraded acuity of TFS and envelope coding:

(1) Degeneration of cochlear synapses and peripheral axons of spiral ganglion cells (Makary *et al.*, 2011; Sergeyenko *et al.*, 2013), which would lead to less phase-locked information over which to aggregate a temporal code.
(2) Imbalances in excitatory and inhibitory neural mechanisms may change envelope coding in the inferior colliculus (Walton *et al.*, 2002).
(3) Reduced synchrony in the transmission of phase-locked signals, which could weaken the strength of the phase locking (Clinard *et al.*, 2010; Marmel *et al.*, 2013).

However, other age-related changes, such as the functioning of neurotransmitter GABA in the inferior colliculus (Caspary *et al.*, 1995), could affect the auditory system in a variety of ways and interact with the other physiological phenomena listed above.

C. Age-related high-frequency SNHL and TFS processing

Age-related hearing loss is characterized by high-frequency rather than low-frequency hearing loss (Morrell *et al.*, 1996; Dubno *et al.*, 2013). While $\mathrm{PTA}_{\mathrm{HF}}$ was significantly positively correlated with age, it was not correlated significantly with any of the IPD thresholds. This is consistent with the findings of Moore *et al.* (2012a), who studied pure-tone IPD discrimination by elderly listeners with minimal hearing loss at low frequencies, but a range of hearing loss severities at higher frequencies. They found that high-frequency loss was only weakly correlated with pure-tone IPD discrimination and this correlation was not significant once the effect of age (which was strongly correlated with pure-tone IPD discrimination) was partialed out. This result contrasts with the results of Smoski and Trahiotis (1986) showing above-normal IPD discrimination thresholds for 500 Hz pure tones for listeners with moderate to severe high frequency hearing loss, but thresholds below 20 dB HL at 500 Hz. However, Smoski and Trahiotis (1986) only tested four listeners with this profile of hearing loss.

V. CONCLUSIONS

The results suggest both SNHL and age have independent relationships with IPD discrimination.

(1) The sensitivity to IPDs in the TFS of AM tones deteriorated with increasing low frequency SNHL.
(2) The correlations between envelope-IPD thresholds and SNHL were weak and non-significant.
(3) Both TFS- and envelope-IPD thresholds increased with age. Temporal processing may deteriorate in the auditory system such that both TFS and envelope processing are affected.

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