Auditory filter shapes and high-frequency hearing in adults who have impaired speech in noise performance despite clinically normal audiograms^{a)}

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Some individuals complain of hearing difficulties in the presence of background noise even in the absence of clinically significant hearing loss (obscure auditory dysfunction). Previous evidence suggests that these listeners have impaired frequency resolution, but there has been no thorough characterization of auditory filter shapes in this population. Here, the filter shapes of adults ($n = 14$) who self-reported speech recognition problems in noise and performed poorly on a sentence-in-noise perception test despite having clinically normal audiograms were compared to those of controls ($n = 10$). The filter shapes were evaluated using a 2-kHz probe with a fixed level of 30, 40, or 50 dB sound pressure level (SPL) and notched-noise simultaneous maskers that were varied in level to determine the masker level necessary to just mask the probe. The filters of the impaired group were significantly wider than those of controls at all probe levels owing to an unusual broadening of the upper slope of the filter. In addition, absolute thresholds were statistically indistinguishable between the groups at the standard audiometric frequencies, but were elevated in the impaired listeners at higher frequencies. These results strengthen the idea that this population has a variety of hearing deficits that go undetected by standard audiometry.

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I. INTRODUCTION

Some listeners have clinically normal audiograms, yet complain about difficulties understanding speech in the presence of background noise. This condition has received a variety of labels including auditory disability with normal hearing (King and Stephens, 1992), King–Kopetzky syndrome (Hinchcliffe, 1992), and—the term we will use—obscure auditory dysfunction (OAD; Saunders and Haggard, 1989). Though these individuals do not display any clinically significant hearing loss, they show deficits in several basic auditory abilities. These impairments include poorer than normal temporal resolution (Saunders and Haggard, 1989; Middelweerd *et al.*, 1990; Mahanes and Peters, 1991; Thibodeau, 1996; Strelcyk and Dau, 2009), poorer than normal frequency resolution (Pick and Evans, 1983; Narula and Mason, 1988; Mahanes and Peters, 1991; King and Stephens, 1992; Saunders and Haggard, 1992; Strelcyk and Dau 2009), and higher than normal absolute thresholds, sometimes in isolated frequency ranges (auditory notches), though these are sub-clinical at standard audiometric frequencies (King and Stephens, 1992; Zhao and Stephens, 2006; 1999; Shaw *et al.*, 1996). Of interest here are the frequency resolving abilities of this population. Previous investigators have demonstrated impaired frequency resolution for these listeners through

measures of a single characteristic, the auditory filter bandwidth, at a single stimulus level. The aim of the current investigation was to provide a more thorough characterization of frequency selectivity in these individuals. To do so, for these listeners as well as for controls, we derived auditory filter shapes at three probe levels from data obtained with a notched-noise method. Using this technique, we estimated and compared across groups not only the filter bandwidth, but also the upper and lower slopes and level dependence of the filter as well as the efficiency of the detection process following the filtering. In addition, to better characterize the listener populations, we measured absolute thresholds at discrete audiometric frequencies up to 14 kHz using methods designed to minimize calibration errors (Dreisbach and Siegel, 2001).

The importance of measuring the slopes and level dependence of filter shapes is apparent from previous evaluations of these parameters in listeners with sensorineural hearing loss. There is considerable evidence that the auditory filter bandwidths estimated through notched-noise techniques, such as the one used here, are wider than normal in listeners with sensorineural hearing loss (e.g., Tyler *et al.*, 1984; Glasberg and Moore, 1986; Leek and Summers, 1993; Moore *et al.*, 1999). However, these listeners also often show altered filter asymmetry. In normal-hearing listeners, auditory filters are generally asymmetric at high levels with the lower slope shallower than the upper one (e.g., Patterson and Nimmo-Smith, 1980; Tyler *et al.*, 1984; Glasberg and Moore, 1990; Leek and Summers, 1993; Wright, 1996). In the majority of hearing-impaired listeners, the filter asymmetry at high levels is more marked, with the upper slope similar to that of normal

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listeners, but the lower slope abnormally shallow (Tyler *et al.*, 1984; Glasberg and Moore, 1986; Leek and Summers, 1993). Thus, these listeners are unusually susceptible to upward spread of masking. A minority of hearing-impaired listeners show a reversed asymmetry, with the upper slope shallower than the lower one, and a corresponding greater-than-normal downward spread of masking (Carney and Nelson, 1983; Tyler *et al.*, 1984; Glasberg and Moore, 1986; Nelson, 1991). These two different patterns of filter asymmetry associated with sensorineural hearing loss suggest that the lower and upper slopes of auditory filters can be affected independently by the underlying pathology and thus that each slope can contribute separately to filter widening. Therefore, one question of interest is whether the wider auditory filters in individuals with OAD are due to widening on the lower, the upper, or both sides of the filter.

Examinations of hearing-impaired listeners have also demonstrated the importance of evaluating the influence of stimulus level on filter shapes. In normal ears, as the stimulus level increases behaviorally derived auditory filters become broader (e.g., Lutfi and Patterson, 1984; Rosen and Baker, 1994; Rosen *et al.*, 1998; Glasberg and Moore, 2000; Baker and Rosen, 2006). The filters of listeners with sensorineural hearing loss show a similar trend, but the degree of change is less than normal (e.g., Stelmachowicz *et al.*, 1987; Baker and Rosen, 2002). Thus, hearing pathology can manifest as abnormal level dependence. To the extent that abnormal frequency selectivity arises from dysfunction in the active cochlear mechanism, abnormalities in the influence of stimulus level on filter shape might be expected to be greatest at relatively low stimulus levels at which these active processes are most robust in normal hearing. Over this level range, changes in filter shape in normal hearing are most noticeable in measures of the peak gain of the filter (Rosen *et al.*, 1998; Glasberg and Moore, 2000). Therefore, another question of interest here is whether the wider auditory filters in individuals with OAD exhibit an abnormal level dependence, particularly in terms of filter gain, at relatively low probe levels [30–50 dB sound pressure level (SPL)].

We also note that the fitting procedure used to estimate auditory filter shape provides a measure of the efficiency of the detection process following the filtering, quantified as the signal-to-noise ratio (SNR) at the output of the filter that is necessary for signal detection at threshold (Patterson *et al.*, 1982). In some cases, the only difference between populations is in efficiency, indicating that a measure of efficiency can provide valuable information that distinguishes functioning between groups. For example, children have poorer efficiency than adults, though similar filter shapes (Olsho, 1985).

Finally, to identify any differences in hearing sensitivity between listeners with OAD and controls, we measured absolute thresholds at the discrete audiometric frequencies from 0.5 to 14 kHz using a Békésy tracking procedure. To minimize calibration errors, the thresholds were referenced to eardrum SPL using a probe tube microphone placed near the eardrum (see Dreisbach and Siegel, 2001). The value of measuring absolute hearing thresholds at extended high frequencies arises because there is some evidence that hearing loss in this frequency range is an early indicator of auditory

pathology (Osterhammel and Osterhammel, 1979; Dreschler *et al.*, 1985). There are two previous investigations of high-frequency hearing loss in individuals with OAD. In each case, high-frequency hearing thresholds were evaluated at four or more frequencies at and above 10 kHz. There was significantly poorer hearing at each of these frequencies in one investigation (Shaw *et al.*, 1996), but only at one frequency in the other (King and Stephens, 1992). The question was whether individuals with OAD have poorer absolute thresholds than controls over the extended audiometric frequency range under these more controlled testing circumstances.

II. METHODS

A. Listeners

Fourteen listeners with OAD (mean age: 28.5 yr; range: 20–50 yr) and ten controls (mean age: 26.4 yr; age range: 18–47 yr) participated in the experiment. The listeners with OAD, referred to as the impaired listeners, were labeled so based on their self-reported difficulties in understanding speech in noise and their performance in a sentence-in-noise perception test (see below). Two additional listeners who self-reported difficulties in understanding speech in noise did not show a deficit in the sentence-in-noise perception test and so failed to meet our criteria for inclusion in the impaired group. Listeners were recruited through flyers posted on the campus of Northwestern University and at the local public library. All listeners had normal pure tone air-conduction [<15 dB hearing level (HL)] and bone-conduction (<10 dB HL) thresholds at all standard audiometric frequencies between 0.25 and 8 kHz in both ears based on routine pure-tone audiometry, demonstrated normal otoscopy, reported no history of middle ear disease, ototoxic drug use, noise exposure, or head injury and were native American English speakers. All listeners who participated in the experiment performed at or above the age appropriate norm for adults on a dichotic digits test (Bellis, 2003) and thus were assumed to have no significant central auditory processing deficits.

B. Sentence-in-noise perception test

The sentence-in-noise perception test as described by Liu *et al.* (2004) was administered to evaluate each listener's ability to recognize speech in quiet and in the presence of noise. The test sentences consisted of a modified version of the Bamford–Kowal–Bench sentences (Bench and Bamford, 1979). The recordings of the speech stimuli were the same as those used by Bradlow *et al.* (2003); each sentence was spoken by a female speaker of American English and recorded with a sampling rate of 16 kHz. The sentences were presented at a level of 65 dB SPL as measured in a Bruel & Kjaer flat-plate coupler (Type 5935). The digitally stored speech stimuli were delivered using a 24-bit sound card (Creative Labs Sound Blaster Audigy 2) to the listener's right ear through Sennheiser HD 265 headphones. All testing took place in a sound-attenuated room.

The speech stimuli were presented in four conditions: in quiet and in the presence of speech-spectrum-shaped noise at

SNRs of -5 , -8 , and -10 dB. Eight different sentences were used for each condition for a total of 32 sentences. Each sentence consisted of three or four keywords, all of which were used for scoring. The scores were converted to percentage scores, which were then transformed to rationalized arcsine units (rau; Studebaker, 1985).

C. Absolute threshold measurements

Absolute thresholds (detection of a pure tone in quiet) for audiometric frequencies of 0.5, 1, 2, 4, 8, 10, 12.5, and 14 kHz were measured in the test ear (right) using a modified Békésy tracking procedure. The equipment set-up and procedure were as described by Dreisbach and Siegel (2001). The stimuli were digitally generated 250-ms tone bursts (Creative Labs Sound Blaster Audigy 2 sound card) that were presented at a rate of 2/s. Listeners used a button to adjust a computer-controlled programmable attenuator in 2-dB attenuation steps to track their thresholds. At each frequency, the midpoints of the attenuation values (threshold crossings) assessed over multiple runs of decreasing attenuation were averaged to obtain the threshold attenuation. The testing stopped automatically when, after a minimum of six successive runs, the standard error (SE) of the mean of the accumulated threshold crossings was less than 1.0 dB. If this criterion was not reached with the first six threshold crossings, additional threshold crossings were measured and the statistics were recomputed until the SE became less than 1.0. The thresholds were referenced to SPL at the eardrum using the pressure response measured in each ear using an Etymotic Research ER-7C probe tube microphone placed near the eardrum at the deepest possible location in the canal under visual observation through a miniature endoscope. This calibration technique has two advantages. First, it is an in-the-ear pressure measurement for each listener that is not sensitive to imperfectly sealing the probe into the ear. Second, it is quite accurate to at least 10 kHz and is likely to be at least as accurate as flat-plate coupler calibration of circumaural headphones at high frequencies.

D. Auditory filter shape measurement

1. Stimuli

The auditory filter shapes were estimated at 2 kHz using the notched-noise simultaneous masking method with fixed-probe paradigm as described by Rosen and Baker (1994). We chose 2 kHz as the probe frequency because the greatest contribution of acoustic cues to speech intelligibility is from frequency bands near this frequency (French and Steinberg, 1947). The 200-ms, 2-kHz sinusoidal probe was temporally centered in a 300-ms notched-noise masker. Both the probe and masker were shaped with 10-ms cosine-squared rise-fall times. Durations were measured between 0 voltage points. The upper and lower noise bands in the masker flanked the probe frequency (f_p) and each had a bandwidth of $0.4f_p$. The placement of the noise bands in frequency is expressed as normalized notch width ($\Delta f/f_p$), where Δf is the deviation of the near edge of each noise band from f_p . For three conditions the notch was placed symmetrically around f_p , with

$\Delta f/f_p$ set at 0, 0.2, and 0.4. For two other conditions the notch was asymmetrical around f_p , with $\Delta f/f_p$ set to 0.2 for the lower band and 0.4 for the upper band and vice versa.

All stimuli were generated digitally at a sampling frequency of 25 kHz using a digital signal processing board (Tucker-Davis Technologies, AP2). Digitally synthesized probe and masker stimuli were presented via 16-bit digital-to-analog converters (TDT DD1) followed by anti-aliasing filters having a low-pass cut-off frequency of 8.5 kHz (TDT FT5). They were then attenuated by programmable attenuators (TDT PA4 and PA5) and finally summed (SM3) and passed through a headphone buffer (TDT HB6) to the listener's right ear through Sennheiser HD450 headphones. All testing took place in a double-walled sound-attenuated room.

2. Procedure

The procedure was two-interval forced-choice with feedback. The probe level was fixed and the masker level was adjusted adaptively, using the maximum likelihood method (Green, 1990), to estimate the masker level at which the probe could be detected on 94.2% of trials. This masker level, referred to hereafter as the masked threshold, was defined as the 94.2% correct point on the most likely of 60 possible psychometric functions after 30 trials. The psychometric functions covered a range of 60 dB in 1-dB steps. Each was a logistic function that increased from 55% to 95% correct over a range of 10 dB, a range that is typical of signal in noise detection tasks (Green and Swets, 1988). The procedure was repeated for probe levels of 30, 40, and 50 dB SPL.

For each notch condition, three thresholds were obtained and averaged. When any one of the three thresholds deviated from either of the others by more than a predetermined cut-off value (6 or 12 dB, see below), an additional threshold was measured. The deviant threshold was then discarded and the remaining three thresholds averaged. However, if the additional threshold also deviated from the others by more than the cut-off value, then all four thresholds were averaged to obtain the mean. The cut-off value was set at 12 dB for the first four listeners tested (two impaired listeners and two controls) and was then reduced to 6 dB for all remaining listeners (12 impaired listeners and 8 controls). The mean standard deviation (SD) across listeners, notch conditions, and levels was 3.2 dB for the impaired listeners and 3.3 dB for the controls.

The raw threshold data were fitted with a rounded-exponential model (Patterson *et al.*, 1982) using the *polyfit* procedure as described by Rosen and colleagues (Rosen and Baker, 1994; Rosen *et al.*, 1998). Using this procedure, the auditory filter shapes for each of the three probe levels were fitted simultaneously as opposed to being estimated separately for each probe level. Our goal was to fit the data with the *polyfit* model that required the fewest parameters to adequately describe them. To do so, we used a heuristic approach as described by Rosen *et al.* (1998). We started with the most complex model [*roex* (p, w, t)] and evaluated the changes in the goodness of fit [as estimated by the root-mean-square (rms) residual] as we progressed to models with fewer parameters. For the upper side of the filter, substituting

the *roex* (p, r) or even the simplest *roex* (p) model for the *roex* (p, w, t) model had little effect on the goodness of fit for either the impaired listeners or controls. However, for the lower side, while simplifying the *roex* (p, w, t) model to the *roex* (p, r) model did not worsen the goodness of fit, the further simplification to the *roex* (p) model resulted in poorer fits for the two groups, indicating that the additional parameter was important for accurately describing the data. Thus, we report the auditory filter shapes derived from a *roex* model in which the upper side of the filter was described by the *roex* (p) shape and the lower side by the *roex* (p, r) shape. Note that the choice of the particular *roex* model did not affect the main conclusions of the investigation.

The equation for the low side of the filter was given by

$$W(g) = (1 - r)(1 + p_l g) \exp(-p_l g) + r$$

where W is the filter weighting function, g is the deviation from the center frequency as a proportion of the center frequency, p_l is the parameter determining the slope of the lower side of the filter and r is the parameter defining the dynamic range of the filter. The equation for the upper side of the filter was

$$W(g) = (1 + p_u g) \exp(-p_u g)$$

The maximum allowed value for either p_l or p_u was 60. The fitting procedure allowed the filter to be centered at a frequency giving the highest SNR at the filter output even if that frequency differed from the probe frequency (off-frequency listening), on the condition that the center frequency shift could not exceed more than 0.15 times the signal frequency. The parameters determining the steepness of the slopes on the two sides of the filter and the dynamic range of the lower frequency side of the filter were allowed to vary linearly with probe level. For example, using the nomenclature of Rosen and colleagues, the steepness of the upper side of the filter p_u was represented as

$$p_u = p_0 + p_1 P_s$$

where p_0 and p_1 are coefficients that depict the changes in p_u with probe level, P_s . The values of these coefficients that provided the best fitting model to the data were estimated and used to calculate the value of p_u . The filter parameters p_l and r were estimated in a similar manner. Varying the parameter K , the efficiency (the SNR at the output of the filter required to achieve threshold), as a function of level, did not improve the goodness-of-fit (see also Rosen *et al.*, 1998) and hence K was kept constant across level. Thus, in all, four parameters (p_l, p_u, r, K) and seven coefficients (two each for p_l, p_u , and r and one for K) were required to adequately fit 15 conditions (five notches $\times$ three levels). The mean of the rms residual between the predicted and the measured results was 1.37 dB (SE = 0.2) for the controls and 1.28 dB (SE = 0.2) for the impaired group, indicating that the data from all listeners were reasonably well fitted by *roex* (p, r) and *roex* (p) models for the lower and upper sides of the filter, respectively.

III. RESULTS

A. Sentence-in-noise perception test

We used performance on the sentence-in-noise perception test as one of the criteria for inclusion in the impaired group. Speech perception in noise is often evaluated by the SNR required for 50% correct performance. In the present case, percent-correct performance did not differ significantly between the listeners who initially self-reported difficulties understanding speech in noise ($n = 16$) and controls ($n = 10$) at the intermediate (-5 and -8 dB) SNR values that straddled the SNR required for 50% correct performance (both $p \geq 0.20$) [also see Pick and Evans (1983), who reported no group differences at 50% correct performance and yet documented abnormal filter shapes in the listeners who had complained of difficulty understanding speech in noise]. Nevertheless, percent-correct performance was significantly lower for the self-reported group ($n = 16$) than the controls ($n = 10$) at the lowest (-10 dB) SNR tested (t test, $p < 0.0001$). We therefore used poorer performance than controls (scores > 1 SD below the control mean) at this SNR as a criterion for inclusion in the impaired group. Of the 16 individuals in the self-reported group 14 individuals met this criterion. Only these 14 listeners comprised the impaired group whose performance is described below. Figure 1 shows the mean scores on the sentence-in-noise perception test for these impaired listeners (triangles; $n = 14$) and controls (circles; $n = 10$) in quiet and for the different S/N ratios. The speech scores of the individual listeners at -10 dB SNR are listed in Table I.

B. Absolute threshold measurements

Hearing sensitivity did not differ between impaired listeners and controls at the standard audiometric frequencies, but was poorer for the impaired listeners at the extended high frequencies. Figure 2 shows absolute thresholds for the impaired listeners (triangles) and controls (circles) for frequencies from 0.5 to 14 kHz. One impaired listener could

FIG. 1. Mean performance on the sentence-in-noise perception test for the impaired listeners (triangles; $n = 14$) and controls (circles; $n = 10$). The sentences were presented in quiet and in the presence of speech-spectrum-shaped noise at three different SNRs. Percent-correct scores were transformed to rau scores. Error bars represent ± 1 SD of the mean across listeners.

TABLE I. For each impaired listener (top half) and control (bottom half), the scores on the sentence-in-noise perception test at -10 dB SNR (rau), the ERB (Hz), lower (p_l) and upper (p_u) slopes of the auditory filters, the efficiency of the detection process (K in dB) and the absolute thresholds (dB SPL) at 12.5 and 14 kHz. The filter measures are listed for each of the three probe levels (30, 40, and 50 dB SPL). Each listener's age is listed in years. Scores that were missing or excluded from the analyses are indicated by dashed lines.

Listener		Speech score	ERB			p_l			p_u			K	Threshold	
Impaired	Age		30	40	50	30	40	50	30	40	50		12.5	14
I1	20	24.6	215.8	240.5	274.2	36.5	31.1	25.7	37.7	35.8	34.0	-0.5	—	—
I2	21	24.6	271.3	281.0	301.8	33.5	36.7	39.9	26.4	23.4	20.4	1.9	31.2	22.8
I3	21	32.9	276.3	318.1	380.0	33.3	27.0	20.8	25.7	23.7	21.7	-5.6	31.5	33.3
I4	22	28.8	217.3	229.9	245.0	35.3	33.0	30.7	38.5	36.9	35.4	4.5	55.1	58.3
I5	22	20.1	225.4	281.9	408.0	45.2	31.3	17.3	29.5	26.0	22.6	-4.3	31.2	39.4
I6	23	32.9	217.1	258.3	327.5	41.8	32.6	23.3	33.0	29.7	26.4	-4.2	33.0	52.6
I7	24	24.6	196.2	250.4	350.0	35.9	29.4	23.0	47.4	35.3	23.2	-5.8	66.0	71.0
I8	28	24.6	226.3	268.9	332.5	36.1	29.9	23.8	34.8	29.9	25.0	-4.7	32.5	45.1
I9	28	28.8	230.4	283.2	375.1	37.2	28.5	19.8	32.7	28.4	24.0	-4.2	19.2	17.9
I10	29	28.8	239.7	259.3	306.0	39.2	30.4	21.5	29.1	31.4	33.8	-1.2	15.9	18.3
I11	32	32.9	—	—	—	—	—	—	—	—	—	—	39.2	50.6
I12	34	15.2	314.2	335.9	462.3	22.8	17.5	12.2	29.1	40.5	51.8	-10	37.0	48.6
I13	45	24.6	337.5	340.0	400.4	33.3	25.5	17.6	18.9	23.6	28.4	-8.4	—	—
I14	50	20.1	239.2	271.9	320.4	34.3	28.2	22.1	32.7	31.0	29.3	-3.4	37.4	71.6
Mean	28.5	25.9	246.8	282.7	349.2	36.0	29.5	23.1	31.6	28.8	26.1	-3.3	35.7	44.1
SD	9.4	4.4	41.8	44.4	70.0	4.5	3.8	6.4	7.3	5.3	5.8	3.6	13.6	18.4
Control														
C1	18	36.8	217.1	242.6	278.1	34.2	29.1	23.9	40.0	38.3	36.6	-2.2	14.9	19.9
C2	21	36.8	225.2	225.1	237.1	37.7	32.4	27.1	33.6	39.4	45.2	1.9	37.4	31.2
C3	22	36.8	228.5	244.0	263.9	31.7	29.2	26.6	39.1	37.6	36.1	0.7	46.3	47.2
C4	22	36.8	177.9	179.9	196.7	36.0	36.0	36.0	59.9	59.7	59.4	-5.9	—	—
C5	24	48.1	186.7	228.5	294.8	34.4	28.6	22.8	56.9	45.3	33.7	-2.8	19.4	20.8
C6	24	44.4	211.3	237.3	272.7	34.3	29.7	25.0	42.5	39.5	36.5	-0.9	19.9	27.3
C7	25	51.9	235.2	301.2	418.9	30.1	23.2	16.4	39.4	31.4	23.4	-6.8	19.2	36.0
C8	27	40.6	151.7	167.3	189.9	47.0	40.0	33.0	59.9	59.6	59.2	0.2	19.6	23.5
C9	34	36.8	191.4	218.4	254.4	39.1	34.3	29.6	44.9	39.3	33.6	1.8	27.1	30.4
C10	47	40.9	203.1	227.5	261.2	40.8	34.5	28.2	38.1	35.9	33.7	3.8	24.3	45.2
Mean	26.4	40.9	202.8	227.2	266.7	36.5	31.7	26.8	45.4	42.6	39.7	-1.0	25.3	31.2
SD	8.4	5.4	26.0	36.5	63.2	4.9	4.7	5.4	9.7	9.6	11.5	3.4	10.2	9.9

not perform the tracking procedure precisely enough to obtain thresholds for any of the tested frequencies. In addition, reliable thresholds could not be obtained from one

FIG. 2. Mean absolute thresholds expressed as eardrum SPL as a function of frequency for impaired listeners (filled triangles; $n = 13$) and controls (open circles; $n = 10$). The error bars represent ± 1 SE of the mean across listeners.

impaired listener and one control for frequencies at and above 10 kHz due to difficulty in probe placement. Thus, the reported results at the standard audiometric frequencies are based on 13 of the 14 impaired listeners and on all 10 controls, while those at the extended high frequencies are based on only 12 impaired listeners and 9 controls. For all controls, thresholds for frequencies from 0.5 to 8 kHz fell below 30–35 dB SPL. The thresholds for frequencies above 8 kHz were, for each individual, within 20 dB of the highest threshold measured for that individual at the standard audiometric frequencies. These findings were similar to those reported by [Dreisbach and Siegel \(2001\)](#). The thresholds of every impaired listener fell within the 95% confidence interval of those of the ten controls at all of the standard audiometric frequencies. However, 7 of the 12 impaired listeners had thresholds above this range for at least two of the three extended high frequencies. A two group $\times$ eight frequency analysis of variance (ANOVA) with repeated measures on frequency revealed a significant interaction between group and frequency [$F(7, 133) = 2.2$; $p = 0.03$] and a significant main effect of frequency [$F(7, 133) = 16.48$; $p < 0.001$], but no significant main effect of group [$F(1, 19) = 2.48$; $p = 0.13$]. When only the standard audiometric

frequencies (0.5–8 kHz) were included in the analysis, there were no significant effects. However, when only the extended high frequencies (>8 kHz) were included, the main effect of group just reached significance [$F(1, 19) = 4.25$; $p = 0.05$]. Thresholds were significantly higher for the impaired listeners than controls at 12.5 and 14 kHz (both t tests, $p = 0.05$; for individual thresholds see Table I), but not at 10 kHz (t test, $p = 0.28$). This pattern of results suggests that the impaired listeners as a group had thresholds similar to those of controls at the standard audiometric frequencies, but elevated thresholds at higher frequencies.

C. Auditory filter shapes

1. Raw data

Figures 3(a)–3(c) show the mean masked threshold plotted as a function of symmetrical notch width for the impaired listeners (triangles; $n = 14$) and controls (circles;

FIG. 3. Mean raw masked thresholds for the symmetrical (left column) and asymmetrical (right column) notches for a 2-kHz probe at three different probe levels (a,d) 30 dB SPL, (b,e) 40 dB SPL, and (c,f) 50 dB SPL. Results for the symmetrical notches are shown as a function of normalized notch width for impaired listeners (filled triangles; $n = 14$) and controls (open circles; $n = 10$). Results for the asymmetrical notches are shown for conditions in which the normalized notch widths were 0.4 and 0.2 (lower-band farthest; left-facing triangles) or 0.2 and 0.4 (upper-band farthest; right-facing triangles) for impaired listeners (filled symbols) and controls (open symbols). Error bars represent ± 1 SE of the mean across listeners. The mean SE calculated across all notch conditions ranged from 0.76 to 1.03 for the impaired listeners and from 0.79 to 1.35 for the controls over the three probe levels.

$n = 10$) for the three probe levels. We analyzed these thresholds using a two group $\times$ three notch width $\times$ three level ANOVA. The three-way interaction was not significant [$F(4, 198) = 0.26$; $p = 0.89$]. However, the masked thresholds of the controls increased more than those of the impaired listeners with increasing notch width [group $\times$ notch, $F(2, 198) = 8.57$; $p < 0.001$], suggesting that the impaired listeners had broader filters. The rate of increase in the masked threshold as a function of notch width decreased with increasing probe level, signifying a widening of the filter with increasing level for the two groups [notch $\times$ level, $F(4, 198) = 11.8$; $p < 0.001$].

Figures 3(d)–3(f) show the mean raw thresholds for the impaired listeners (filled symbols) and controls (open symbols) obtained in the two asymmetrical notch conditions at the three probe levels. The three-way interaction was not significant [$F(2, 132) = 0.45$; $p = 0.63$], but the group $\times$ notch interaction was [$F(1, 132) = 6.79$; $p = 0.01$]. The masked thresholds were lower for the impaired listeners than for the controls when the lower frequency band was shifted farther from the signal (left-facing triangles), but were similar for the two groups when the upper-frequency band was shifted (right-facing triangles), suggesting an abnormal broadening of the high-frequency side of the filter. In addition, the difference between the masked thresholds for the two asymmetric conditions increased with increasing probe level [notch $\times$ level, $F(2, 132) = 3.11$; $p = 0.048$], indicating that the filter asymmetry increased with increasing probe level.

2. Fitted data

We fitted the raw data of all but one of the individuals with the *roex* model. The data of one impaired listener were excluded from these calculations because his p_u value was twice that of his p_l value, a situation in which the larger value (the steeper skirt) of the filter may not be accurately defined (Glasberg and Moore, 1986). Thus, we estimated filter shapes for 13 of the 14 impaired listeners and for all ten controls. The mean estimated auditory filter shapes obtained by averaging fitted parameter values are shown in Fig. 4 for the impaired listeners (bold solid line) and controls (dashed thin line). All of the filter shapes of the impaired listeners are normalized to have the same gain as controls at slightly more than 1 octave below the 2-kHz center frequency. We analyzed the filter bandwidth, slopes, and peak gain (see below) using separate two group $\times$ three level ANOVAs with repeated measures on level for each filter measure. In all cases, there was a main effect of level (all $p \leq 0.001$), and, except where otherwise noted, no interaction between group and level. Therefore, in the following sections we focus primarily on main effects of group. Overall, these analyses confirmed and extended the conclusions drawn from the raw data. Table I lists the bandwidth and slope values for the individual impaired listeners and controls.

a. Filter bandwidth The auditory filters for the impaired listeners had wider bandwidths than for the controls. Figure 5 shows the auditory filter bandwidths quantified as the

FIG. 4. Mean auditory filter shapes, fitted with the *roex* model, of the impaired listeners (bold solid line) and controls (dashed thin line) for probe levels of (a) 30, (b) 40, and (c) 50 dB SPL. All of the filter shapes of the impaired listeners are normalized to have the same gain as controls at slightly more than 1 octave below the 2-kHz center frequency. Error bars represent ± 1 SE of the mean across listeners.

equivalent rectangular bandwidth (ERB) values for the two groups. The ERB was significantly larger for the impaired listeners (triangles) than for the controls (circles) [main effect of group; $F(1, 21) = 10.38$; $p = 0.004$]. The filter bandwidths of 10 of the 13 impaired listeners were outside of the 95% confidence interval of those of the ten controls at each of the three probe levels. There was also a non-significant trend for the ERB to increase at a faster rate with increasing stimulus level in the impaired listeners than controls [group $\times$ level interaction; $F(2, 42) = 2.96$; $p = 0.065$]. The ERB increased by 106 Hz in the impaired listeners compared with 64 Hz in the controls between the probe levels of 30 and 50 dB, with most of the change occurring from 40 to 50 dB.

FIG. 5. Mean ERBs as a function of probe level in impaired listeners (filled triangles) and controls (open circles). Error bars represent ± 1 SE of the mean across listeners.

b. Filter slopes The wider auditory filters for the impaired listeners were mainly a consequence of the filters being abnormally shallow on the upper side. Figure 6 shows the upper (p_u) and lower (p_l) slopes of the auditory filters for the two groups. The mean upper slopes for the impaired listeners (triangles) were significantly shallower than for the controls (circles) [main effect of group; $F(1, 21) = 19.16$; $p < 0.001$]. However, the mean values of the lower slopes

FIG. 6. Mean values of (a) upper slopes (p_u) and (b) lower slopes (p_l) as a function of probe level for impaired listeners (filled triangles) and controls (open circles). Error bars represent ± 1 SE of the mean across listeners.

were similar for the two groups [$F(1, 21) = 1.47$; $p = 0.20$]. Out of the 13 impaired listeners, at every probe level, nine had shallower slopes on the high-frequency side of the filter than the 95% confidence interval of controls, but had normal slopes on the low-frequency side, one had abnormally shallow slopes on both sides, and three had normal slopes on both sides.

c. Peak gain The peak gain, or tip-to-tail gain, is a sensitive measure of the influence of stimulus level on filter shape. It is quantified as the gain at the tip of the filter when the lower tail of the filter shape is held fixed across level (Rosen *et al.*, 1998; Glasberg and Moore, 2000). The peak gain was significantly smaller for the impaired listeners than for the controls [main effect of group; $F(1, 21) = 6.32$; $p = 0.02$] (see Fig. 4), consistent with the wider ERBs for the impaired group. At each of the three probe levels, the filters of 9 of the 13 impaired listeners had peak gains that were outside of the 95% confidence interval of those of the ten controls. The decrease in the peak gain with increasing stimulus level for the impaired listeners also tended to be smaller than for the controls, though this difference did not reach statistical significance [group $\times$ level interaction; $F(2, 42) = 2.64$; $p = 0.08$]. It is noteworthy that while the filters of the impaired listeners showed less gain at the peak, they actually showed more gain at frequencies above the peak, compared to the filters of the controls [for example, gain at 2.7 kHz: main effect of group; $F(1, 21) = 11.41$; $p = 0.003$].

d. Efficiency Processing efficiency did not differ significantly between groups (t test, $p = 0.13$). The mean K value was -3.3 dB (SE = 1.0) for the impaired listeners and -1.0 dB (SE = 1.1) for the controls (for individual values see Table I).

There were no significant correlations between the sentence-in-noise perception test scores (at -10 dB SNR) and the various filter measurements as well as the absolute thresholds at high frequencies among the 11 impaired listeners for whom we had a full data set (all $p > 0.05$; Pearson correlations).

IV. DISCUSSION

A. Auditory filter shapes

1. Filter measurements

The primary aim of this investigation was to characterize auditory filter shapes in people who complain of speech recognition difficulties in noise despite having clinically normal audiograms [obscure auditory dysfunction (OAD)]. The main finding was that the majority of the present listeners with this disorder (impaired listeners) had abnormally wide auditory filter shapes resulting from shallower-than-normal upper slopes at the probe frequency of 2 kHz. The upper slope of the filter is somewhat difficult to derive accurately with the *roex* fitting procedure (Glasberg and Moore, 1990; Rosen *et al.*, 1998). However, there was evidence of shallower upper slopes in the raw data, in all variants of the *roex* model fitted to those data, and only in impaired listeners and not

controls, suggesting that the estimated abnormalities in the slopes are real. The filter shapes in the impaired listeners thus differed markedly from those typically observed in listeners with normal hearing as well as in most listeners with sensorineural hearing loss, for whom the filter is shallower on the lower side at least at high levels (see Introduction). In fact, none of the present impaired listeners showed this more typical asymmetry. It also differs somewhat from the few previous reports of filters with shallower than normal upper slopes in individuals with sensorineural hearing loss (see Introduction). In only two of those four investigations did the abnormal broadening of the upper slope *exclusively* contribute to reduced frequency resolution (Tyler *et al.*, 1984; Nelson, 1991), as was found here.

Another aim of this investigation was to determine the influence of stimulus level on auditory filter shapes in individuals with OAD. There were no marked differences in the level-dependent changes in filter shape between the present impaired listeners and controls, but the implications of several patterns in the data are worth noting. The consistently smaller peak gain as well as the tendency for the peak gain to decrease less with increasing stimulus level for impaired listeners than controls suggests that there may have been some dysfunction of the cochlear active mechanical mechanism in the impaired listeners, which was not revealed in absolute thresholds. However, the greater gain at frequencies above the filter peak for the impaired listeners than controls, the tendency for the ERB to increase more than normal with increasing stimulus level for the impaired listeners, and the correspondingly larger group differences in ERB at higher than lower stimulus levels have no known correlate in basilar membrane gain functions (e.g., Robles and Ruggero, 2001). These results are thus incompatible with conventional views of changes in auditory filter shape due to impaired active cochlear mechanics. Assessment of level-dependent behavior over a wider range of levels than used here would help to confirm these patterns, if they are real, and to clarify their implications.

Another outcome of the present investigation was that the efficiency of the detection process following filtering did not differ between the impaired listeners and controls. Efficiency represents any contribution to the detection of sounds in noise other than frequency selectivity itself (Patterson *et al.*, 1982). These contributions are thought to arise primarily from central processes that are responsible not only for auditory processing but also for broader factors such as attention, memory, and learning (Patterson *et al.*, 1982; Werner and Bargones, 1991; Hartley and Moore, 2002). The similarity in the estimates of processing efficiency for the impaired listeners and controls suggests that the impaired listeners had normal central auditory processing, though the possibility remains that they had some subtle central processing deficit that was not reflected in the efficiency measure.

2. Potential explanations

One potential explanation for the abnormal filter shapes in listeners with OAD is that they are a consequence of impaired peripheral mechanisms. This possibility arises

because cochlear mechanisms are thought to influence the characteristics of the auditory filter estimated psychophysically (Fletcher, 1940; Moore, 1986; Evans *et al.*, 1989). The presence of clinically normal hearing sensitivity at standard audiometric frequencies in this population does not exclude the possibility of peripheral damage. For example, there are reports of normal pure tone sensitivity in spite of the loss of 20%–40% of outer hair cells and 10% of inner hair cells due to noise exposure (e.g., Cody, 1992; Clark and Bohne, 1978) and of the loss of 60%–80% of spiral ganglion cells following partial section of the cochlear nerve (Schuknecht and Woellner, 1953). Indeed, there is some evidence that listeners with OAD have mild cochlear pathology. A larger proportion of individuals in this population compared to controls have been found to have notches in their audiograms, as measured with finer frequency steps than in standard audiometry (Zhao and Stephens, 1999). In addition, there is a recent report that distortion product otoacoustic emissions in this population are reduced compared to those of controls (Zhao and Stephens, 2006). There is also some indication that OAD runs in families and may be autosomal dominant (e.g., Stephens and Zhao, 2000). Such dominant inheritance is more frequently associated with cochlear lesions than with retrocochlear or central disorders.

Another possibility is that the broader filters in this population result from an impairment in central processes themselves or their influences on the periphery. The idea that impairments in central processes may contribute to altered tuning, even when the periphery appears to be normal, gains some support from a report by Sanes and Constantine-Paton (1985). They showed that frequency tuning curves in the inferior colliculus of mice who were raised in an environment of continuous clicks were wider than those of controls, especially on the high side, even though the two groups had identical cochlear thresholds. Auditory filter shapes could also be altered by problems associated with the influence of descending pathways, such as the olivocochlear efferent system on peripheral function. Efferent fibers, the medial olivocochlear fibers in particular, synapse at the outer hair cells and are thought to influence cochlear sensitivity, frequency selectivity, and the perception of auditory signals in the presence of background noise (see Guinan, 2006, for review). Measurements of the acoustic reflex and auditory brainstem responses could help to elucidate the status of the efferent system in these listeners.

Finally, it is possible that faulty or non-optimal listening strategies contribute to distorted auditory filter shapes. For example, off-frequency listening occurs when listeners monitor an auditory filter that is centered at a frequency that is slightly higher or lower than the signal frequency in order to optimize the SNR at the output of the filter (e.g., Johnson-Davis and Patterson, 1979). Off-frequency listening is limited in measurements of auditory filter shape, which employ notched-noise maskers. However, when these maskers are asymmetric, with one noise band closer to the signal frequency than the other, off-frequency listening still influences the behaviorally derived filter shapes (Patterson and Nimmo-Smith, 1980). Therefore, it is possible that the present impaired listeners failed to pick the individual filter that provided the best SNR, resulting in an

abnormal shape of the derived auditory filter. It should be noted, though, that if the impaired listeners did not pick the best filter their detection efficiency presumably should have been worse than normal, but it was not.

B. Absolute threshold measurements

At the standard (lower) audiometric frequencies, absolute thresholds referenced to eardrum SPL did not differ between the present impaired listeners and controls. Therefore, we did not replicate previous reports of thresholds that were “clinically” normal but elevated compared with controls in this population (King and Stephens, 1992; Zhao and Stephens, 2006). However, more than half of the impaired listeners had higher absolute thresholds than controls at frequencies >8 kHz. This result is consistent with previous reports of high-frequency hearing loss in this population (King and Stephens, 1992; Shaw *et al.*, 1996). Such hearing loss is typically attributed to cochlear pathology (e.g., Ryan and Dallos, 1975). It is noteworthy that these impaired listeners had elevated high-frequency thresholds as well as abnormal auditory filter shapes at a standard audiometric frequency even though their absolute thresholds at the standard audiometric frequencies were statistically indistinguishable from those of controls. These results thus add to the evidence that absolute thresholds that are “within normal limits,” or even with the more restrictive criterion of being statistically indistinguishable from those of controls at the standard audiometric frequencies, do not necessarily imply “normal hearing” (e.g., Dorn *et al.*, 1998; Mills, 2002). They also confirm that measuring absolute thresholds over the full frequency range of hearing provides a more sensitive assay of impaired hearing capabilities than conventional audiometry.

C. Relationship of speech scores to filter measurements and absolute thresholds at high frequencies

The significant mean differences in the filter measurements and high-frequency hearing thresholds between the impaired listeners and controls—who were classified based upon their speech perception abilities—suggest that there could be a connection between these measures and speech perception in noise. If so, the lack of correlation among these measures for the impaired listeners alone could be attributed to the relatively narrow range of their speech scores. It could also be that difficulty understanding speech in noise becomes noticeable only after filters broaden (or high-frequency hearing deteriorates) beyond some critical value and that further broadening (or deterioration) is not necessarily associated with greater impairment at least in the range over which normal absolute thresholds at the standard audiometric frequencies are maintained. It is noteworthy that the scores on the sentences-in-noise perception test of the impaired listeners differed from those of controls only at the most adverse SNR tested. Thus, it appears that listeners who self-report difficulties understanding speech in noise can be sensitive to this problem at a stage that would be missed by conventional clinical standards (the SNR required for 50% correct performance) (also see Pick and Evans, 1983). The accuracy of the

self-assessment of hearing status in these listeners is bolstered by the other measurable deficits in hearing function documented in them. However, while every impaired listener showed a deficit on one or more of the present measures, the affected measure differed to some extent across individuals, suggesting that self-perceived difficulties understanding speech in noise can signal different constellations of additional hearing problems. Such individual differences are consistent with previous reports of heterogeneous deficits in listeners with OAD (Saunders and Haggard, 1989; Zhao and Stephens, 2000).

We are aware of only a few previous published studies that address the influence of shallower upper filter slopes and elevated high-frequency absolute thresholds on speech intelligibility in noise. In terms of the upper filter slope, in one investigation Noordhoek *et al.* (2000) measured speech intelligibility in quiet and noise for listeners with hearing loss and controls. They inferred that the poor performance in noise in listeners with hearing loss was due to increased downward spread of masking through an analysis based on a speech intelligibility index model. Such an increase could arise from shallower upper filter slopes. In another investigation, Baer and Moore (1993) examined the effects of simulated increases in auditory filter bandwidths on speech intelligibility in noise in listeners with normal absolute thresholds. Intelligibility was impaired in conditions that simulated abnormally shallow upper filter slopes. However, the reduction in speech intelligibility was greater when the lower slopes of the simulated filter were shallower than the upper slopes. Note, though, that in all of these cases both the upper and lower slopes were abnormally shallow. Therefore, the extent to which the broadening of the upper side alone contributed to the observed impairments cannot be evaluated. In terms of absolute thresholds at high frequencies, Strickland *et al.* (1994) concluded that high-frequency information in speech did not contribute substantially to speech perception in noise based on an evaluation of the influence of an intense high-pass noise on speech perception in listeners with normal absolute thresholds. Horwitz *et al.* (2002) reached the opposite conclusion from an investigation of the perception of low-pass and unfiltered speech stimuli in noise in listeners with high-frequency hearing loss and controls. The listeners with hearing loss performed more poorly than the controls in both speech conditions. Horwitz *et al.* attributed the deficits for the unfiltered as well as the low-pass speech to the presumed damage at the base of the cochlea that caused the high-frequency hearing loss. However, Strickland *et al.* (2004) argued that these deficits could have arisen from damage in apical regions of the cochlea that did not yet manifest as elevated absolute thresholds at low frequencies.

Finally, there is some reason to think that the magnitude of filter broadening observed in the present impaired listeners may have been sufficient to affect their ability to hear speech in noise. ter Keurs *et al.* (1992) evaluated the influence of simulated increases in filter bandwidth on speech intelligibility in noise in normal-hearing listeners. Intelligibility declined for filter bandwidths that were ≥ 2 times broader than normal, a value greater than the broadening factor of 1.2–1.3 seen in the impaired listeners here. However, limitations to their

simulation technique may have underestimated the influence of filter broadening (see Baer and Moore, 1993). For example, their simulations did not account for increases in the upward and downward spread of masking which are also consequences of frequency selectivity loss. In addition, the measure used by ter Keurs *et al.* was the speech reception threshold at 50% correct, but the present impaired listeners only showed deficits at lower percent-correct values. Thus it is possible that broadening factors < 2 might degrade performance in more adverse conditions than are assessed with conventional criteria. Leek and Summers (1996) suggested that auditory filters that are broader than normal may contribute to speech perception problems in noise in listeners with sensorineural hearing loss because the internal representation of speech is spectrally smeared and the SNR at the output of each auditory filter is reduced. These two factors may also contribute to the difficulties understanding speech in noise in listeners with OAD.

V. SUMMARY AND CONCLUSIONS

Auditory filter shapes and absolute thresholds were evaluated for listeners with reduced speech recognition in noise and “clinically normal” audiograms [obscure auditory dysfunction (OAD); impaired group] and for controls. Despite the absence of any statistically significant differences in absolute thresholds between groups in the conventional audiometric frequency range (< 8 kHz), the impaired group had broader auditory filter shapes than the controls at the 2-kHz probe frequency. The wider auditory filters in the impaired listeners resulted from an unusual broadening of the upper side of the filter. In addition, the impaired group had higher absolute thresholds than controls at frequencies approaching the upper limit of hearing (12.5 and 14 kHz). The mean between-group differences suggest that these factors may either contribute to the communication difficulties faced by this population in the presence of background noise or be a marker of those difficulties. The present results also serve to underscore the risk of using normal absolute thresholds as the sole definition of normal hearing.

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