Effects of cochlear compression and frequency selectivity on pitch discrimination of complex tones with unresolved harmonics

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Physiological studies have shown that noise-induced sensorineural hearing loss (SNHL) enhances the amplitude of envelope coding in auditory-nerve fibers. As pitch coding of unresolved complex tones is assumed to rely on temporal envelope coding mechanisms, this study investigated pitch-discrimination performance in listeners with SNHL. Pitch-discrimination thresholds were obtained in 14 normal-hearing (NH) and 10 hearing-impaired (HI) listeners for sine-phase (SP) and random-phase (RP) unresolved complex tones. The HI listeners performed, on average, similarly as the NH listeners in the SP condition and worse than NH listeners in the RP condition. Cochlear compression and auditory filter bandwidths were estimated in the same listeners. A significant correlation was found between the reduction of cochlear compression and the difference between RP and SP pitch-discrimination thresholds. The effects of degraded frequency selectivity and loss of compression were considered in a model as potential factors in envelope enhancement. The model revealed that a broadening of the auditory filters led to an increase of the modulation depth in the SP condition, while it did not have any effect for the RP condition. Overall, these findings suggest that both reduced cochlear compression and auditory filter broadening alter the envelope representation of unresolved complex tones, leading to changes in pitch-discrimination performance.

INTRODUCTION

Sensorineural hearing loss (SNHL) is commonly associated with reduced frequency selectivity and a reduced ability to extract temporal fine structure information (Moore et al., 2006; Hopkins and Moore, 2007; Strelcyk and Dau, 2009). However, recent physiological studies in animals showed that noise-induced SNHL increases the temporal precision and the amplitude of envelope coding in single auditory-nerve fibers (Kale and Heinz, 2010; Henry et al., 2014). These findings were ascribed to a variety of factors, such as broader auditory filters, a reduction of cochlear compression due to outer hair cell damage and altered auditory-nerve response temporal dynamics. Thus, while fine spectro-temporal cues are disrupted,

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temporal envelope cues may be enhanced and the relative importance of spectral and temporal cues for pitch processing may be altered in listeners with SNHL. Although it is commonly reported that hearing-impaired (HI) listeners have disrupted abilities in pitch discrimination of complex tones (Hoekstra and Ritsma, 1977; Arehart, 1994; Bernstein and Oxenham, 2006), a more precise examination of these findings suggests that the performance of HI listeners is not always disrupted as compared to NH listeners. In fact, some studies showed a similar performance of HI *vs.* NH listeners in pitch discrimination of complex tones with unresolved harmonics (Arehart, 1994; Bernstein and Oxenham, 2006). Since the broadening of auditory filters in HI listeners leads to an increased amount of unresolved harmonics as compared to NH listeners, it seems plausible that HI listeners rely more on the temporal information conveyed by the unresolved complex tones than on the fine spectro-temporal information conveyed by the resolved complexes. It is still unclear whether the altered importance of temporal *vs.* spectral cues for pitch discrimination may be additionally due to the suggested enhancement of temporal envelope coding with SNHL (Kale and Heinz, 2010; Henry *et al.*, 2014).

The aim of the present behavioural study was to clarify (i) whether human listeners with SNHL show an enhanced pitch discrimination performance for unresolved complexes, and (ii) if this enhancement is related to the broadening of auditory filters and/or to the reduction of cochlear compression. Pitch discrimination of complex tones was investigated behaviourally as a function of the fundamental frequency (F_0) in NH listeners and listeners with SNHL. Additionally, auditory filter bandwidths and cochlear compression were estimated in the same listeners to assess how SNHL was related to pitch discrimination performance. Finally, a simplified peripheral model was used to predict how filter broadening and cochlear compression affected the envelope representation of unresolved complex tones.

METHOD

Listeners

Fourteen NH listeners and ten HI listeners participated in this study. All NH listeners had hearing thresholds of less than 20 dB hearing level (HL) at all audiometric frequencies between 125 Hz and 8 kHz. The HI listeners had hearing thresholds between 30 and 60 dB HL at the audiometric frequencies between 1 and 4 kHz.

Pitch discrimination of complex tones

A three-alternative forced-choice (3-AFC) paradigm was used in combination with a weighted up-down method (Kaernbach, 1991) to measure the 75% point on the psychometric function. For each trial, two intervals contained a reference complex tone with a fixed F_0 and one interval contained a deviant complex tone with a larger F_0. The listeners' task was to select the interval containing the tone with the highest pitch. Before the actual test, the listeners performed three repetitions of training. The final value of F_0DL was calculated from the mean of three repetitions.

All signals consisted of 300-ms complex tones embedded in threshold equalizing noise (TEN; Moore *et al.*, 2000). The level of each component of the complex tone was set at 12.5 dB sensation level (SL) relative to the mean pure tone thresholds (at 1.5, 2, and 3 kHz) in TEN. For the NH listeners, the level of the TEN was set to 55 dB SPL per equivalent rectangular bandwidth (ERB; Glasberg and Moore, 1990) to mask the combination tones. For the HI listeners, pure-tone detection in quiet was performed at 1.5, 2, and 3 kHz and the level of the TEN was set at the maximum threshold measured in this range. The complex tones were created by summing harmonic components either in sine phase (SP) or random phase (RP) to vary the envelope peakiness. All HI listeners carried out the SP and RP conditions, whereas only 9 out of the 14 NH listeners completed the measurements for both conditions. Conditions of varying resolvability were achieved by bandpass filtering the complexes between 1.5 and 3.5 kHz, with 50 dB/octave slopes.

Auditory-filter bandwidth estimation

The auditory-filter bandwidth at 2 kHz was estimated from the temporal modulation transfer functions (TMTFs) in the 10 HI listeners. A 3-AFC paradigm, in combination with a weighted up-down rule, was used to measure modulation detection thresholds at the 75% point of the psychometric function. For each trial, two intervals contained a 300-ms pure tone at 2 kHz and one interval contained a sinusoidally amplitude-modulated 2-kHz tone at modulation frequencies (f_ms) between 25 and 1500 Hz. For each listener, the auditory-filter bandwidth was estimated at the f_m leading to a modulation threshold that was 9.5 dB below the maximum point of the TMTF. This point was selected since it led to an estimated filter bandwidth of 325 Hz at 2 kHz for NH listeners, which corresponds to the mean equivalent rectangular bandwidth (ERB) estimated via the notched-noise method by Bernstein and Oxenham (2006).

Cochlear compression estimation

Masker thresholds were measured in nine out of the 10 HI listeners as a function of the temporal gap between a 16-ms probe at 2 kHz and a 200-ms masker, either “on-frequency” at 2 kHz or “off-frequency” at 0.6 of the probe frequency (Fereczkowski, 2015). The on-frequency and off-frequency masker thresholds were paired to form a set of basilar membrane input/output (BM I/O) points (Nelson et al., 2001). A two-section function was fitted to the set of points to approximate the listener’s BM I/O function and the inverse slope of the shallow section was taken as an estimate of the compression ratio at 2 kHz (CR).

RESULTS

Figure 1 depicts the mean pitch-discrimination thresholds for NH listeners (black solid symbols), as well as the individual thresholds for HI listeners (open symbols), for the SP condition (left panel) and the RP condition (right panel). The thresholds for both conditions showed similar trends for the NH listeners, whereby F_0DLs decreased with increasing F_0. A one-way ANOVA confirmed a significant effect of

F_0 for both conditions [SP: $F(8,117) = 10$, $p < 0.001$; RP: $F(8,72) = 12.6$, $p < 0.001$]. The current findings are in agreement with previously reported pitch-discrimination thresholds (Bernstein and Oxenham, 2006), where the improvement in performance with increasing F_0 was thought to reflect the progressive increase of the resolvability of the harmonics. The grey shaded area in Fig. 1 depicts the two conditions (at F_0s of 100 and 125 Hz) for which the harmonics are considered to be completely unresolved – i.e., no significant effect of F_0 between the mean thresholds of NH listeners [SP: $F(1,26) = 0.05$, $p = 0.833$; RP: $F(1,16) = 0.69$, $p = 0.420$].

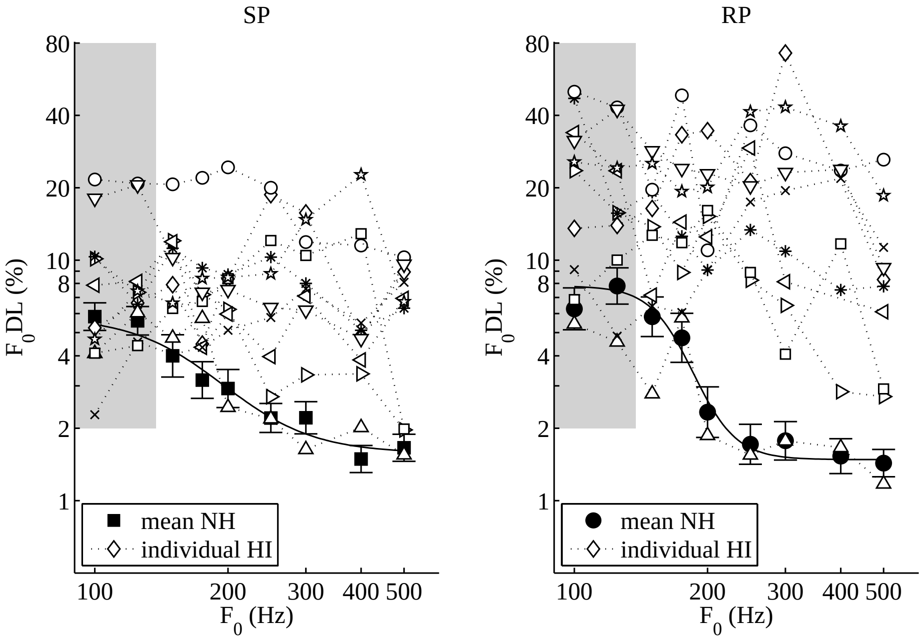

Fig. 1: Pitch-discrimination thresholds for the SP condition (left panel) and RP condition (right panel). The solid symbols depict the mean results for 14 NH listeners (left panel) and 9 NH listeners (right panel). The open symbols depict the individual results for the 10 HI listeners. Error bars depict the standard error of the mean. The grey-shaded region highlights the unresolved conditions.

The performance for the 10 HI listeners was generally worse than for the NH listeners, whereby the mean threshold across HI listeners differed significantly from the mean threshold of the NH listeners [SP: $F(1,16) = 26.21$, $p < 0.001$; RP: $F(1,16) = 33.93$, $p < 0.001$]. However, for the two unresolved conditions in the grey-shaded area there was no significant difference between the mean of the NH vs. the HI listeners for the SP condition [100 Hz: $F(1,22) = 0.6$, p = 0.446; 125 Hz: $F(1,22) = 2.63$, $p = 0.119$], while a post-hoc one-tailed *t*-test revealed significantly larger mean thresholds for the HI vs. the NH listeners for the RP condition [100 Hz: $p = 0.002$; 125 Hz: $p = 0.020$]. Overall, these findings revealed that HI listeners performed similarly as NH listeners in pitch discrimination of unresolved complex tones for the SP condition and worse than NH listeners for the RP condition.

In order to quantify and compare these changes in performance across participants, the ratio between the RP and SP threshold (F_0DL ratio) was calculated for the individual HI listeners and for the mean of the NH listeners. Figure 2 depicts the calculated F_0DL ratios as a function of the estimated cochlear compression (i.e., the slope of the BM I/O function, 1/CR; left panel) and filter bandwidth (right panel). Nine out of 10 HI listeners had F_0DL ratios larger than the upper boundary of the confidence interval for the ratio of the NH listeners (y-axis in the left and right panels). The increase of F_0DL ratios positively correlated with the estimated loss of cochlear compression for all listeners (left panel in Fig. 2) [$R^2 = 0.58$, $p = 0.011$]. Thus, the lower the residual cochlear compression, and thus CR, the larger was the difference in performance between RP-complex tones and SP-complex tones. Three HI listeners (asterisk, left-pointing triangle and star) showed the largest loss of cochlear compression and the largest F0DL ratio, while their filter bandwidths were similar to the average in the remaining HI listeners. Thus, for these three listeners, the loss of cochlear compression seemed to be the dominant factor increasing the F0DL ratio. No significant correlation was found between F_0DL ratio and auditory filter bandwidth (right panel in Fig. 2), although a significant positive correlation [$R^2 = 0.66$, $p = 0.015$] was reported when leaving out the three HI listeners. Overall, these findings suggest that both auditory filter broadening and loss of cochlear compression contribute in altering the pitch discrimination performance of the unresolved complexes, although the relative contribution of each factor remains unclear.

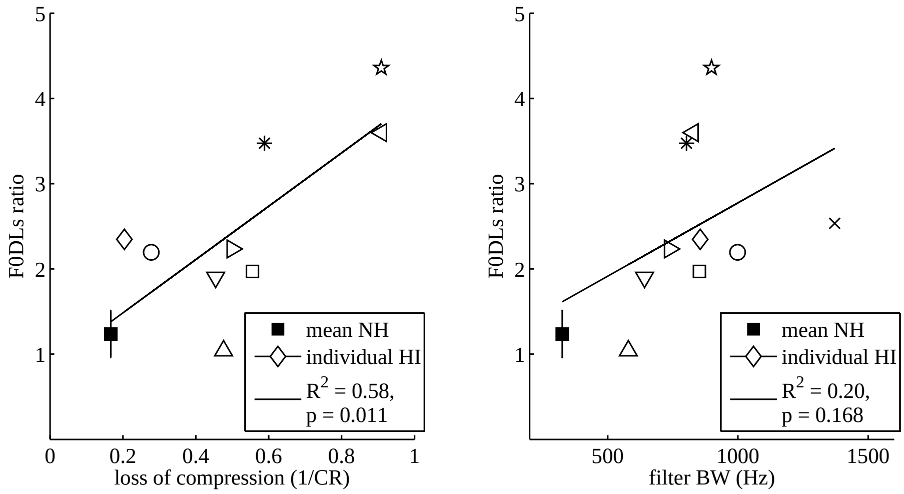

Fig. 2: F_0DL ratios as a function of the estimated loss of cochlear compression (left panel) and filter bandwidth (right panel). Solid symbols depict the mean results for NH listeners. The open symbols depict the individual results for HI listeners. Error bars depict the standard deviation of the mean (for the 9 NH listeners that measured both SP and RP conditions).

DISCUSSION

The hypothesis of the current study was that if the envelope representation is enhanced in listeners with SNHL (Kale and Heinz, 2010; Henry *et al.*, 2014), pitch cues for unresolved complex tones should also be enhanced if one assumes an envelope coding mechanism for pitch extraction of unresolved complexes. The pitch-discrimination thresholds measured in the present study revealed that the performance of the HI listeners for the unresolved conditions was similar to that of the NH listeners when the harmonics were added in SP (left panel in Fig. 1) and worse for the RP condition (right panel in Fig. 1). Although for most HI listeners pitch-discrimination performance was not better than for the NH listeners, these findings do not rule out an enhanced envelope representation following SNHL. In fact, other factors might be involved in limiting the behavioural performance of HI listeners (e.g., disrupted temporal fine structure cues, higher internal noise, other central limitations). Overall, these findings suggest that changes in the internal envelope representation occurred in listeners with SNHL.

The difference in performance between the RP and SP conditions (F_0DL ratio) was considered as an indicator of envelope coding. Correlations between F_0DL ratios and individual estimates of cochlear compression and filter bandwidth (Fig. 2) revealed that both cochlear compression reduction and filter broadening increased the F_0DL ratio. Although these two factors are known to be physiologically linked and dependent on outer-hair cell damage (Ruggero, 1992), the behavioural estimates of cochlear compression and filter bandwidth obtained in the present study did not show a one-to-one correspondence. Thus, a simplified peripheral model was used to qualitatively explain the relative effect of one factor versus the other on the envelope representation of the unresolved complex tones. SP and RP complexes were processed via a gammatone filter centred at 2 kHz, the output of which was processed by a broken stick non-linearity, as defined by Jepsen and Dau (2011). After envelope extraction, the modulation depth of the output signal was calculated for the SP and RP conditions, as well as their modulation depth ratio. Four different filter bandwidths were used (i.e., from 1 to 2.5 ERBs), as well as three levels of compression (NH compression, mild compression loss, and severe compression loss). The model parameters of the broken stick non-linearity were adjusted according to the fits of Jepsen and Dau (2011).

Figure 3 depicts the obtained modulation depth ratio between the SP and RP envelopes together with the F_0DL ratios calculated for the NH (solid symbol) and HI listeners (open symbols). The output of the model qualitatively predicted the trends in the data, whereby both compression reduction and filter broadening increased the modulation depth ratio. The larger the loss of cochlear compression (indicated by the different lines in Fig. 3), the larger was the effect of filter broadening on increasing the modulation depth ratio (i.e., the steeper the curve). Additionally, the model revealed that a broadening of the auditory filters led to an increase of the modulation depth (i.e., a peakier envelope) in the SP condition, since more components added up in phase, while it did not have any effect for the RP condition. The reduction of cochlear compression led to an increase of the modulation depth for both SP and RP conditions, although the envelope enhancement was larger for the SP condition. Thus, for the SP condition both filter broadening and loss of compression increased the envelope amplitude, whereas for the RP condition only loss of compression led to a moderate envelope enhancement.

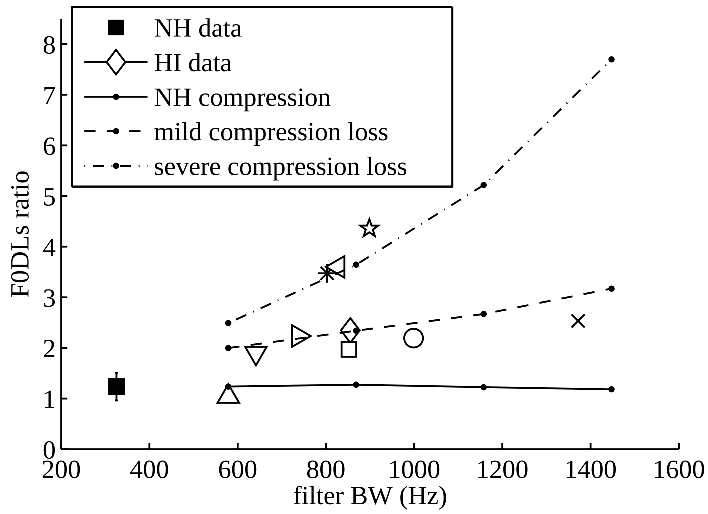

Fig. 3: Modelling results for 3 levels of residual compression (solid line: NH compression; dashed line: mild compression loss; dash-dot line: severe compression loss) and 4 levels of filter broadening, in comparison with the F_0DL ratios for NH listeners (solid square symbol) and for the HI listeners (open symbols).

CONCLUSION

Overall, the results of the pitch-discrimination experiment revealed that the performance of the HI listeners was, on average, similar to that of the NH listeners for the SP unresolved complex tones, and worse for the RP complexes. This difference in performance (F_0DL ratio) was significantly correlated with the decrease in residual cochlear compression. These findings suggest that changes in the internal envelope representation of unresolved complex tones occurred in listeners with SNHL, possibly as a result of their reduced compression, and altered their performance in pitch discrimination. Moreover, the outcomes of a simplified peripheral model revealed that both auditory filter broadening and loss of cochlear compression contributed to enhance the envelope peakiness of the unresolved complex tones, especially in the SP condition. Thus, the internal envelope representation of the unresolved complexes might be enhanced in listeners with SNHL for both the SP and the RP conditions, with the largest enhancement for the SP condition, while the behavioral performance of HI listeners could be affected by more central limitations.

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