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Original Article

Relationship between tinnitus pitch and edge of hearing loss in individuals with a narrow tinnitus bandwidth

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Abstract

Objective: Psychoacoustic measures of tinnitus, in particular dominant tinnitus pitch and its relationship to the shape of the audiogram, are important in determining and verifying pathophysiological mechanisms of the condition. Our previous study postulated that this relationship might vary between different groups of people with tinnitus. For a small subset of participants with narrow tinnitus bandwidth, pitch was associated with the audiometric edge, consistent with the tonotopic reorganization theory. The current study objective was to establish this relationship in an independent sample. *Design:* This was a retrospective design using data from five studies conducted between 2008 and 2013. *Study sample:* From a cohort of 380 participants, a subgroup group of 129 with narrow tinnitus bandwidth were selected. *Results:* Tinnitus pitch generally fell within the area of hearing loss. There was a statistically significant correlation between dominant tinnitus pitch and edge frequency; higher edge frequency being associated with higher dominant tinnitus pitch. However, similar to our previous study, for the majority of participants pitch was more than an octave above the edge frequency. *Conclusions:* The findings did not support our prediction and are therefore not consistent with the reorganization theory postulating tinnitus pitch to correspond to the audiometric edge.

Key Words: Audiogram; audiometric edge; tinnitus pitch; narrow bandwidth; multiple regression

Different neural mechanisms of tinnitus generation postulate somewhat different relationships between dominant tinnitus pitch and audiometric profile. The tonotopic reorganization model postulates a dominant tinnitus pitch corresponding to the frequency at the edge of the hearing loss due to an over-representation of neurons tuned to frequencies at that audiometric edge (see Eggermonts & Roberts, 2004 for a review). In contrast, the recent homeostatic plasticity model postulates increased neuronal activity spanning the hearing loss region as a compensatory mechanism that stabilizes the neural activity after hearing loss (Schaette & Kempter, 2006; Noreña, 2011). Increased central gain and stabilization of mean neuronal activity may lead to the increase of neuronal noise and tinnitus percept in the area of hearing loss (Schaette & Kempter, 2006). Thus, empirical investigation of this relationship in patient populations is informative. Not only can this approach be used to put competing neurophysiological theories to the test, it can also be fruitful in identifying meaningful subgroups of tinnitus to tailor more effective intervention strategies (see Baguley et al, 2013; Heijneman et al, 2013).

A number of studies to date have explored this relationship, but with mixed results (König et al, 2006; Pan et al, 2009; Moore et al, 2010; Sereda et al, 2011; Schecklmann et al, 2012; Heijneman et al, 2013; Shekhawat et al, 2013). The typical relationship seen within large cohort studies is one in which the dominant tinnitus frequency falls within the region of hearing loss (n = 286, Schecklmann et al, 2012; n = 195, Pan et al, 2009; n = 67, Sereda et al, 2011). However, the tinnitus population is well known for its heterogeneity (Baguley et al, 2013) and so it is probably unreasonable to expect statistically significant and meaningful relationships to emerge from analyses of large unselected groups. Of note, studies that claim a close mapping between audiometric edge frequency and dominant tinnitus frequency have either recruited a small cohort of participants selected for a high-frequency sloping audiogram and tonal tinnitus (n = 11, Moore et al, 2010) or were performed on a subset chosen for their narrow tinnitus bandwidth (n = 23, Sereda et al, 2011; n = 24, König et al, 2006; see also group #2, n = 22, Heijneman et al, 2013). Methodological differences between studies can make the comparison difficult. Noteworthy differences are: (1) the degree of

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Abbreviations

IHC	Inner hair cells
OHC	Outer hair cells
RCT	Randomized controlled trial

hearing loss of the participant sample; (2) the frequency range of the audiometric and tinnitus spectrum measurements; (3) the method for determining dominant tinnitus pitch; and (4) the method for determining audiometric edge. We expand on these points below.

While some of the studies included participants with a wide range of audiometric profiles from normal to severe hearing loss (Pan et al, 2009; Sereda et al, 2011), others limited their sample to participants with mild to moderate hearing loss (Moore et al, 2010; Schecklmann et al, 2012) or moderate to severe hearing loss (König et al, 2006). There is also a marked difference in the choice and number of audiometric variables taken into consideration. One study suggested the frequency at the worst hearing level as most relevant for tinnitus generation (e.g. Schecklmann et al, 2012). On the other hand, Shekhawat et al (2013) postulated that the frequency of the audiometric profile equating to a threshold of 50 dB HL was more relevant to tinnitus than the edge or maximum hearing loss frequencies, as it represents the approximate degree of hearing loss required from transition from outer (OHC) to inner (IHC) hair cell loss (Schuknecht, 1993). The authors confirmed that in their study the strongest audiometric predictor for tinnitus pitch was indeed the frequency at which threshold was 40–60 dB HL (T50). Other studies have tested the relationship between tinnitus pitch and audiometric variables such as slope and degree of hearing loss (Pan et al, 2009; Sereda et al, 2011).

Since the majority of studies reported tinnitus pitch within the area of hearing loss, it is likely that the dominant tinnitus pitch may exceed the 8 kHz standard clinical range for audiometric assessment for those people with a mild hearing loss or a sloping hearing loss affecting high frequencies (see Shekhawat et al, 2013). Wherever the tinnitus likeness spectrum has been assessed only up to 8 kHz, it would not be possible to distinguish those patients with an ‘increasing spectrum’ (e.g. Heijneman et al, 2013) from those with a dominant tinnitus pitch at 8 or 10 kHz (e.g. Shekhawat et al, 2013). This can limit the accuracy of patient subgrouping, as well as the interpretation of the results.

There are marked differences in methods of calculating tinnitus pitch between studies. While some of the studies perform pitch matching procedures, where a single frequency tone is selected that best matches the dominant tinnitus pitch, others use ‘likeness’ ratings for the whole range of frequencies, resulting in tinnitus spectrum rather than a single-tone match (see Sereda et al, 2011 for more detailed review). In consequence, studies using single-tone matching methods rely on self-report when determining bandwidth of the tinnitus (Schecklmann et al, 2012) rather than calculating it objectively from the tinnitus spectrum (Sereda et al, 2011). Similar differences are observed when it comes to determining the edge frequency where methods vary from visual inspection of the audiogram to fully automated computer algorithms (see Sereda et al, 2011 for more detailed review).

In Sereda et al (2011) we found that, while tinnitus pitch generally fell within the area of hearing loss, in a small subset of participants with narrow tinnitus bandwidth it was associated with the audiometric edge, which would be consistent with the tonotopic reorganization theory. We postulated that this relationship should be confirmed in a large (n = 100) group of participants with narrow tinnitus bandwidth. A recent study by Heijneman et al (2013) identified a subgroup of tinnitus participants with tinnitus spectra showing a peak in likeness ratings for frequencies close to the edge of the hearing loss (5 kHz group median) and decreasing towards higher frequencies. That group of participants could potentially correspond to subgroup of participants with narrow tinnitus bandwidth as identified by Sereda et al (2011).

In the current study, we conduct an independent test of the prediction made in Sereda et al (2011) using the same experimental methodology and statistical analysis, but an independent participant cohort. Our prediction was that people experiencing a narrow (tonal) tinnitus bandwidth should report a dominant tinnitus pitch that corresponds closely to the edge of the hearing loss. We tested this prediction using methods that address some of the limitations described above. A secondary analysis assessed the prediction made by Shekhawat et al (2013) of a positive correlation between dominant tinnitus pitch and the T50.

Methods

Participants

Audiometry and tinnitus data were collected between 2008 and 2013 from 380 participants with chronic subjective tinnitus. Participants were taking part in one of four randomized controlled trials (RCTs), (RCT 1 and 2 reported in Hoare et al, 2012; RCT 3 reported in Hoare et al, 2013; RCT 4 is unpublished: ClinicalTrials.gov Identifier: NCT02095262), or a clinical cohort study (Davies et al, 2014). The inclusion criterion for all studies was presence of chronic subjective tinnitus for more than three months. Participants with significant hyperacusis, anxiety, or depression were excluded. From those 380 participants, 129 met the pre-defined criteria for a narrow tinnitus bandwidth (34%; 94 men and 35 women, aged from 21 to 82 years; mean = 53.16 years and SD = 12.28 years). Participants were tested at the Nottingham Hearing Biomedical Research Unit (n = 80) or University College London (n = 49) which was a participating site in one of the RCTs. Overall, 82 participants reported tonal tinnitus, 18 reported ringing tinnitus, and 29 reported hissing tinnitus (see later for definitions). Almost all participants (n = 120) reported a tinnitus percept that was steady over time, although a small number (n = 9) reported pulsatile tinnitus. For 64 participants, the onset of tinnitus was abrupt, while for 65 it was gradual. As high frequency audiometric data were collected for all participants, we were able to include all participants with narrow tinnitus bandwidth, including those with a dominant tinnitus pitch above 8 kHz.

Among the possible etiologies, most often reported by participants were noise exposure/loud sound (n = 35), ear infections (n = 11), change in hearing (n = 7), stress (n = 5), head trauma (n = 5), flu/cold (n = 5), and acoustic neuroma (n = 2). Fifty participants reported unknown etiology.

Testing procedures

Hearing levels for the two ears were measured between 0.125 and 12.5 kHz (n = 96) or between 0.125 and 16 kHz (n = 33) depending on the study (see Figure 1). Pure-tone audiometry was conducted in a soundproof booth using the Unity 2 system (Siemens, Berlin, Germany) and HDA 200 headphones (Sennheiser, Wademark, Germany), see Table 1. The Tinnitus Tester software (Roberts et al, 2006, 2008) was used to assess the psychoacoustical properties of tinnitus in all patients, including tinnitus laterality, spectral properties

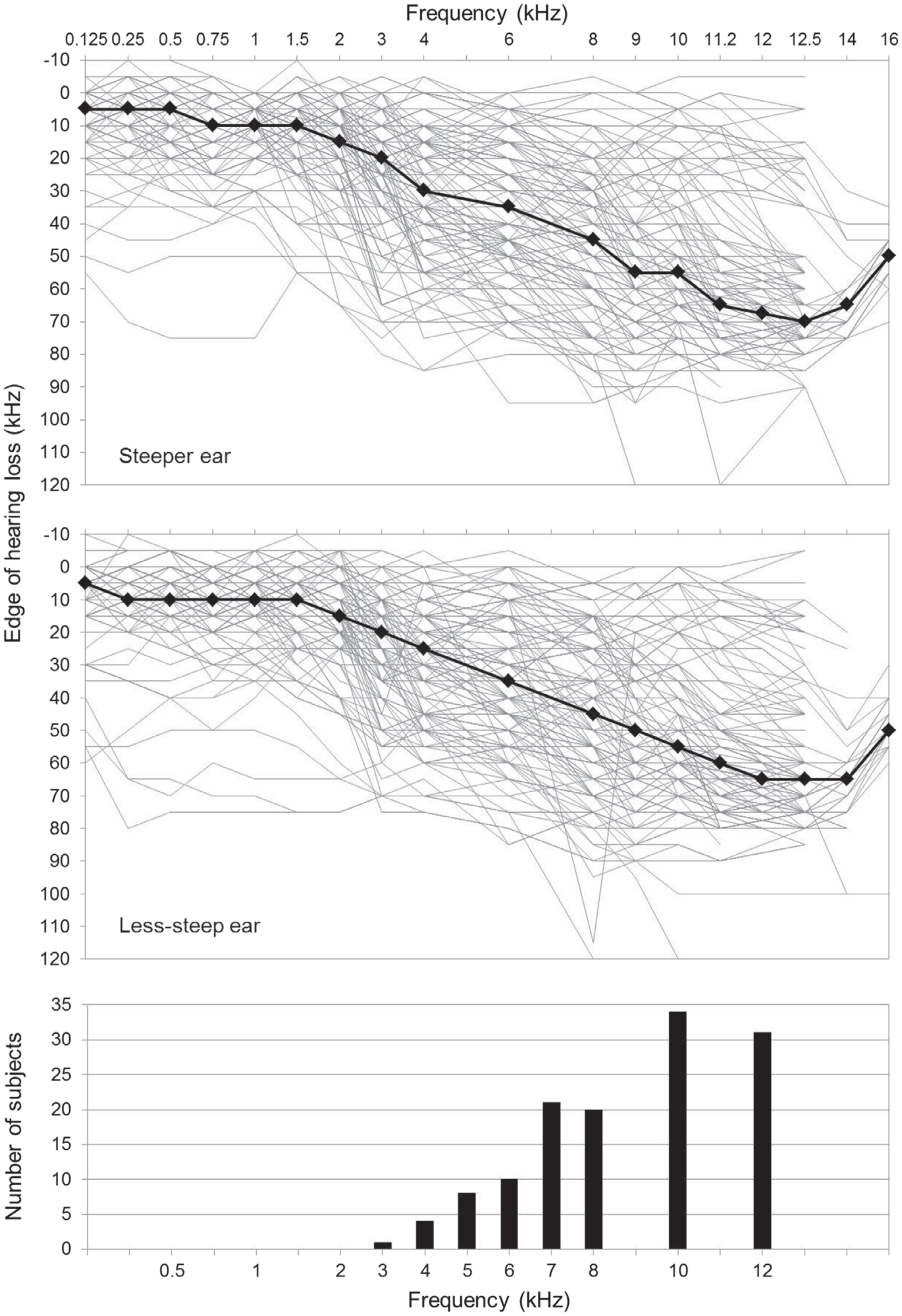

Figure 1. Association between hearing level and the dominant tinnitus pitch. Top and middle panels illustrate audiometric thresholds for all 129 patients in the steeper (top panel) and less-steep (middle panel) ear with median shown by the solid black line. Bottom panel shows the distribution of the dominant tinnitus pitch derived from the similarity ratings.

(tonal, ringing, or hissing), temporal properties (steady or pulsing), loudness, and tinnitus frequency spectrum. Spectral properties were classified by asking participants to select one of the three sounds that best characterized their tinnitus (Roberts et al, 2008). For tonal tinnitus, the sound was a 5-kHz pure tone; for 'ringing' tinnitus, it was a bandpassed noise with a spectrum of ± 5% of the 5-kHz centre frequency; and for 'hissing' tinnitus it was a bandpassed noise at ± 15% of the 5-kHz centre frequency, each measured at 10 dB below the spectral peak. Using the automated computerized Tinnitus Tester assured the same procedures for all patients regardless of the study. The choice of tinnitus spectral property (tonal, hissing, ringing) determined the bandwidth of the target frequencies

Table 1. Summary of audiometric information for included studies.

Study	*Total number of participants with narrow tinnitus bandwidth*	*Frequency range of pure-tone audiometry (kHz)*	*Audiometer type*	*Type of earphone*
RCT 1	10	0.125–16	Unity 2 system (Siemens, Berlin, Germany)	HDA 200 headphones (Sennheiser, Wademark, Germany)
RCT 2	9	0.125–16	Unity 2 system (Siemens, Berlin, Germany)	HDA 200 headphones (Sennheiser, Wademark, Germany)
RCT 3	7	0.125–16	Unity 2 system (Siemens, Berlin, Germany)	HDA 200 headphones (Sennheiser, Wademark, Germany)
RCT 4	96	0.125–12.5	Unity 2 system (Siemens, Berlin, Germany)	HDA 200 headphones (Sennheiser, Wademark, Germany)
Clinical cohort study	7	0.125–16	Unity 2 system (Siemens, Berlin, Germany)	HDA 200 headphones (Sennheiser, Wademark, Germany)

in the loudness and frequency stages of the test battery. Participants were asked to adjust the level of each frequency (in dB SPL) to match the loudness of their tinnitus. Eleven different centre frequencies (from 0.5 to 12 kHz) were presented. The frequency spectrum was quantified by asking people to indicate the similarity of their tinnitus to each presented frequency (each frequency was presented at the loudness chosen to match participants' tinnitus loudness). Loudness and pitch ratings were performed using a Borg CR100 scale (Borg & Borg, 2001).

Quantification of the audiometric data

The audiometric profile was used to quantify audiometric edge, slope, degree of hearing loss, frequency of the worst hearing level, and the ear with steeper hearing loss for each participant by fitting a function to the observed values using Matlab procedure. Simple linear regression (0-break), or non-linear 'broken-stick' regressions with one or two breaks were fitted to the audiometric data. The best fitting broken-stick function was assessed using parametric bootstrap approach (see Sereda et al, 2011 for a more detailed description of the procedure). The frequency at which the break of the function occurred and the function passed from clinically normal to impaired hearing was taken as the edge of the hearing loss. The slope of the regression function represented the slope of the hearing loss, calculated in dB/octave. In the case of the 1- or 2-break solutions, the slope was taken as the portion of the regression line that occurred directly after the edge of the hearing loss. For all analyses, the slope of the hearing loss was used as a categorical variable for investigating effects of the other audiometric and tinnitus variables according to 'steeper' and 'less steep' ear (see Sereda et al, 2011). Degree of hearing loss was represented by the area underneath the fitted curve, calculated in dB×octave (i.e. dB HL in octave bands, and then summing those values across the frequency range).

Additionally for each participant we calculated the frequency at which the threshold was equal or close to 50 dB HL (i.e. T50), according to Shekhawat et al (2013).

Quantification of the tinnitus data

DOMINANT PITCH

The dominant pitch was derived from the Tinnitus Tester pitch similarity ratings using the same analysis procedure for all participants. Dominant tinnitus pitch was taken as the frequency that was rated as the most similar to the tinnitus pitch. Two out of 129 participants rated two frequencies equally to be 'most like' their tinnitus. In those cases, the frequency closer to the edge of the hearing loss was selected as the dominant tinnitus pitch (see Sereda et al, 2011 for a more detailed description of the procedures).

BANDWIDTH

The width of the tinnitus spectrum was also derived from the pitch similarity ratings and was calculated as the standard deviation of the weighted frequencies, where large weights were given to those frequencies rated as most similar to the tinnitus. The Borg scale was used to assess similarity (Borg & Borg, 2001) and the values obtained were used as the weights. For this study, only participants with narrow tinnitus bandwidth ≤ 0.25 kHz, as defined in Sereda et al (2011), were included.

Statistical analysis

Many of the variables were not normally distributed and so these were transformed by taking a natural logarithmic transform of the values. We report the results of the Pearson correlation analysis between dominant tinnitus pitch and edge frequency for comparison with our previous study (Sereda et al, 2011), as well as previous literature. To account for other audiometric variables, principal components analysis was used to derive a set of predictor variables that are not intercorrelated, and these were implemented in a multiple regression analysis (see Sereda et al, 2011).

Additionally, for comparison with the study by Shekhawat et al (2013), we performed Pearson correlation analysis between the dominant tinnitus pitch and the T50 frequency. We also used a paired t-test to compare the differences between tinnitus pitch and the T50 frequency and tinnitus pitch and the frequency of the worst hearing level.

Results

Descriptive statistics

AUDIOMETRIC DATA

From the broken-stick fitting procedure that was applied to the 258 ears (129 participants), a 0-break fit best described the audiogram for 32 ears, a 1-break fit best described the audiogram for 171 ears, and 2-break fit was chosen for 55 ears (Figure 1). We were able to determine the edge frequency for 205 ears. For 112 out of 129 patients we were able to determine the edge frequency in at least one

Table 2. Correlations between dominant tinnitus pitch and audiometric variables. HL = hearing loss.

		Steeper ear			*Less-steep ear*		
	Audiometric variable	*Number of ears*	*Correlation coefficient*	*P value*	*Number of ears*	*Correlation coefficient*	*P value*
Primary analysis	Edge of the HL	107	0.282	0.003	98	0.271	0.007
Secondary analysis	Frequency with threshold of around 50 dBHL	104	0.282	0.004	104	0.204	0.038

ear. Therefore the sample of 100 participants with a narrow tinnitus bandwidth, as recommended in Sereda et al (2011), was reached.

As in our previous paper there was a large amount of inter-subject variability in the values obtained for this group of participants. Audiometric edge ranged from 0.25 to 12 kHz (mean = 3.03; SD = 2.58) where it could be identified. Across all 258 ears, the slope of the hearing loss ranged from 0.05 to 248.16 dB/octave (mean = 30.75; SD = 31.33), and degree of hearing loss ranged from 0 to 126.76 dB/octave (mean = 57.05; SD = 24.94).

TINNITUS DATA

As for this analysis we have specifically chosen participants with narrow tinnitus bandwidth (≤ 0.25 kHz), there was considerably less variability associated with that variable than in Sereda et al (2011). Tinnitus bandwidth varied from 0.12 to 0.25 kHz (mean = 0.20; SD 0.035). As in our previous paper, there was a large amount of inter-subject variability in the dominant tinnitus pitch that ranged from 3 to 12 kHz (mean = 8.82; SD = 2.45).

Relationship between tinnitus pitch and edge frequency

The results demonstrated a statistically significant positive relationship between dominant tinnitus pitch and edge frequencies for both steeper and less-steep ears (one-tailed Pearson's test, $p < 0.002$ and $p < 0.004$, respectively; Table 2). These correlations survived correction for multiple comparisons (Bonferroni corrected; alpha < 0.05). Similarly to Sereda et al (2011) the lower and upper limits of the correlation coefficient (r) were rather broad (steeper ear: 0.098 to 0.45; less-steep ear: 0.08 to 0.45). Calculations of the coefficient of determination (r^2) demonstrated that only 8% and 7.3% of the variance in the tinnitus pitch could be accounted for by the edge frequency (for the steeper and less-steep ears, respectively; see Figure 2). This result is much lower than our previous study where 23% and 52% of variability in tinnitus pitch could be accounted for by the edge frequency in a similar subgroup. For comparison, Pearson's correlation coefficients between the current data and those reported by Sereda et al (2011) are shown in Figure 3. Current correlation estimates fall within the confidence intervals of our previous study. Hence, despite statistical significance, the size of the correlation coefficient indicates only a weak relationship between tinnitus pitch and audiometric edge.

Multiple regression analysis

The association was scrutinized further by accounting for the contribution of other audiometric variables to tinnitus pitch. All the audiometric data were first subjected to a principal component analysis. From the original set of eight variables, eight components were generated (Table 3). Of the eight components, only three explained at least 10% of variance and had an eigenvalue of at least 0.7. These were carried forward to the multiple regression analysis (Jolliffe, 1972, 1986). We report absolute loadings of 0.5 and more to be high (Stevens, 2002). The first factor explained 36% of variance and had high positive loadings from the edge frequency and slope of the hearing loss in both ears. The second factor explained 26% of variance and had high positive loadings for the degree of hearing loss in both ears. The third factor explained 18% of variance and had high positive loadings for the frequency of worst hearing levels in both ears.

The multiple regression model specified the dominant tinnitus pitch as the criterion variable with the three selected principal components as predictor variables. The model was successful in predicting tinnitus pitch (F[3, 88] = 4.453, p = 0.006) and showed that component 2 was a predictor of tinnitus pitch (F[1, 88] = 6.75, p = 0.011). As component 2 had high positive loadings mainly for degree of hearing loss, this finding therefore indicates that the degree of hearing loss

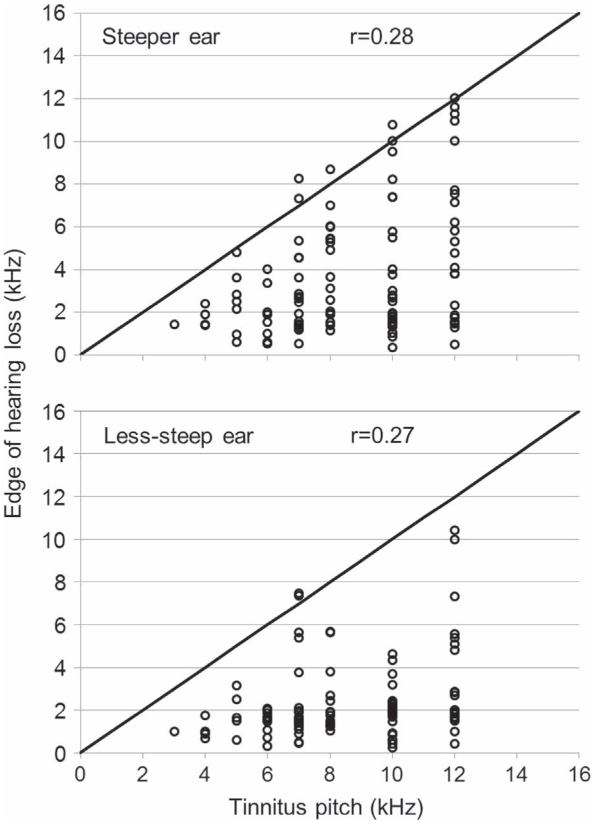

Figure 2. Scatterplots examining the relationship between dominant tinnitus pitch and the edge of the hearing loss in the steeper (top graph) and less-steep ear (bottom graph) in all participants with narrow tinnitus bandwidth.

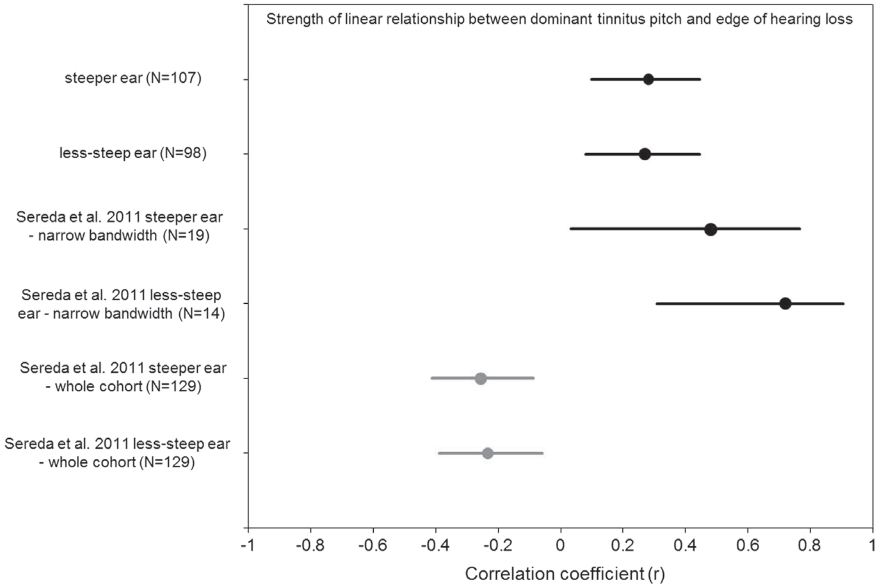

Figure 3. Comparison of Pearson's correlation coefficients (dots) and confidence intervals (lines) in the current study and in Sereda et al (2011). Lines shown in black represent the subgroup of participants reporting a narrow tinnitus bandwidth. Lines shown in grey represent the whole recruited sample.

is the main driver of dominant tinnitus pitch (Figure 4). Component 1, which had high positive loadings for edge frequency, was not a significant predictor of tinnitus pitch (F[1, 88] = 0.65, p = 0.8).

As we postulated in our previous study that edge frequency could be a potential predictor of tinnitus pitch in participants with narrow tinnitus bandwidth and the correlation between tinnitus pitch and edge frequency was significant, we have also performed multiple regression analysis where dominant tinnitus pitch was a criterion variable and edge frequencies in steeper and less-steep ear were predictor variables. Edge frequency was not a good predictor of tinnitus pitch (F[1, 90] = 0.652 and F[1, 90] = 2.244, p > 0.05 in steeper and less-steep ear respectively).

Secondary analysis

To explore the postulates of Shekhawat et al (2013), a secondary correlation analysis was performed between the dominant tinnitus pitch and the frequency equating threshold of 50 dBHL (T50). We were able to determine the T50 in 208 out of 258 ears (104 participants). Similarly to their study, we found weak but significant correlation between that frequency and tinnitus pitch for both steeper and less steep ears (two-tailed Pearson's test; 0.282, p < 0.004 and 0.204, p < 0.038 respectively). Tinnitus pitch increased with higher threshold at 50 dB HL. However, only the correlation for the steeper ear survived the correction for the multiple comparisons (Bonferroni correction; alpha < 0.05). The mean difference between tinnitus pitch and T50 was 1.44 (SD = 3.38) and 1.51 (SD = 3.76) in the steeper and less-steep ear respectively. Similarly to Shekhawat et al (2013), the frequency of the worst hearing threshold was higher than the tinnitus pitch (mean difference = − 2.12; SD = 3.13 and − 1.63; SD = 3.73 in steeper and less-steep ear respectively). However, in contrast to Shekhawat et al (2013) the difference between tinnitus pitch and T50 frequency was not significantly different than the difference between tinnitus pitch and the frequency of the worst hearing level (paired T-test, p = 0.55 and p = 0.59 in steeper and less-steep ears respectively).

Table 3. Details of the loadings of each of the eight principal components derived from the principal component analysis onto the original audiometric variables. Components are statistical constructs, but the individual loadings indicate the 'meaning' of each one. For example, principal component 1 most strongly represents the edge and the slope of hearing loss.

	Principal components							
Audiometric variables	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Edge of the HL in the steeper ear	0.813	− 0.357	0.043	− 0.308	− 0.113	− 0.184	− 0.254	− 0.055
Edge of the HL in the less-steep ear	0.745	− 0.460	0.134	0.138	0.340	− 0.204	0.179	0.082
Slope of the HL in the steeper ear	0.732	− 0.023	−0.454	− 0.220	− 0.385	0.108	0.221	0.017
Slope of the HL in the less-steep ear	0.709	− 0.066	− 0.498	0.333	0.238	0.246	− 0.119	− 0.053
Degree of the HL in the steeper ear	0.303	0.911	− 0.020	0.019	0.111	− 0.167	0.108	− 0.158
Degree of the HL in the less-steep ear	0.304	0.904	− 0.193	− 0.054	0.040	− 0.042	− 0.123	0.175
Frequency of the worst hearing level in the steeper ear	0.471	0.135	0.623	0.475	− 0.381	0.000	− 0.027	0.010
Frequency of the worst hearing level in the less-steep ear	0.428	0.189	0.752	− 0.327	0.199	0.260	0.031	− 0.004
Variance explained (%)	35.6	25.6	18.3	7.6	6.6	3.1	2.4	0.9
Eigenvalue	2.8	2.1	1.5	0.6	0.5	0.2	0.2	0.07

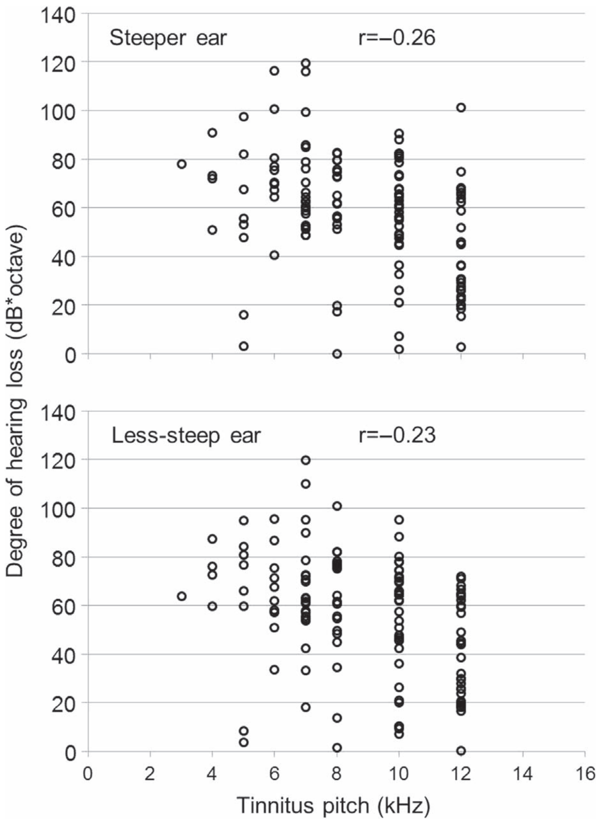

Figure 4. Scatterplots examining the relationship between dominant tinnitus pitch and degree of the hearing loss in the steeper (top graph) and less-steep ear (bottom graph).

Discussion

The current study tested the prediction made in our earlier article that people with a narrow tinnitus bandwidth report a dominant tinnitus pitch that corresponds closely to the edge of the hearing loss. The same experimental methodology and statistical analysis was used as in Sereda et al (2011) and we have again demonstrated the importance of accounting for strongly intercorrelated covariates when examining relationships between variables. Multiple regression results did not confirm our previous findings, instead demonstrating that tinnitus pitch generally falls within the area of hearing loss in this participant subgroup, as it does for the general tinnitus population. Indeed, for the majority of participants in the current study, dominant tinnitus pitch corresponded to a frequency that was more than one octave *above* the edge frequency (see Figure 2). Interpretation of this pattern of results is inconsistent with the reorganization theory, but rather supports a homeostatic plasticity model for people reporting a narrow tinnitus bandwidth, in the same way as it does for those experiencing a broader tinnitus spectrum.

We argued in Sereda et al (2011) that correlational analysis is inappropriate for examining the relationship between several audiometric variables and tinnitus pitch when variables are intercorrelated. As an alternative, we proposed using multiple regression analysis to assess the relationship between several audiometric variables and tinnitus pitch, and principal component analysis to derive the set of variables that are not intercorrelated. In contrast with Sereda et al (2011) where we failed to find an audiometric variable that would be a good predictor of tinnitus pitch, in the current study multiple regression analysis pointed to the degree of hearing loss as the best predictor of tinnitus pitch. The lower the degree of hearing loss, the higher the dominant tinnitus pitch. As a majority of participants had normal hearing at low frequencies and hearing loss at higher frequencies, that result is consistent with findings of our (Sereda et al, 2011) and other studies (Henry & Meikle, 1999; Noreña et al, 2002; Pan et al, 2009; Schecklmann et al, 2012) showing that tinnitus pitch falls within the area of hearing loss in a majority of cases. The simple linear correlation showed a weak relationship between tinnitus pitch and the edge frequency, which was not confirmed by the more rigorous multiple regression analysis.

Recent papers looking at the relationship between psychometric measures of tinnitus and audiometric variables have highlighted the possibility that different mechanisms might play a role in tinnitus generation and therefore that relationship might be different in different groups of patients (Pan et al, 2009; Sereda et al, 2011; Heijneman et al, 2013). Conclusions point to the possibility that inconsistent results in the literature might be explained by the lack of sub-group analysis. Identifying the sub-groups of participants is not an easy task as there is a lack of a priori evidence regarding which factors might comprise relevant grouping criteria (Landgrebe et al, 2012). In Sereda et al (2011), we suggested that tinnitus bandwidth might be one such criterion and we have tested that hypothesis in the current study. A similar approach was taken by Schecklmann et al (2013), where the authors did not find a relationship between edge frequency and tinnitus pitch but rather between the frequency of maximum hearing loss in patients with tonal and narrow-band tinnitus. However both studies took a very different approach to assessing the spectral properties of tinnitus. Our definition of narrow tinnitus bandwidth was derived from the pitch matching spectra rather than being based on the subjective report as in the study of Schecklmann et al (2012). The rationale for such classification was the discrepancy between the participants' classification of their tinnitus spectral properties (even when compared to an external sound) and their subsequent similarity ratings found in our previous study (Sereda et al, 2011). Moreover, due to lack of high-frequency audiometric data, Schecklmann and colleagues excluded all participants with tinnitus pitch above 8 kHz, which characterized 73% of the patient population, which could be the serious limitation of that study. In the current study, the high-frequency audiometric data were collected for all participants and all participants with narrow tinnitus bandwidth were included in the analysis, regardless of their tinnitus pitch. Given these methodological differences, one cannot be certain whether participant sub-groups in our study were equivalent to those reported in the study by Schecklmann and colleagues (2012).

Moore and colleagues (2010) postulated that the lack of clear relationship between dominant tinnitus pitch and edge frequency in majority of the studies might be due to octave confusion in the pitch matches. They tested 11 participants with tonal tinnitus and trained them to avoid octave errors in their pitch matches. They reported lower pitch matches after the training in some participants and a clear relationship between edge frequency and tinnitus pitch matches after the training. Although in our study the majority of participants rated tinnitus pitch as more than an octave above the edge frequency, there was, however, a lack of systematic difference between edge frequency and tinnitus frequency, which would be expected if the higher pitch matches were the effect of octave confusion.

In their recent study Shekhawat et al (2013) postulated a new audiometric variable–T50–that might be more relevant for driving dominant tinnitus pitch. Our findings do not support this claim. The correlation between frequencies at which the threshold was approximately 50 dB HL was significant only for steep ear and the tinnitus pitch. While in Shekhawat et al (2013), the tinnitus frequency was close to T50 frequency (mean difference = 1.12) and much closer to the tinnitus frequency than frequency of the worst hearing loss (mean difference = − 4.47), in the current study the difference between the tinnitus pitch and T50 frequency was similar to that between tinnitus pitch and the frequency of the worst hearing level.

Conclusion

In summary, these results confirm our previous findings that tinnitus pitch generally falls within the area of hearing loss and the strongest predictor of tinnitus pitch is the degree of hearing loss. These findings are consistent with a homeostatic plasticity view of tinnitus, rather than a tonotopic reorganization theory.

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