Narrow-band ripple glide direction discrimination and its relationship to frequency selectivity estimated using psychophysical tuning curves

Vijaya Kumar Narne[a)] [1]

Department of Audiology, JSS Institute of Speech and Hearing, Mysore, India

Saransh Jain and Chitkala Sharma

Department of Audiology, JSS Institute of Speech and Hearing, Mysore, India

Thomas Baer and Brian C.J. Moore

Department of Experimental Psychology, University of Cambridge, Cambridge, UK

[a)] Author to whom correspondence should be addressed. Electronic mail: vijaynarne@gmail.com

[1] Also at Clinical Institute of South Denmark University, Odense, Denmark

Abstract

The highest spectral ripple density at which the discrimination of ripple glide direction was possible ($STRt_{dir}$ task) was assessed for one-octave wide (narrowband) stimuli with center frequencies of 500, 1000, 2000, and 4000 Hz and for a broadband stimulus. A pink noise lowpass filtered at the lower edge frequency of the rippled-noise stimuli was used to mask possible combination ripples. The relationship between thresholds measured using the $STRt_{dir}$ task and estimates of the sharpness of tuning (Q10) derived from fast psychophysical tuning curves was assessed for subjects with normal hearing (NH) and cochlear hearing loss (CHL). The $STRt_{dir}$ thresholds for the narrowband stimuli were highly correlated with Q10 values for the same center frequency, supporting the idea that $STRt_{dir}$ thresholds for the narrowband stimuli provide a good measure of frequency resolution. Both the $STRt_{dir}$ thresholds and the Q10 values were lower (worse) for the subjects with CHL than for the subjects with NH. For the NH subjects, mean $STRt_{dir}$ thresholds for the narrowband stimuli were similar to the mean $STRt_{dir}$ threshold for the broadband stimulus, while for the CHL subjects the latter was slightly but not significantly higher than the former, suggesting little ability to combine information across center frequencies.

1. INTRODUCTION

A popular method for estimating the frequency resolution of the auditory system involves the detection or discrimination of spectral ripples imposed on a noise-like carrier (SRn) (Supin et al., 1994; Supin et al., 1998). SRn stimuli are composed of a "carrier" that is either white or pink noise or multiple sinusoids covering a certain frequency range. The spectrum of the carrier is modulated so as to give spectral ripples that are uniformly spaced on a linear frequency scale (Henry and Turner, 2003; Supin et al., 1994) or logarithmic frequency scale (Drennan et al., 2014; Won et al., 2011; Won et al., 2007). In the latter case, the ripple density, D, is usually specified in ripples per octave, RPO. The highest value of D at which a spectral ripple can be detected or discriminated (from an SRn stimulus with a very high value of D or with a different ripple phase) has often been employed to assess the frequency resolution of people with normal hearing (NH), cochlear hearing loss (CHL), and cochlear implants (CI) (Henry et al., 2005; Won et al., 2007).

Azadpour and McKay (2012) have shown that confounding cues are available for SRn stimuli and these can affect estimates of frequency resolution, especially for subjects with CHL or CI, who have relatively poor frequency resolution. One such cue is a change in excitation level on the low-frequency slope of the excitation patterns evoked by the stimuli when the ripple phase, depth or density are changed. To avoid this problem, Aronoff and Landsberger (2013) introduced a test using stimuli with temporally varying (gliding) ripples, called STRn stimuli. The task was to distinguish an STRn stimulus with variable ripple density from an STRn stimulus with a high ripple density of 20 RPO for which the ripples were assumed to be unresolved. However, Narne et al. (2016) showed that performance of this test was affected by the use of cues at the outputs of auditory filters centered below and above the passband of the STRn stimuli, leading to over-estimates of frequency resolution. To avoid this problem, Narne et al. (2018; 2019) measured the ability to discriminate the direction of spectral ripples that were gliding in frequency. They measured the highest ripple density at which the task could be performed. This test is called the STRt$_{dir}$ test. They presented evidence that performance of this test is not affected by the use of cues related to changes at the spectral edges of the stimuli, so the test should give valid estimates of frequency resolution (Narne et al., 2018; 2019). Therefore, the STRt$_{dir}$ test may be suitable for the assessment of frequency selectivity for both broadband and narrowband STRn stimuli.

This paper addresses two questions: (1) Is frequency selectivity as estimated using the STRt$_{dir}$ test with narrowband stimuli correlated with frequency selectivity estimated using a well-established method, namely psychophysical tuning curves (PTCs)?; (2) Does performance of the STRt$_{dir}$ test for broadband stimuli depend on the combination of information over a wide range of frequencies (the global model) or on the use of information from a limited frequency range where frequency resolution is best (the local model)?

It has often been assumed that performance with broadband SRn and STRn stimuli provides a global measure of spectral resolution, i.e. it depends on the combination of information over a wide range of frequencies (Drennan et al., 2014; Henry et al., 2005; Won et al., 2007). If this assumption is correct, then the discrimination of broadband SRn or STRn stimuli should be better than the discrimination of narrowband SRn or STRn stimuli. However, data in the literature are inconsistent about whether this is the case. Eddins and Bero (2007) found that the ripple depth required to discriminate an SRn stimulus with a fixed ripple density (for example 4 RPO) from a stimulus with a flat spectrum did not vary markedly with carrier bandwidth, although discrimination was worse for one-octave wide stimuli centered at low frequencies (frequency range from 200 to 400 Hz) than for stimuli centered at higher frequencies.

Supin and co-workers (Supin, 2011; Supin et al., 1998; Supin et al., 2001) studied spectral ripple resolution using a test that required the detection of a 180° shift in the phase of the spectral ripples, using a fixed ripple depth; this is referred to as the ripple-reversal test. They measured the highest ripple density at which a stimulus with ripple-phase reversal could be discriminated from a stimulus with constant ripple phase, using stimuli with a large ripple depth. For stimuli with logarithmically spaced ripples, Supin et al. (1998) found that thresholds hardly varied with carrier bandwidth for a center frequency of 1 kHz, while thresholds tended to decrease (worsen) with increasing bandwidth for center frequencies of 2 and 4 kHz. In contrast, Milekhina et al. (2018) found that threshold increased slightly (improved) with increasing bandwidth from about 8.5 RPO for a bandwidth of 0.5 octave to 10 RPO for a bandwidth of 5 octaves (using a fixed center frequency of 2 kHz), suggesting some ability to integrate information across frequency. However, the improvement may have been partly due to the spread of the stimulus spectrum towards higher frequencies with increasing bandwidth, since spectral ripple resolution for narrowband stimuli tends to be better for center frequencies above 4 kHz than for lower center frequencies (Eddins and Bero, 2007; Supin et al., 1998).

To test whether the discrimination of spectral ripples in broadband STRn stimuli depends on the integration of information across center frequencies, Narne et al. (2018) compared thresholds for the $STRt_{dir}$ test obtained using a broadband carrier with auditory filter bandwidths (defined in terms of the equivalent rectangular bandwidth, ERB) estimated for center frequencies of 0.5, 1, 2, and 4 kHz using the notched-noise (NN) method (Glasberg and Moore, 1990). Both NH and CHL subjects were tested. The $STRt_{dir}$ thresholds were significantly negatively correlated with the ERB values for low center frequencies, even after partialing out the effect of absolute threshold (a negative correlation is expected, since good frequency resolution is indicated by high values of D at threshold and by low values of the ERB). Excitation patterns for the STRn stimuli were calculated for each subject using the estimated ERB values. These excitation patterns were used to predict the $STRt_{dir}$ thresholds using a local excitation-pattern model, based on the assumption that the threshold is reached when the peak-to-valley ratio (PVR) in the excitation pattern in any one-octave-wide frequency region reaches a criterion value, and using a global model, based on the assumption that threshold is determined by the average PVR across the whole excitation pattern. The predicted $STRt_{dir}$ thresholds were closer to the measured thresholds for the local model than for the global model. This suggests that the discrimination of spectral ripples in a broadband stimulus depends largely on information from frequency regions where the relative ERB values (ERB divided by center frequency) are smallest, which, for subjects with CHL, are usually the frequency regions where hearing thresholds are better.

A few studies have compared thresholds for narrowband SRn stimuli to those obtained using broadband SRn stimuli or to measures of frequency resolution obtained in other ways. Anderson et al. (2011) measured SRn resolution for narrowband and broadband stimuli and also measured spatial tuning curves obtained in forward masking for CI subjects. The spatial tuning curves provide a measure of channel interaction. They showed that broadband SRn thresholds were similar to average narrowband SRn and/or best narrowband SRn thresholds. They found that the bandwidths of the spatial tuning curves were highly correlated with thresholds measured using narrowband SRn stimuli centered on the same electrode. The bandwidths of the spatial tuning curves were less highly correlated with the SRn discrimination thresholds for broadband stimuli, supporting the local model.

In summary, the results are somewhat mixed, but overall the results of previous studies tend to favor the local model over the global model. However, the results of some of these studies may have been affected by the confounding cues described earlier. Also, the detection and discrimination of spectral ripples in narrowband stimuli may have been affected by the presence of combination ripples (Narne et al., 2016; Supin et al., 2001). These ripples would be better resolved than ripples within the passband of the stimuli, because the bandwidths of the auditory filters decrease with decreasing center frequency (Glasberg and Moore, 1990). For example, if the two lowest ripples within the passband of the stimuli have center frequencies of 1600 and 1800 Hz, combination ripples with center frequencies 1400 and 1200 Hz may be produced. The frequencies 1800 and 1600 are separated by 0.96 Cams on the ERB_N-number scale (Glasberg and Moore, 1990), while the frequencies 1400 and 1200 Hz are separated by 1.21 Cams. The combination ripples would therefore be better resolved than the lowest ripples in the physical stimulus (Moore et al., 2006; Moore and Ohgushi, 1993). In the present study, a lowpass-filtered pink noise was used with the narrowband stimuli, to mask potential combination ripples.

In summary, this paper had two objectives. The first was to compare estimates of frequency resolution obtained using the $STRt_{dir}$ test and narrowband stimuli with those obtained using PTCs determined using signals at the same center frequencies, to assess whether the $STRt_{dir}$ test provides valid estimates of frequency resolution for narrowband stimuli. The second was to estimate thresholds obtained using the $STRt_{dir}$ test with narrowband stimuli and to compare the results to those obtained using broadband stimuli, to assess the extent to which information is integrated across frequency when broadband stimuli are used. Both NH and CHL subjects were used. Since thresholds for the $STRt_{dir}$ test with narrowband and broadband stimuli were measured as part of the same experiment, that experiment is described first.

2. Experiment 1: $STRt_{dir}$ thresholds for one-octave-wide and broadband stimuli

All testing was conducted in a sound-attenuating chamber. The stimuli were generated and responses were collected via a personal computer and a 32-bit sound card (Realtek, Hsinchu, Taiwan), using a sampling rate of 44,100 Hz. Stimuli were presented through one earpiece of Sennheiser HD 202 II headphones (Wedemark, Germany).

2.1. Subjects

There were two groups of subjects, NH and CHL. The audiometric thresholds of all subjects were assessed using a calibrated diagnostic audiometer (Piano, Padova, Italy) and Sennheiser HDA300 headphones (Wedemark, Germany). All subjects had normal tympanograms, with ipsilateral acoustic reflexes at normal levels in both ears, indicating normal middle-ear function. The ten NH subjects (6 female, mean age = 22 years, standard deviation, SD = 2.4 years) were recruited from students at the JSS Institute of Speech and Hearing and the authors' social networks. All had air-conduction thresholds <15 dB hearing level (HL) between 250 and 8000 Hz. None had a history of neurological and/or otological disorder. The 12 CHL subjects (6 female, mean age = 45 years, SD = 12 years) were recruited from the JSS hospital. The CHL subjects had "flat" or gently sloping audiograms with air-bone gaps ≤ 10 dB from 500 to 4000 Hz. All subjects were assessed monaurally. The test ear was randomly selected. Individual audiograms for the test ears of both groups are shown in Fig. 1. The CHL subjects had a pure-tone average (PTA) threshold for the test ear across 500, 1000, 2000, and 4000 Hz of 35 dB HL (SD = 10 dB).

Insert Fig.1 Here

2.2. Measurement of absolute thresholds

Absolute thresholds were measured for signal frequencies of 500, 1000, 2000, and 4000 Hz using the method incorporated in the software for measuring "fast" PTCs (Sęk et al., 2005; Sęk and Moore, 2011). A two-alternative forced-choice method with a two-down one-up adaptive procedure was used. The two intervals in which the signal might occur were indicated by boxes on the screen. The duration of the signal was 200 ms (including 20-ms raised-cosine ramps) and the gap between observation intervals lasted 500 ms. The starting level of the signal was set 10 dB above the anticipated absolute threshold, as estimated from the audiometric threshold. The subject responded by 'clicking' on virtual buttons on the screen. Feedback was provided by flashing the box that was selected, using a green flash for correct and a red flash for wrong. The step size was 5 dB until two reversals had occurred and was 2 dB thereafter. Eight reversals were obtained, and the threshold was taken as the mean level at the last six reversals.

2.3. Estimation of $STRt_{dir}$ thresholds

The STRn stimuli were generated exactly as described in Narne et al. (2016). For both narrowband STRn (NB-STRn) and broadband STRn (BB-STRn) stimuli, the carrier was composed of 201 equal-amplitude sinusoidal frequency components. For the NB-STRn stimuli, the carrier components were spaced every 0.005th octave over a one-octave-wide frequency range. The octave center frequencies (and edge frequencies) were: 500 Hz (355 to 710 Hz); 1000 Hz (710 to 1420 Hz); 2000 Hz (1420 to 2840 Hz) and 4000 Hz (2840 to 5680 Hz). For the BB-STRn stimuli, the sinusoidal components were spaced every 0.03rd octave and the frequency range was from 100 to 6400 Hz. The level of the sinusoidal components for both the NB-STRn and BB-STRn stimuli was a function of *D* and of the ripple rate (*R*, in Hz). The peak-to-valley depth of the spectral modulation was 20 dB, as used by Narne et al. (2016). This was chosen to be large enough to make performance of the task easy for low ripple densities. The value of *R* was the same as used by Narne et al. (2018), namely 5 Hz. This was chosen to be within the range where threshold does not depend on *R* (Narne et al., 2019).

The level of the NB-STRn stimuli was set 30 dB above the absolute threshold for a pure tone at the corresponding center frequency. This level was chosen to make the stimuli clearly audible while avoiding excessive loudness for the subjects with CHL. The level of the BB-STRn stimuli was chosen based on the level per ERB_N, where ERB_N is the mean value of the equivalent rectangular bandwidth of the auditory filter for subjects with normal hearing (Glasberg and Moore, 1990). This level was at least 25 dB above the absolute threshold at all center frequencies with the constraint that the overall level did not exceed 90 dB SPL. The method used to achieve this is the same as described by Narne et al. (2018). The reader is referred to that paper for details.

The NB-STRn stimuli were presented together with pink noise that was bandpass filtered between 125 Hz and the lower edge frequency of the NB-STRn, which is denoted $f_{\min}$. For example, for the NB-STRn stimulus centered at 1000 Hz, the pink noise was bandpass filtered between 125 and 710 Hz. The filter had a slope of 100 dB/oct on each side. This noise was intended to prevent the detection of combination ripples falling below the passband of the stimuli. The level of the pink noise was chosen based on excitation patterns calculated as described by Moore et al. (1997), such that the excitation level evoked by the pink noise alone at frequency $f_{\min}$ was 15 dB below the excitation level evoked by the NB-STRn stimulus alone at $f_{\min}$. This relative level was chosen so that the pink noise would mask combination ripples, whose level is likely to be at least 15 dB below the level of the signal (Zwicker, 1981), while having a have minimal effect within the passband of the stimuli. The overall level of the pink noise was 13, 11, 10, and 9 dB below the level of the NB-STRn stimuli for center frequencies of 500, 1000, 2000, and 4000 Hz, respectively. The pink noise was turned on 100 ms before the start of the first STRn burst and was turned off 100 ms after the end of the last STRn burst. The onset and offset of the noise had 80-ms cosine-squared ramps.

$STRt_{dir}$ thresholds were estimated using a three-alternative forced-choice (3-AFC) procedure. Within each trial there were three pairs of stimulus bursts, each burst with a duration of 750 ms, including 100-ms $\cos^2$ onset and offset ramps, giving six successive bursts in total. The silent interval between bursts within a pair was 150 ms, and the silent interval between pairs was 500 ms. Two of the pairs were identical, both containing two downward-gliding STRn bursts (denoted DD). The other pair contained a downward-gliding STRn burst followed by an upward-gliding burst (denoted DU). The order of the pairs was random. Thus, the possible orders within a trial were DU DD DD, DD DU DD, and DD DD DU. The task was to indicate the pair in which the bursts were different. Correct-answer feedback was given on each trial, after the subject had responded. The value of *D* was initially set to 1.5 RPO for NH subjects and 0.5 RPO for CHL subjects. *D* was increased following two correct responses and decreased following one incorrect response, so as to track the 70.7% correct point on the psychometric function (Levitt, 1971). The step size was initially 0.5 RPO and after two reversals it was decreased to 0.2 RPO. The arithmetic mean of the values of *D* at the last six reversal points in a block of eight was taken as the threshold. All subjects were given two practice runs with each of the center frequencies of the NB-STRn stimuli and with the BB-STRn stimuli before commencing the experiment. In the main experiment, threshold was measured first for the BB-STRn and then for the NB-STRn stimuli. For the latter, the order of testing the different center frequencies was randomized across subjects.

3. Results of experiment 1

3.1. $STRt_{dir}$ *thresholds*

Fig. 2 shows individual and mean $STRt_{dir}$ thresholds for the NB-STRn stimuli and for the BB-STRn stimulus (right) for NH (open squares) and CHL (filled squares) subjects. An analysis of variance (ANOVA) with group as between-subjects factor and frequency band as within-subjects factor (including the data for the BB-STRn) showed no significant effect of frequency band [$F_{(4, 80)} = 2.22$, $p = 0.07$], a significant effect of group [$F_{(1, 20)} = 432.09$, $p < 0.001$, $\eta^2 = 0.9$] and no significant interaction [$F_{(4, 80)} = 1.23$, $p = 0.304$]. Independent samples *t*-tests showed that the difference between groups was significant for all frequency bands, including BB-$STRt_{dir}$, after Bonferroni correction for multiple comparisons ($t = -7.5$ to -13.9, $p < 0.001$). This is as expected from previous work showing that CHL is associated with reduced frequency selectivity (Glasberg and Moore, 1986; Narne et al., 2018). The BB-$STRt_{dir}$ thresholds are similar to those found previously for NH and CHL subjects using the same stimuli (Narne et al., 2018).

Insert Fig.2 Here

For the NH group, the mean BB-$STRt_{dir}$ threshold was similar to the mean NB-$STRt_{dir}$ threshold for each center frequency. Thus, there was no clear benefit of the presence of ripples over a wide frequency range. For the CHL group, the mean BB-$STRt_{dir}$ threshold was slightly higher (better) than any of the mean NB-$STRt_{dir}$ thresholds. However, the failure to find a significant interaction in the ANOVA described above indicates that this effect is not significant. Overall, these results are more consistent with the local model than with the global model.

3.2. Relationship between pure-tone thresholds and NB-$STRt_{dir}$/BB-$STRt_{dir}$ thresholds

To assess whether our results were consistent with those of previous studies showing a trend for frequency selectivity to worsen with increasing absolute threshold, the correlation between NB-$STRt_{dir}$ thresholds and pure-tone thresholds was calculated for each center frequency. For the two groups combined, all correlations were high and significant [$r = -0.81$ ($p<0.001$), -0.77 ($p<0.001$), -0.61 ($p<0.001$) and -0.68 ($p<0.001$), for center frequencies of 500, 1000, 2000 and 4000 Hz, respectively]. However, for the CHL group alone, NB-$STRt_{dir}$ thresholds were not significantly correlated with pure-tone thresholds for any center frequency (r ranged from -0.16 to 0.33).

For the two groups combined, the correlation between BB-$STRt_{dir}$ thresholds and pure-tone thresholds at the individual frequencies (500, 1000, 2000 and 4000 Hz) was high and significant for all frequencies [$r = -0.77$ ($p<0.001$), -0.87 ($p<0.001$), -0.88 ($p<0.001$) and -0.83 ($p<0.001$), for frequencies of 500, 1000, 2000 and 4000 Hz, respectively]. For the CHL group alone, BB-STRt$_{dir}$ thresholds were not significantly correlated with pure-tone thresholds for the individual frequencies (r ranged from -0.37 to 0.22) or with the mean absolute threshold across 500 to 4000 Hz ($r = -0.29$, $p = 0.37$). The group results are consistent with previous research showing that greater hearing loss is associated with poorer frequency resolution (Glasberg and Moore, 1986; Moore, 2007). The lack of significant correlations for the CHL group alone contrasts with the finding of significant correlations in a previous study in which BB-STRt$_{dir}$ thresholds were measured for subjects with CHL (Narne et al., 2018). The discrepancy may have occurred because the subjects in the earlier study mostly had more steeply sloping audiograms than the subjects tested here. Also, the subjects in the earlier study had a wider range of PTA values than the subjects tested here.

3.3. Relationship between BB-STRt$_{dir}$ thresholds and NB-STRt$_{dir}$ thresholds

The correlations between BB-STRt$_{dir}$ thresholds and NB-STRt$_{dir}$ thresholds were calculated for each center frequency for the two groups combined. All correlations were high and significant [$r = 0.84$ ($p<0.001$), 0.85 ($p<0.002$), 0.82 ($p<0.001$) and 0.80 ($p<0.001$), for center frequencies of 500, 1000, 2000 and 4000 Hz, respectively]. However, for the CHL group alone, the only significant correlation was for the center frequency of 0.5 kHz ($r = 0.68$, $p<0.05$).

As described above, both the NB-STRt$_{dir}$ thresholds and the BB-STRt$_{dir}$ thresholds were correlated with pure-tone thresholds. This mutual correlation with audiometric thresholds could account for the significant correlations between the NB-STRt$_{dir}$ thresholds and the BB-STRt$_{dir}$ thresholds when the data for the two groups were combined. To assess whether this was the case, correlations between the BB-STRt$_{dir}$ thresholds and the NB-STRtdir thresholds were calculated for each center frequency with the effect of the pure-tone threshold at that frequency partialed out. The partial correlation was significant at 500 Hz [r = 0.53 (p < 0.01)] for the combined data and also for the CHL group alone (r = 0.64, p<0.01). The partial correlation was not significant for the other center frequencies, indicating that the correlations between BB-STRt$_{dir}$ thresholds and NB-STRt$_{dir}$ thresholds for those frequencies may have been caused by their mutual correlation with absolute thresholds.

The significant partial correlation between BB-STRt$_{dir}$ thresholds and the NB-STRt$_{dir}$ thresholds for the center frequency of 500 Hz suggests that some factor other than absolute threshold, presumably frequency selectivity, contributed to the correlation between the NB-STRt$_{dir}$ thresholds and the BB-STRt$_{dir}$ thresholds. However, the mean NB-STRt$_{dir}$ threshold across subjects was not better for the center frequency of 500 Hz than for the other center frequencies (see Fig. 2), which does not support the idea that the correlation between BB-STRt$_{dir}$ thresholds and the NB-STRt$_{dir}$ thresholds for the center frequency of 500 Hz occurred because frequency resolution was best at 500 Hz.

3.4. Discussion

The mean BB-STRt$_{dir}$ threshold was lower (worse) for the CHL group than for the NH group by a factor of about 2.5. The BB-STRt$_{dir}$ thresholds obtained in the present study for the NH and CHL groups are comparable to those reported by Narne et al. (2018) using the STRt$_{dir}$ task and to those obtained in other studies using static broadband spectral-ripple stimuli (Henry et al., 2005; Won et al., 2007). For the three highest center frequencies, the mean NB-STRt$_{dir}$ thresholds for the NH subjects were lower (worse) than those obtained by Supin and colleagues (Supin, 2011; Supin et al., 1998; Supin et al., 2001; Supin et al., 2003) for narrowband SRn stimuli using their ripple-reversal test. They found that for narrowband

SRn stimuli with logarithmically spaced ripples the threshold value of *D* for NH subjects was about 5 RPO at 500 Hz, 8 RPO at 1000 and 2000 Hz, and 9 RPO at 4000 Hz (Supin et al., 1998; Supin et al., 2001), whereas we obtained thresholds of about 5.5 RPO for all center frequencies. The difference may partly reflect the fact that our stimuli had a peak-to-valley spectral modulation depth of 20 dB while their stimuli were “fully” (100%) spectrally modulated. However, for a spectral modulation depth comparable to that used here, Supin et al. (1999) found ripple densities at threshold of about 5 RPO at 500 Hz, 6 RPO at 1000 Hz, 8 RPO at 2000 Hz, and 8.5 RPO at 4000 Hz. The values at 2 and 4 kHz are still higher than found here.

Two factors may have contributed to the discrepancy across studies. One is that in the stimuli used by Supin and colleagues the ripple phase shifted five times within the target stimuli, providing the opportunity for “multiple looks” and perhaps making the task easier. The other is that their subjects may have made use of a cue related to changes in excitation level at center frequencies corresponding to the low-frequency spectral edges of the stimuli (Azadpour and McKay, 2012; Narne et al., 2016). Consistent with this, Supin et al. (2001) found that the addition of a noise in the frequency region just below or overlapping with the lower spectral edge of one-octave-wide SRn stimuli led to markedly worse performance than obtained with a noise that was centered well below the passband of the SRn stimuli or just above the upper spectral edge. The threshold value of *D* in the presence of a noise in the frequency region just below or slightly overlapping with the lower spectral edge of the SRn stimuli was 5-6 RPO, depending on the center frequency, consistent with the thresholds obtained here using the $STRt_{dir}$ test. Supin et al. argued that the deleterious effect of the added noise may be due to lateral inhibition or suppression. It seems more plausible to us that the noise impaired performance because it reduced the ability to use a cue related to fluctuations in excitation level on the low-frequency sides of the excitation patterns of the SRn stimuli.

The $STRt_{dir}$ stimuli also lead to fluctuations in excitation level on the low-frequency sides of the excitation patterns evoked by the stimuli, but the fluctuations are very similar for upward-gliding and downward-gliding ripples, as described in our earlier papers (Narne et al., 2018; 2019). Hence, they should not provide a useful cue for performing the $STRt_{dir}$ test. To confirm that this was the case, ten NH subjects were tested using the NB-$STRt_{dir}$ test in the presence and absence of pink noise whose level was the same as used in the main experiment reported here. The center frequencies were 500, 1000, 2000 and 4000 Hz. The results are shown in Fig. 3. The noise had no effect, indicating that subjects did not make use of cues related to fluctuations in excitation level on the low-frequency sides of the excitation patterns. These results also indicate that performance of the NB-$STRt_{dir}$ test was not influenced by combination ripples when the pink noise was absent.

Insert Fig.3. Here

For the NH group, the mean BB-$STRt_{dir}$ threshold was not higher than the mean NB-$STRt_{dir}$ thresholds, which is not consistent with the global model, which holds that thresholds for broadband stimuli depend on the integration of information across a wide frequency range. Our results are consistent with those of Eddins and Bero (2007) and Supin et al. (1998), but not consistent with the results of Milekhina et al. (2018). For the CHL group, the mean BB-$STRt_{dir}$ threshold was slightly but not significantly higher than the NB-$STRt_{dir}$ thresholds. Similar observations were made by Anderson et al. (2011) for CI subjects and the discrimination of BB and NB SRn stimuli. These results may indicate a small amount of integration of information across frequency regions.

4. Experiment 2: measurement of PTCs

PTCs were measured using a "fast" method that employs a masker that is slowly swept in center frequency from a low to a high value, or vice versa (Sęk et al., 2005; Sęk and Moore, 2011).

4.1. Subjects and equipment

The subjects and equipment were the same as for experiment 1.

4.2. Method

The signal was a pulsed sinusoidal tone of 200-ms duration (20-ms rise-fall time) with an interval of 200 ms between pulses. The use of a pulsed signal helps the subject to "know what to listen for" (Sęk et al., 2005). The signal was presented 10 dB above the absolute threshold estimated using the forced-choice method. The signal frequencies were 500, 1000, 2000, and 4000 Hz.

The masker was a narrowband noise with a bandwidth of 180 Hz for the signal frequencies of 500 and 1000 Hz and 320 Hz for the signal frequencies of 2000 and 4000 Hz. The bandwidths were chosen to reduce the salience of beats as a cue while limiting the masker bandwidth to be close to the value of ERB_N at that center frequency (Kluk and Moore, 2004; Kluk and Moore, 2005). The level of the noise required just to mask the signal was determined as a function of the masker center frequency, f_c, using a procedure similar to that used in Békèsy audiometry. Initially, subjects were presented with several pulses of the signal without the masker to help them to "know what to listen for". After these initial pulses, the masker was turned on. The starting level of the masker was 50 dB SPL for the NH subjects, and 70 dB SPL for the CHL subjects. The subjects were instructed to press the spacebar on the keyboard when the signal was audible and to release the spacebar when the signal was inaudible. While the spacebar was pressed, the level of the noise increased at a rate of 2 dB/s. While the spacebar was released, the level decreased at the same rate. This rate was chosen to avoid more variable PTCs that can occur with higher rates of change in masker level (Sęk et al., 2005; Warnaar and Dreschler, 2012). The value of f_c was swept logarithmically from an octave below f_c to half an octave above f_c (upward sweep) or vice versa (downward sweep) over a duration of 240 s.

Subjects were given practice until they produced PTCs of the expected general shape that were consistent across runs. Then, two PTCs were measured for each signal frequency, one with an upward and one with a downward masker sweep. The order of testing the different center frequencies was randomized across subjects. The raw PTCs have a jagged shape. The PTCs were smoothed using a method described by Sęk and Moore (2011) called "double lowpass filtering with a filter bandwidth of 0.25 times the Nyquist frequency". The data were passed through a lowpass filter, the output was reversed in time and the resulting data were filtered again using the same lowpass filter. Finally, the output from the second filtering stage was reversed again. This double lowpass filtering effectively removes any phase shifts produced by the filter, which leads to an unbiased estimate of the tip frequency. Some examples of the smoothed PTCs are shown in Fig. 4. The sharpness of the PTCs was quantified by estimating Q10, which is the signal frequency divided by the bandwidth 10 dB above the level at the tip. For each signal frequency, the Q10 value was estimated separately for the upward sweep and downward sweep, and the two estimates were averaged.

Insert Fig.4 Here

5. Results of experiment 2

5.1. Q10 values for the NH and CHL groups

Fig. 5 shows Q10 values derived from the PTCs. The Q10 values were higher for the NH group than for the CHL group by a factor of 1.7 to 2.0. An ANOVA on the Q10 values with group as a between-subjects factor and signal frequency as a within-subjects factor showed a significant effect of signal frequency [$F_{(3,60)} = 3.80$, $p < 0.05$, $\eta^2 = 0.18$], a significant effect of group [$F_{(1,20)} = 309.00$, $p < 0.001$, $\eta^2 = 0.81$], and a significant interaction [$F_{(3,60)} = 3.31$, $p < 0.05$, $\eta^2 = 0.16$). Independent samples *t*-tests showed that the difference between groups was significant for all signal frequencies after Bonferroni correction for multiple comparisons ($t = -7.59$ to -12.8, $p < 0.01$).

Insert Fig.5. Here

To explore the interaction, separate one-way repeated-measures ANOVAs were conducted for each group with frequency as the factor. For the NH subjects, there was a significant effect of frequency ($F_{(3,27)} = 4.07$, $p < 0.05$, $\eta^2 = 0.23$). Bonferroni corrected pairwise comparisons showed that the mean Q10 at 2000 Hz was higher than at 500 and 1000 Hz (both $p < 0.05$). However, the effect was small. No other comparisons were significant. For the CHL subjects, there was no significant effect of frequency ($F_{(3,33)} = 1.62$, $p = 0.20$, $\eta^2 = 0.08$).

5.2. Relationship between pure-tone thresholds and Q10 values

The correlation between Q10 values and pure-tone thresholds was calculated for each center frequency. For the two groups combined, all correlations were high and significant [$r = -0.87$ ($p<0.001$), -0.87 ($p<0.001$), -0.86 ($p<0.001$) and -0.79 ($p<0.001$), for center frequencies of 500, 1000, 2000 and 4000 Hz, respectively]. For the CHL group alone, Q10 values were not significantly correlated with the pure-tone thresholds at any frequency (r ranged from -0.1 to -0.4), although the correlations were in the expected direction.

5.3. Relationship between Q10 values and NB-STRt$_{dir}$ thresholds

If the NB-STRt$_{dir}$ thresholds provide a good measure of frequency resolution at the corresponding center frequency, then the NB-STRt$_{dir}$ thresholds should be correlated with the

Q10 values of the PTCs at the same center frequency. For the two groups combined, this prediction was supported; all correlations were high and significant [$r = 0.90$ ($p<0.001$), 0.91 ($p<0.002$), 0.91 ($p<0.001$) and 0.93 ($p<0.001$), for center frequencies of 500, 1000, 2000 and 4000 Hz, respectively]. However, for the CHL group alone, the correlations were significant only for the center frequencies of 500 and 1000 Hz ($r = 0.60$ and 0.58, respectively, both $p<0.05$). Correlations between the Q10 values and the NB-STRt$_{dir}$ threshold values for each center frequency were also calculated with the effect of the absolute threshold at each center frequency partialed out. For the two groups combined, the partial correlations were moderate and significant for all center frequencies [$r = 0.75$ ($p < 0.05$), $r = 0.58$ ($p < 0.05$), $r = 0.72$ ($p < 0.05$), $r = 0.67$ ($p < 0.05$) at 500, 1000, 2000 and 4000 Hz, respectively]. For the CHL group alone, the only significant correlation was at 500 Hz ($r = 0.63$, $p<0.05$).

Overall, these results support the idea that the NB-STRt$_{dir}$ thresholds provide a good measure of frequency resolution at the corresponding center frequency. The failure to find significant correlations between the NB-STRt$_{dir}$ thresholds and the Q10 values of the PTCs for the CHL group alone at 2000 and 4000 Hz may reflect errors of measurement and the limited ranges of the NB-STRt$_{dir}$ thresholds and Q10 values for the CHL group alone.

6. Discussion

The mean Q10 values of the PTCs for the NH and CHL groups were in good agreement with those obtained in previous studies using fast PTCs (Charaziak et al., 2012; Kluk and Moore, 2004; Kluk and Moore, 2005; Moore et al., 2019; Sęk et al., 2005; Shabana et al., 2014), although Bidelman et al. (2016) found somewhat higher Q10 values for musically trained subjects. At each center frequency, the NB-STRt$_{dir}$ thresholds were highly correlated with the Q10 values derived from the PTCs, supporting the idea that the NB-STRt$_{dir}$ thresholds provide a good measure of frequency resolution in the frequency region corresponding to the center frequency. To quantify the relationship between Q10 values and NB-STRt$_{dir}$ thresholds, linear regression lines were fitted to the data for the individual subjects. This was done separately for each center frequency and for the data for all frequencies combined. The outcomes are illustrated in Fig. 6. The regression lines fitted separately to the data for each center frequency (solid lines, blue online) accounted for at least 82% of the variance in the data. Furthermore, the slopes and intercepts were similar across center frequencies, as would be expected if the NB-STRt$_{dir}$ thresholds provide a good measure of frequency resolution. The regression line fitted to the data for all center frequencies combined (dashed lines in Fig. 6) was close to the regression lines for the individual center frequencies. The regression equation for the combined data was:

$$Q10 = 1.23 + 0.53D \qquad \text{for } 0.5 < D < 6.5 \qquad \text{(Eq. 1)}$$

It should be noted that both the Q10 values estimated from the PTCs and the NB-STRt$_{dir}$ thresholds have limitations as measures of frequency resolution. PTCs are probably influenced by “off-frequency listening”, which refers to the detection of the signal using an auditory filter that is not centered at the signal frequency (Johnson-Davies and Patterson, 1979; O'Loughlin and Moore, 1981b). When a low-level noise with a notch at the signal frequency is used to limit off-frequency listening, the tips of PTCs become broader and Q10 values become smaller (Moore et al., 1984; O'Loughlin and Moore, 1981a). Hence, the Q10 values estimated without such a low-level noise may over-estimate frequency resolution. The NB-STRt$_{dir}$ thresholds are probably not influenced by off-frequency listening, but they depend partly on “detection efficiency”, i.e. the ability to make use of a given amount of sensory information, whereas the Q10 measure derived from the PTCs depends on the shapes of the PTCs rather than on the masker levels required to reach threshold and is therefore hardly affected by detection efficiency. The CHL group were, on average, older than the NH group, and there is evidence that detection efficiency decreases with increasing age (Moore, 2019; Peters and Moore, 1992; Whiteford et al., 2017). The differences between $STRt_{dir}$ thresholds for the NH and CHL groups may reflect the combined effects of reduced frequency resolution and reduced detection efficiency, while differences in Q10 values between groups may reflect mainly reduced frequency resolution.

7. Conclusions

1. NB-$STRt_{dir}$ thresholds for octave-wide bands were highly correlated with the sharpness of PTCs (Q10 values) for each of the four center frequencies tested, suggesting that NB-$STRt_{dir}$ thresholds provide a good measure of frequency resolution at the corresponding center frequency.
2. NB-$STRt_{dir}$ thresholds were not affected by whether or not a pink noise was present in the frequency region below the passband of the NB-STRn stimuli, indicating that the results of the NB-$STRt_{dir}$ test when the pink noise was absent were not influenced by edge effects or by the presence of combination ripples.
3. BB-$STRt_{dir}$ thresholds were similar to NB-$STRt_{dir}$ thresholds for the NH group and were only slightly higher (better) than NB-$STRt_{dir}$ thresholds for the CHL group, suggesting at most a limited ability to combine information across frequency regions.

Acknowledgements

The first author extends his appreciation for support to Prof. N. P. Nataraja, Director, JSS Institute of Speech and Hearing. We thank Prof. Alexander Supin for assistance in understanding the stimuli used in his studies and thank the subjects for their co-operation.

References

Anderson, E. S., Nelson, D. A., Kreft, H., Nelson, P. B., Oxenham, A. J., 2011. Comparing spatial tuning curves, spectral ripple resolution, and speech perception in cochlear implant users. J. Acoust. Soc. Am. 130, 364-375.

Aronoff, J. M., Landsberger, D. M., 2013. The development of a modified spectral ripple test. J. Acoust. Soc. Am. 134, EL217-EL222.

Azadpour, M., McKay, C. M., 2012. A psychophysical method for measuring spatial resolution in cochlear implants. J. Assoc. Res. Otolaryngol. 13, 145-157.

Bidelman, G. M., Nelms, C., Bhagat, S. P., 2016. Musical experience sharpens human cochlear tuning. Hear. Res. 335, 40-46.

Charaziak, K. K., Souza, P., Siegel, J. H., 2012. Time-efficient measures of auditory frequency selectivity. Int. J. Audiol. 51, 317-325.

Drennan, W. R., Anderson, E. S., Won, J. H., Rubinstein, J. T., 2014. Validation of a clinical assessment of spectral-ripple resolution for cochlear implant users. Ear Hear. 35, e92-98.

Eddins, D. A., Bero, E. M., 2007. Spectral modulation detection as a function of modulation frequency, carrier bandwidth, and carrier frequency region. J. Acoust. Soc. Am. 121, 363-372.

Glasberg, B. R., Moore, B. C. J., 1986. Auditory filter shapes in subjects with unilateral and bilateral cochlear impairments. J. Acoust. Soc. Am. 79, 1020-1033.

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

Henry, B. A., Turner, C. W., 2003. The resolution of complex spectral patterns by cochlear implant and normal-hearing listeners. J. Acoust. Soc. Am. 113, 2861-2873.

Henry, B. A., Turner, C. W., Behrens, A., 2005. Spectral peak resolution and speech recognition in quiet: Normal hearing, hearing impaired, and cochlear implant listeners. J. Acoust. Soc. Am. 118, 1111-1121.

Johnson-Davies, D., Patterson, R. D., 1979. Psychophysical tuning curves: Restricting the listening band to the signal region. J. Acoust. Soc. Am. 65, 765-770.

Kluk, K., Moore, B. C. J., 2004. Factors affecting psychophysical tuning curves for normally hearing subjects. Hear. Res. 194, 118-134.

Kluk, K., Moore, B. C. J., 2005. Factors affecting psychophysical tuning curves for hearing-impaired subjects with high-frequency dead regions. Hear. Res. 200, 115-131.

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

Milekhina, O. N., Nechaev, D. I., Supin, A. Y., 2018. Estimates of frequency resolving power of humans by different methods: The role of sensory and cognitive factors. Hum. Physiol. 44, 357-363.

Moore, B. C. J., 2007. Cochlear Hearing Loss : Physiological, Psychological and Technical Issues, John Wiley & Sons, Sussex, UK.

Moore, B. C. J., 2019. The roles of temporal envelope and fine structure information in auditory perception. Acoust. Sci. Technol. 40, 61-83.

Moore, B. C. J., Glasberg, B. R., Baer, T., 1997. A model for the prediction of thresholds, loudness, and partial loudness. J. Audio Eng. Soc. 45, 224-240.

Moore, B. C. J., Glasberg, B. R., Low, K. E., Cope, T., Cope, W., 2006. Effects of level and frequency on the audibility of partials in inharmonic complex tones. J. Acoust. Soc. Am. 120, 934-44.

Moore, B. C. J., Glasberg, B. R., Roberts, B., 1984. Refining the measurement of psychophysical tuning curves. J. Acoust. Soc. Am. 76, 1057-66.

Moore, B. C. J., Ohgushi, K., 1993. Audibility of partials in inharmonic complex tones. J. Acoust. Soc. Am. 93, 452-461.

Moore, B. C. J., Wan, J., Varathanathan, A., Naddell, S., Baer, T., 2019. No effect of musical training on frequency selectivity estimated using three methods. Trends Hear. 23, 1-9.

Narne, V. K., Antony, P. J., Baer, T., Moore, B. C. J., 2019. Effect of ripple repetition rate on discrimination of ripple glide direction and the detection of brief tones in spectro-temporal ripple noise. J. Acoust. Soc. Am. 145, 2401-2408.

Narne, V. K., Prabhu, P. P., Van Dun, B., Moore, B. C. J., 2018. Ripple glide direction discrimination and its relationship to frequency selectivity estimated using notched noise. Acta Acust. united with Acust. 104, 1063-1074.

Narne, V. K., Sharma, M., Dun, B. V., Bansal, S., Prabhu, L., Moore, B. C. J., 2016. Effects of spectral smearing on performance of the spectral ripple and spectro-temporal ripple tests. J. Acoust. Soc. Am. 140, 4298-4306.

O'Loughlin, B. J., Moore, B. C. J., 1981a. Improving psychoacoustical tuning curves. Hear. Res. 5, 343-346.

O'Loughlin, B. J., Moore, B. C. J., 1981b. Off-frequency listening: effects on psychoacoustical tuning curves obtained in simultaneous and forward masking. J. Acoust. Soc. Am. 69, 1119-1125.

Peters, R. W., Moore, B. C. J., 1992. Auditory filters and aging: filters when audiometric thresholds are normal. In: Cazals, Y., Horner, K., Demany, L. (Eds.), Auditory Physiology and Perception, Pergamon, Oxford, pp. 179-187.

Sęk, A., Alcántara, J., Moore, B. C. J., Kluk, K., Wicher, A., 2005. Development of a fast method for determining psychophysical tuning curves. Int. J. Audiol. 44, 408-420.

Sęk, A., Moore, B. C. J., 2011. Implementation of a fast method for measuring psychophysical tuning curves. Int. J. Audiol. 50, 237-242.

Shabana, M., Moore, B. C. J., el-Khosht, M., Selim, M., Dokla, M., 2014. Fast psychophysical tuning curves of the cochlea in normal hearing individuals. Adv. Arab. Acad. Audio-Vestibul. J. 1, 12-17.

Supin, A. Y., 2011. Spectrum resolving power of hearing: measurements, baselines, and influence of maskers. Audiol. Res. 1, e27.

Supin, A. Y., Popov, V. V., Milekhina, O. N., Tarakanov, M. B., 1994. Frequency resolving power measured by rippled noise. Hear. Res. 78, 31-40.

Supin, A. Y., Popov, V. V., Milekhina, O. N., Tarakanov, M. B., 1998. Ripple density resolution for various rippled-noise patterns. J. Acoust. Soc. Am. 103, 2042-2050.

Supin, A. Y., Popov, V. V., Milekhina, O. N., Tarakanov, M. B., 1999. Ripple depth and density resolution of rippled noise. J. Acoust. Soc. Am. 106, 2800-4.

Supin, A. Y., Popov, V. V., Milekhina, O. N., Tarakanov, M. B., 2001. The effect of masking noise on rippled-spectrum resolution. Hear. Res. 151, 157-166.

Supin, A. Y., Popov, V. V., Milekhina, O. N., Tarakanov, M. B., 2003. Rippled-spectrum resolution dependence on level. Hear. Res. 185, 1-12.

Warnaar, B., Dreschler, W. A., 2012. Agreement between psychophysical tuning curves and the threshold equalizing noise test in dead region identification. Int. J. Audiol. 51, 456-464.

Whiteford, K. L., Kreft, H. A., Oxenham, A. J., 2017. Assessing the role of place and timing cues in coding frequency and amplitude modulation as a function of age. J. Assoc. Res. Otolaryngol. 18, 619-633.

Won, J. H., Clinard, C. G., Kwon, S., Dasika, V. K., Nie, K., Drennan, W. R., Tremblay, K. L., Rubinstein, J. T., 2011. Relationship between behavioral and physiological spectral-ripple discrimination. J. Assoc. Res. Otolaryngol. 12, 375-393.

Won, J. H., Drennan, W. R., Rubinstein, J. T., 2007. Spectral-ripple resolution correlates with speech reception in noise in cochlear implant users. J. Assoc. Res. Otolaryngol. 392, 384-392.

Zwicker, E., 1981. Dependence of level and phase of the (2f1−f2)-cancellation tone on frequency range, frequency difference, level of primaries, and subject. J. Acoust. Soc. Am. 70, 1277-1288.

Figure Legends

Fig. 1. Thick lines with square symbols show mean audiometric thresholds for the NH subjects (unfilled squares) and CHL subjects (filled squares). Individuals audiograms are shown by thin dashed grey lines without symbols for the NH subjects and grey lines with symbols for the CHL subjects (color online).

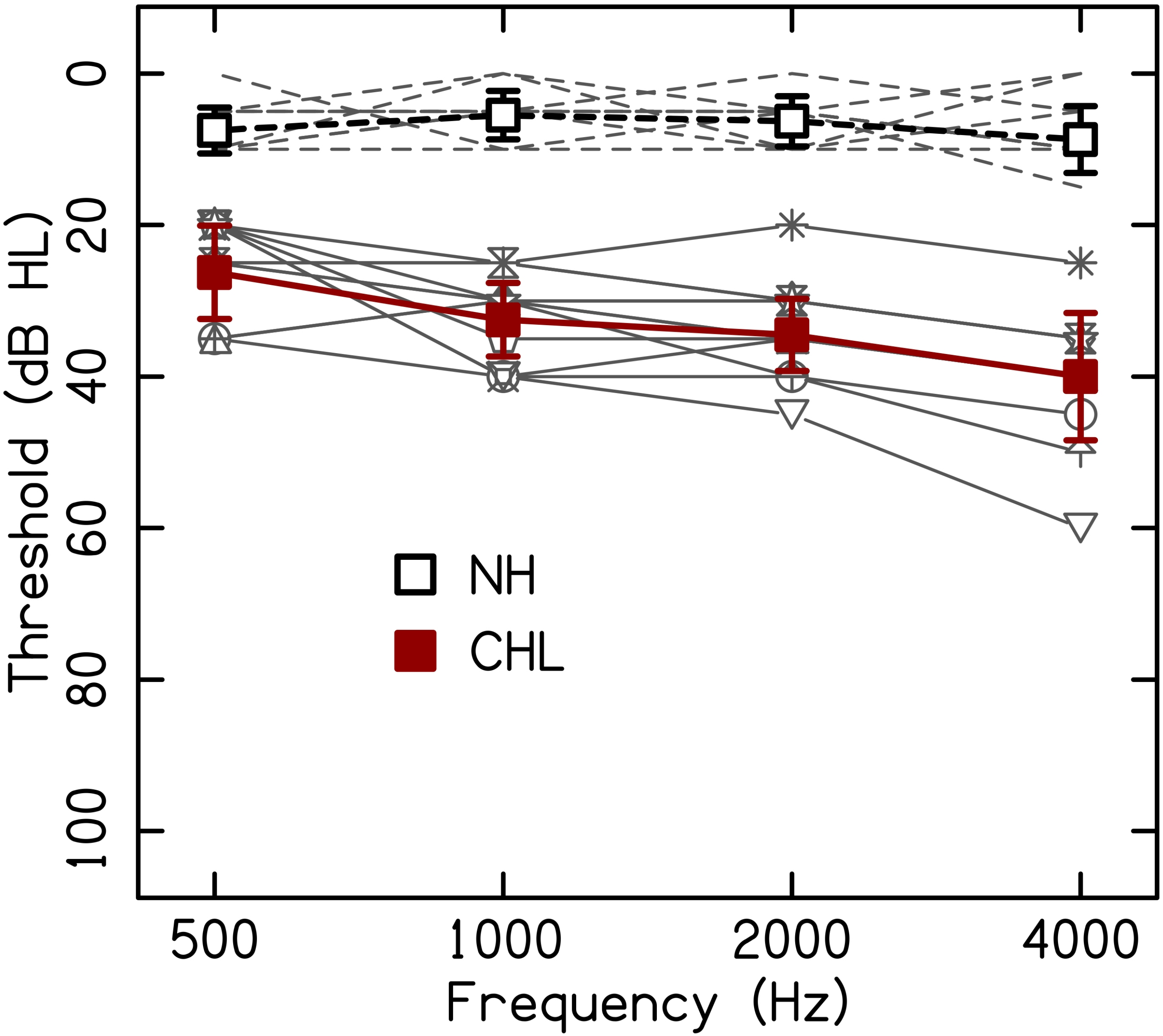
Fig. 2. Thick lines with square symbols show mean $STRt_{dir}$ thresholds as a function of center frequency for the narrowband stimuli and for the broadband stimuli (right) for NH subjects (unfilled squares) and CHL subjects (filled squares) (color online). Error bars indicate ±1 SD across subjects. Individual data are shown by thin dashed grey lines for the NH subjects and thin grey lines with symbols for the CHL subjects.

Fig. 3. Mean NB-$STRt_{dir}$ thresholds as a function of center frequency with pink noise (filled squares) and without pink noise (open squares) (color online). Error bars indicate ±1 SD

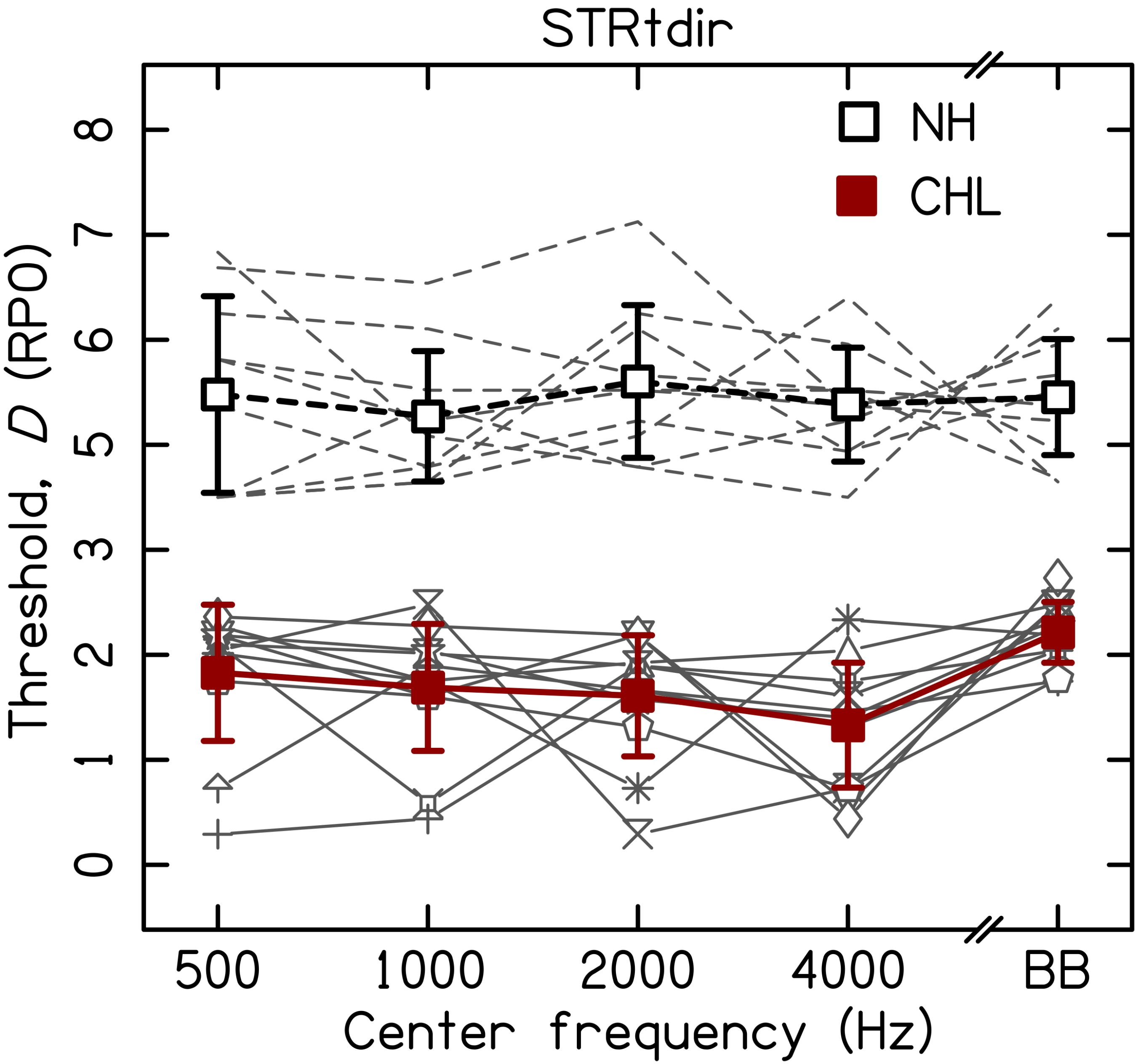
Fig. 4. Examples of PTCs after smoothing using double low-pass filtering. For each signal frequency, the solid curve is for an upward masker frequency sweep and the dashed curve is for a downward frequency sweep.

Fig. 5. Thick lines with square symbols show mean Q10 values derived from the PTCs as a function of center frequency for NH subjects (unfilled squares) and CHL subjects (filled squares) (color online). Error bars indicate ±1 SD. Individual data are shown by thin dashed grey lines for the NH subjects and thin grey lines with symbols for the CHL subjects.

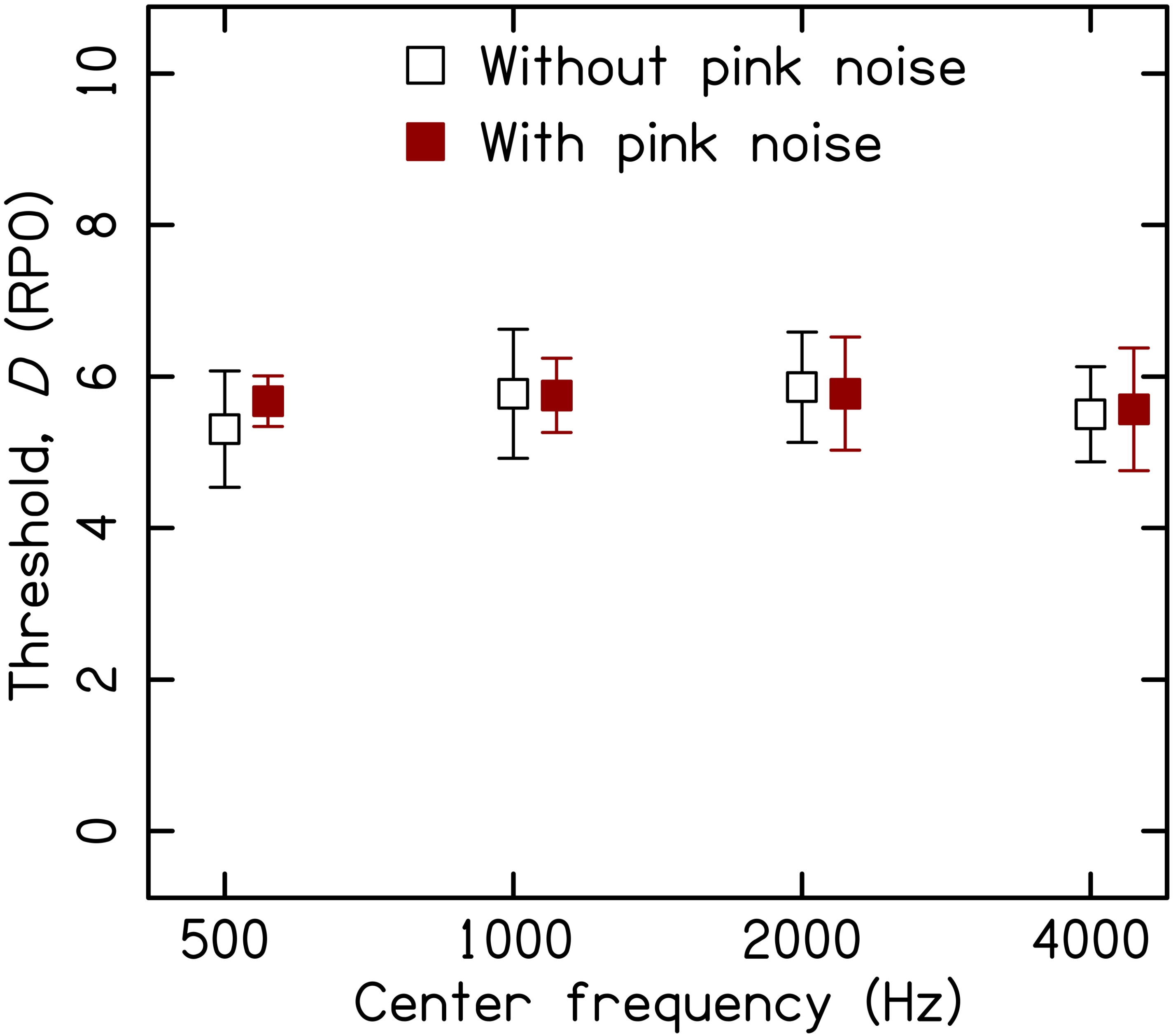
Fig. 6. Scatter plots of individual Q10 values versus NB-$STRt_{dir}$ thresholds. Each panel shows results for one center frequency. The solid lines are linear regression lines fitted to the data for each center frequency (color online). The equations for these lines are given in the respective panels. The dashed lines are the regression line fitted to the data for all frequencies combined.



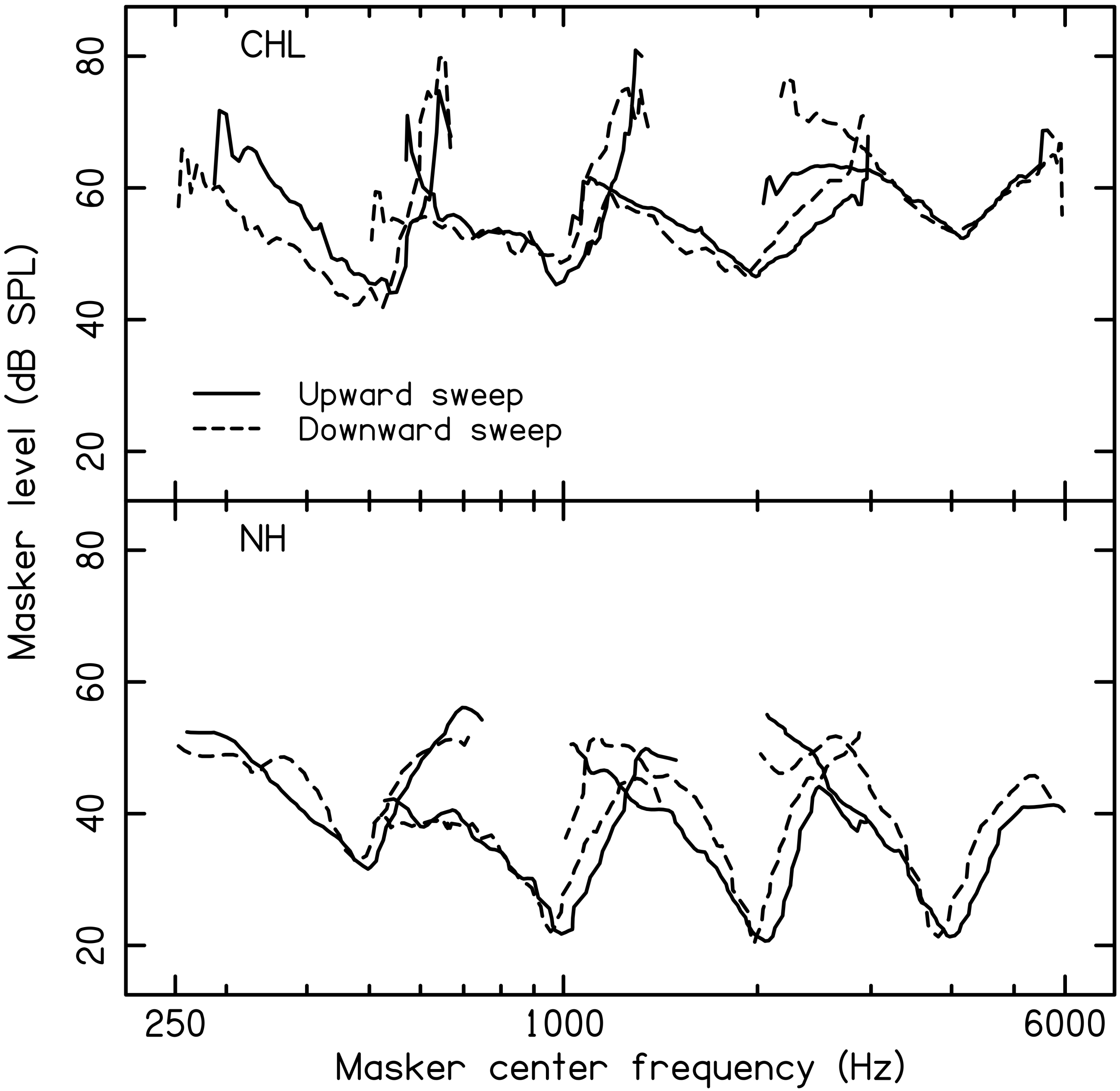
Threshold (dB HL)
0
20
40
60
80
100
500
1000
2000
4000
Frequency (Hz)
NH
CHL



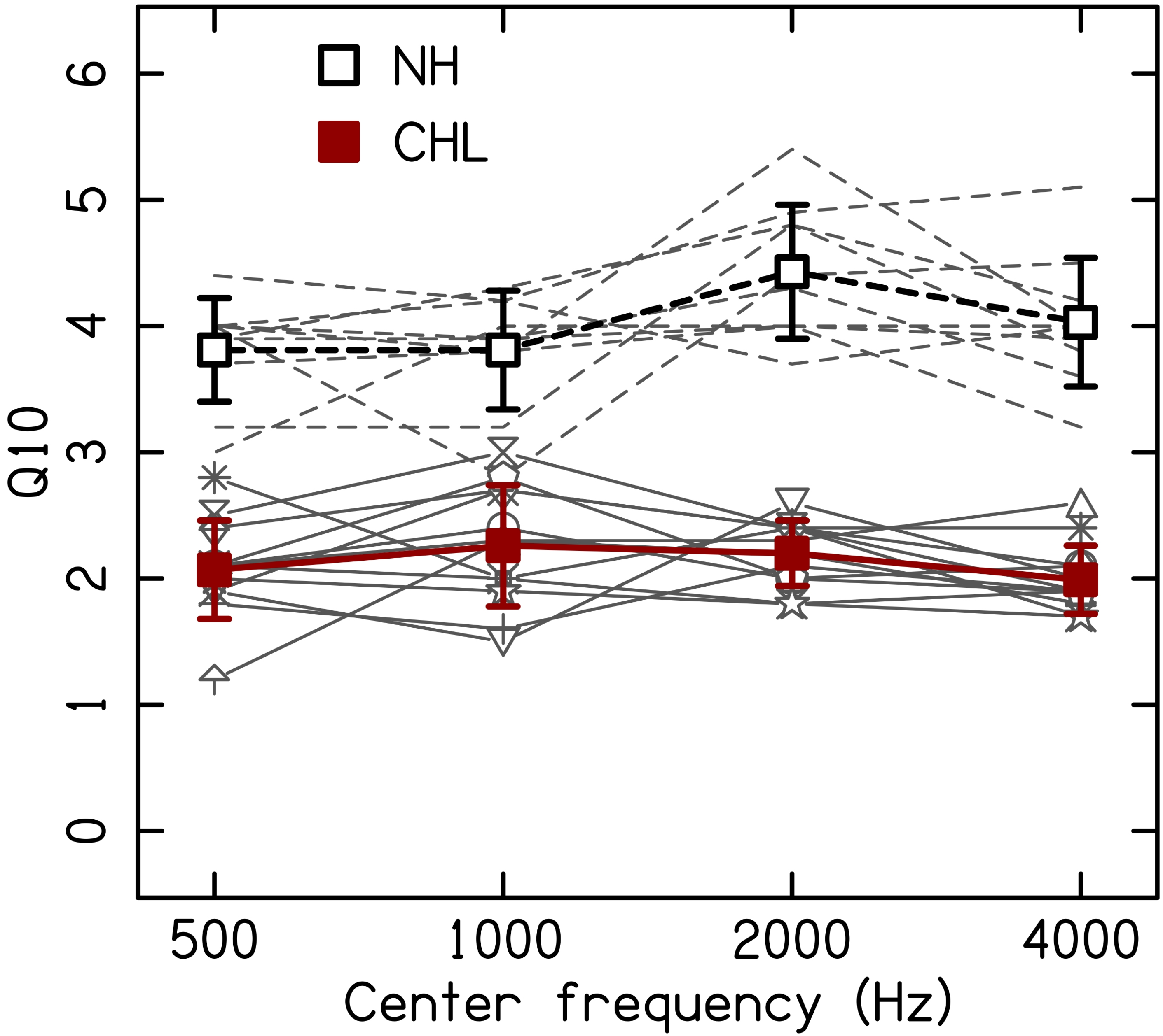
STRtdir
NH
CHL
Threshold, D (RPO)
0
1
2
3
5
6
7
8
500
1000
2000
4000
BB
Center frequency (Hz)



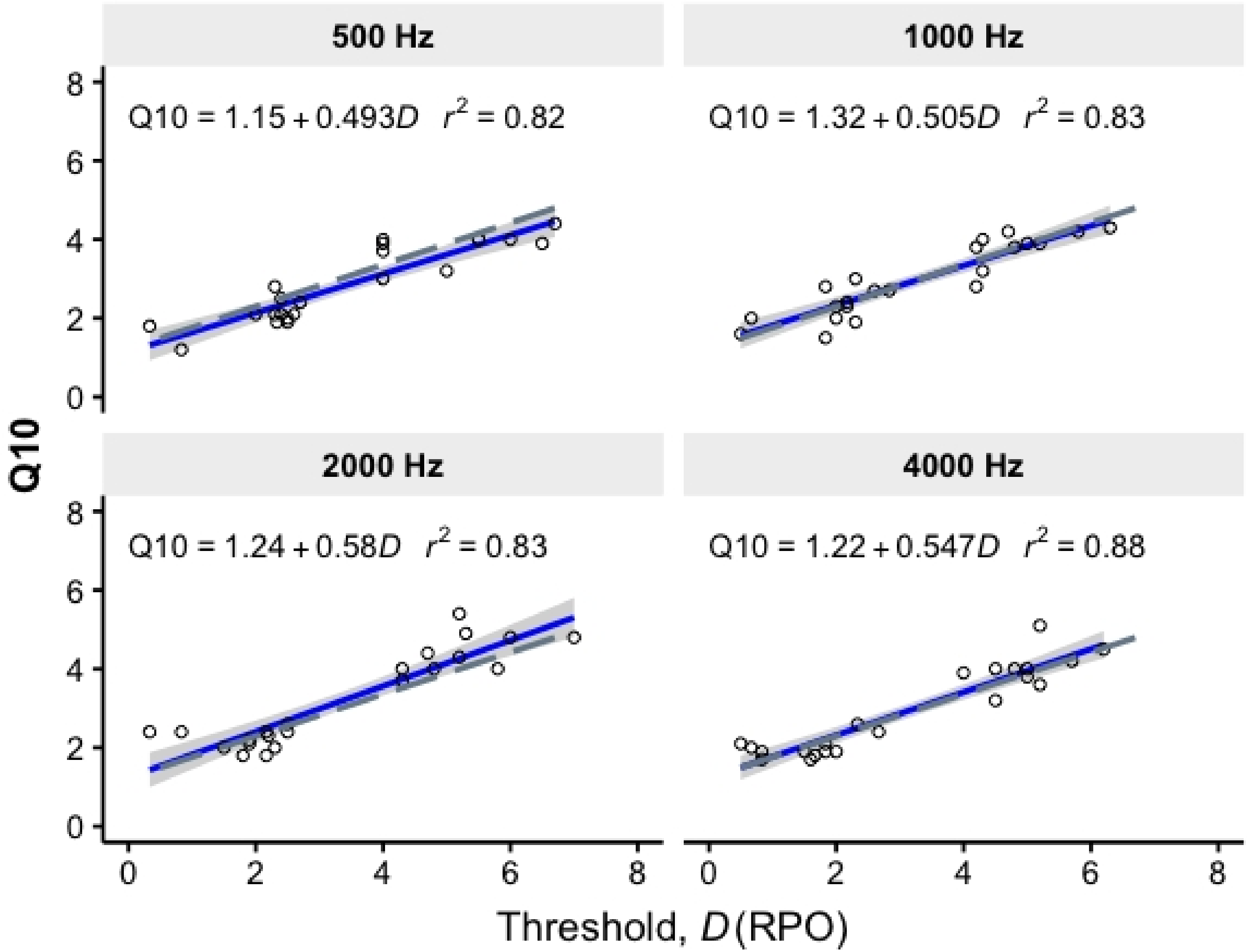
Without pink noise
With pink noise
Threshold, D (RPO)
0
2
4
6
8
10
500
1000
2000
4000
Center frequency (Hz)



CHL
80
60
40
20
Upward sweep
Downward sweep
NH
80
60
40
20
Masker level (dB SPL)
250
1000
6000
Masker center frequency (Hz)



NH
CHL
Q10
0
1
2
3
4
5
6
500
1000
2000
4000
Center frequency (Hz)



500 Hz
1000 Hz
2000 Hz
4000 Hz
Q10 = 1.15 + 0.493D r2 = 0.82
Q10 = 1.32 + 0.505D r2 = 0.83
Q10 = 1.24 + 0.58D r2 = 0.83
Q10 = 1.22 + 0.547D r2 = 0.88
Q10
0
2
4
6
8
Threshold, D (RPO)