Tinnitus Synthesis: Fluctuant and Stable Matches to the Pitch of Tinnitus

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Abstract: Five subjects mimicked the sensation caused by their tinnitus with a complex sound pattern consisting of the sum of sine waves. The imitation tinnitus was generally broadband, spanning an average of 2.94 kHz. Measures of the pitch of the tinnitus were made using both a forced-choice double-staircase (FCDS) task and a method of adjustment (MOA) task. Even tinnitus portrayed as broadband was matched reliably using a FCDS task, presumably because all but one component of the tinnitus was ignored. With the MOA task, successive matches to the predominant tinnitus pitch were fluctuant, presumably because disparate components of the tinnitus were subsequently matched. Because tinnitus is a broad-band signal, clinical trials evaluating the effect of a treatment on tinnitus should involve assessing changes occurring at any location in tinnitus spectrum.

INTRODUCTION

A previous study from this laboratory reported that the sensation of tinnitus could be mimicked more accurately with a complex sound pattern consisting of the sum of widely separated sine waves than with a single sine wave.[1] Indeed, the subjects never limited themselves to a single sine wave, and tinnitus imitations spanned a frequency region as wide as 7 kHz.[1] Because of the broadband nature of tinnitus, it seems reasonable to expect that, as one or another component of a broadband tinnitus dominated, the frequency of a tone matching the "predominant" pitch of tinnitus would be erratic. Some data confirm this expectation.[2-5] If, however, only one component of a broadband tinnitus were attended, then matches might be less erratic. In fact, some data indicate that matches to the pitch of tinnitus do not fluctuate markedly.[3-10]

Data which do not display marked fluctuation in the frequency of a tone matched to the predominant pitch of tinnitus have employed psychophysical procedures which converged only after the subject matched the tinnitus pitch with tones of "nearby" frequency. Casting the issue in terms of classical psychophysics, it seems that some psychophysical procedures induce subjects to attend to a "listening band"[11-13] around an isolated tinnitus component thereby resulting in stable matches.

If the tinnitus sensations were well-represented by a broad-band stimulus, as the tinnitus imitation in Penner[1] suggests, then it might be possible to reconcile incompatible reports concerning the variability of matches to tinnitus. That reconciliation is the goal of the present report.

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METHODS

Subjects

Four male subjects (Subjects 1-4) and one female subject (Subject 5) all of whom reported having annoying tinnitus participated in this experiment. Subjects 1-4 had taken part in previous experiments in this laboratory.

Audiograms for all five subjects, including those of Subjects 1-4 which have already been published, are displayed in Table 1. Table 1 also specifies the ear in which the external stimuli were presented. All stimuli in the tinnitus synthesis were monaural, in the ear with the louder tinnitus, as Tyler and Conrad-Armes[5] recommended.

Four of the subjects (1-4) had no spontaneous otoacoustic emissions (SOAEs). However, the tinnitus of subject 5 may have been caused, at least in part, by SOAEs, sounds which may be measured when a sensitive miniature microphone is inserted into the ear canal. The SOAEs of this subject were recorded using techniques described in Penner[14] which only permitted SOAEs below 10 kHz to be observed.

In the subject's right ear, as many as 14 SOAEs with signal-to-noise ratios exceeding 3 dB or appearing on five or more of eight consecutive spectra were observed

Table 1. Audiograms
Note: Thresholds are in dB SPL. The signal was 500-ms, and a two-interval forced-choice (2IFC) adaptive procedure with 10 reversals per point was employed. A dash is entered whenever the signal level exceeded 90 dB SPL. The subject number and the ear in which the tinnitus was measured appear in the first column of the table.

Subject, Ear	Right Ear, Frequency (kHz)					Left Ear, Frequency (kHz)				
	0.5	1	2	4	8	0.5	1	2	4	8
1,R	8	3	14	15	26	10	-2	6	10	18
2,R	25	29	47	74	90	21	16	39	54	73
3,L	0	10	20	40	70	5	5	15	45	-
4,L	49	51	40	90	-	50	39	35	90	-
5,R	3	5	11	17	45	3	4	7	4	35

from 0.815 to 9.692 kHz (at nominal frequencies of 0.815, 0.983, 1.051, 1.262, 2.125, 2.745, 4.515, 5.384, 6.435, 6.439, 7.941, 7.950, 8.645, 9.692 kHz). In her left ear, as many as eight SOAEs were observed from 1.070 kHz to 8.742 kHz (at nominal frequencies of 1.071, 1.242, 2.653, 2.753, 5.920, 7.829, 8.126, 8.742 kHz). The levels of the emissions in the left ear at 1.071 kHz and 1.242 kHz were inversely related. Unstable alternating SOAEs such as these have been associated with tinnitus[15-17] and, indeed, even in normal-hearing subjects, SOAEs which are released from suppression become audible momentarily.[18]

The association of SOAEs and tinnitus in this subject was supported by the following observations. First, when a sound duplicating her SOAEs was presented to her, it was judged to be similar to her tinnitus. Second, there were more SOAEs in her right than in her left ear and the SOAEs in the right ear were more fluctuant than those in her left ear, perhaps corresponding to her report that the tinnitus was worse in her right than in her left ear.

On the other hand, for Subject 5, the masking/suppression demonstration[19] produced in-conclusive evidence linking SOAEs and tinnitus. In the demonstration, suppressing all SOAEs should eliminate the tinnitus caused by SOAES. Any tones which do not suppress the SOAEs should not affect the tinnitus. Unfortunately, for Subject 5, the difference between the tinnitus and the sensation arising when all but one of many SOAEs were suppressed was unclear.

Apparatus

The timing and presentation of the stimuli were controlled by a computer. All stimuli were generated by a 16-bit digital-to-analog converter (Data Translation, Model 2823, or by Tucker-Davis Technologies, system 2), filtered, and attenuated before serving as input to the headsets (TDH 49). The second harmonic of all the computer-generated pure tones was at least 90 dB below the primary level. The remaining harmonics were at least 70 dB below the primary throughout the frequency and amplitude range tested.

Protocol

All subjects participated in three two-hour testing sessions. In the first, threshold sensitivities were measured using a two-interval forced-choice adaptive task[20] and a test for spontaneous otacoustic emissions (SOAEs) was undertaken. Interested readers are referred to Penner and Bilger[21] for procedural details relating to threshold measurement and to Penner[1] for a description of the measurement of SOAEs.

Six conditions served as the focus of the data reported here. The conditions involved (1) tinnitus synthesis, (2) a forced-choice double staircase (FCDS) task in which a pure tone was matched to a fixed external pure tone (1 kHz at 40 dB SPL), (3) a FCDS task in which a pure tone at 40 dB SPL was matched to a remembered 1-kHz tone, (4) a FCDS task in which a pure tone fixed in level was matched to the lowest pitch of the tinnitus, (5) a FCDS task in which a pure tone fixed in level was matched to the highest pitch of the tinnitus, and (6) a method of adjustment (MOA) procedure in which the frequency of a variable pure tone was adjusted to match the predominant pitch of the tinnitus.

Tinnitus synthesis: Condition 1

The tinnitus synthesis procedure is described in Penner.[1] Briefly, the subject was seated in a double-walled Industrial Acoustics Chamber (IAC 1201A) in which a keyboard and a video screen were placed. At the beginning of the synthesis, the screen displayed only axis labels, and a sound was created in response to key strokes. The video screen displayed the level and frequency of the imitation tinnitus which was presented over headsets (for one-second) whenever the subject touched the space bar. Adjustments of the frequency (in a zoom feature of the program by 1 Hz) and level (by 1 dB) of the components could easily be made by the subject. Pressing the enter key on the keyboard switched the video screen display between the zoom (100 Hz bandwidth) and the broadband (15 kHz) options. The subject touched the right and left arrows on the keyboard to control the location of the cursor (a cross) on the abscissa, and depressed the up and down arrows on the keyboard to create or control the level of a tone at the frequency corresponding to the cursor location.

Matches to external tones and to tinnitus: Conditions 2-5

A FCDS procedure was used to measure tinnitus pitch. The FCDS procedure as applied to tinnitus matches has been described elsewhere.[9-10] Briefly, the FCDS procedure consisted of two randomly interleaved independent staircases with two different decision rules. In the double staircase, the experimenter selected two starting points for two sequences of trials. One of the sequences began with trials that were clearly above the tinnitus pitch and the other with comparison stimuli that were clearly below.

In the forced-choice procedure, the listener chose one of two clearly defined one-second temporal intervals, each marked by a flash of light. During the first flash, the subject was instructed to listen to the tinnitus which was the "standard" stimulus. During the second flash, an external comparison tone was presented. The subject chose between two subjective labels in responding to each pair of stimuli. For example, the subject might have been instructed to pick the interval with the higher pitched tone, in which case the first interval should be picked if the tinnitus (the standard) seemed higher in pitch than the comparison, or the second interval should be picked if the converse were true. The selection of stimuli, governed by Levitt's[20] adaptive tracking rules, was controlled only by the subject's use of the two subjective response categories.

The data presented here are based on 14 reversals, with the first four reversals in each track discarded. All stimuli were one-second in duration. The step size of the FCDS task was 2 Hz. The levels of the matching tones in the FCDS tinnitus matching tasks were fixed at the levels of the lowest or highest tones in the preceding tinnitus synthesis.

Method of adjustment (MOA) matches to tinnitus: Condition 6

In the MOA task, the subjects were instructed to bracket the predominant pitch of the tinnitus before making a final judgment. Each subject made 30 pitch and loudness judgments. The level of the external tone and its frequency were simultaneously adjusted. The subject controlled the frequency of the matching tone with key strokes which raised or lowered the level of the stimulus (by 2 dB) or adjusted its frequency (by 100 Hz). A larger step size was used in the MOA task than in the FCDS task in order to decrease the time needed to complete the MOA task and to make the task comparable to other MOA procedures.[9] The matching stimuli were presented for one-second with a silent interval of one-second between presentations. The subjects were instructed to halt the run and inform the experimenter if the tinnitus became inaudible in the silent interval between presentations (i.e., if residual inhibition was affecting the task).

RESULTS

The data are presented in Table 2. For each subject, the frequency of a tone matching the pitch of the lowest component of the tinnitus in the FCDS tinnitus matching task was near a low-frequency component of the tinnitus synthesis, and the frequency of a tone matching the highest component of the tinnitus in a FCDS task was near a high-frequency component of the tinnitus synthesis.

Could the matches to the tinnitus actually involve matches to remembered components of the tinnitus synthesis? In order to explore the possibility that matches to the tinnitus involved matches to the remembered tinnitus synthesis, we compared matches to an external tone at 1 kHz with matches obtained when the subjects were instructed to match to the remembered 1-kHz tone in the preceding block of trials. Three of the five subjects (Subjects 1, 3, and 4) could not match or could not accurately match a remembered 1-kHz tone, indicating that their pitch matches to tinnitus did not involve matches to the remembered tonal components in the tinnitus. Two of the subjects (Subjects 2 and 5) could match to a remembered tone, indicating that their pitch matches to tinnitus could have involved matches to remembered frequencies of the tinnitus imitation, although they were instructed to match to the tinnitus.

The range of the frequencies in the MOA matches to tinnitus are presented in the last column of Table 2. Despite each subject's ability to focus solely on the lowest and highest component of the tinnitus and match to it in a FCDS task, the frequency of the MOA matches to the

Table 2. Tinnitus imitation (column 2), FCDS pitch matches to the lowest and highest component of the tinnitus (column 3), FCDS pitch matches to an external tone (column 4), and to the remembered tone (column 5), and the range of frequencies matched to the tinnitus in the MOA task (column 6). Entries are in kHz.
Note. The frequencies of the synthesized tinnitus and of the matches to the tinnitus are rounded to the nearest 100 Hz when the components of the tinnitus were widely separated in frequency. DNC (did not converge) means that 10 reversals had not occurred in three times the number of trials required for convergence in matching the 1-kHz tone.

Subject	Synthesized Tinnitus	Match to tinnitus	Match to 1.0 kHz	Match to Remembered	Range (MOA)
1	2.2, 5.6, 7.4, 7.8	2.2; 7.8	1.000	DNC	3.5
2	4.5, 5.4, 5.7, 6.0	4.5; 5.5	0.999	1.004	1.8
3	5.100, 5.513, 5.529	5.041; 5.446	1.002	DNC	3.0
4	2.0, 3.4	2.5; 3.8	0.992	1.662	2.7
5	4.9, 5.3, 7.7, 8.1 8.2, 8.9, 10.7	5.0; 10.7	0.998	1.043	4.4

predominant pitch of the tinnitus spanned a wide frequency region, averaging 3 kHz. Although none of the ranges of frequency matches in the MOA task equalled the frequency range of the components of the synthesized tinnitus, the disparity exhibited by Subject 3 (about 0.4 kHz versus 3 kHz) is surprising. One possible explanation is that the tinnitus of this subject was quite fluctuant.

Table 3 presents the standard deviation (SD) of the FCDS and of the MOA matches to the tinnitus. In the FCDS task, the SD of each individual staircase from each track was computed, and the two SDs constituting a track were averaged. In the MOA task, the SD of all the matches was computed. Note that the SD of the matches in the MOA task involving tinnitus matching is generally more than two orders of magnitude greater than the SD for the FCDS task.

Table 3. Standard deviations of the pitch matches to the tinnitus displayed in columns 3 and 6 of Table 2. Entries are in Hz.

Subject	Match to tinnitus	Range (MOA)
1	2; 9	1534
2	15; 17	863
3	7; 8	1086
4	5; 4	1399
5	6; 1	1960

One point of interest for Subject 5 involves the comparison of the tinnitus synthesis with the SOAEs observed. Except for the 10.7 kHz component of the tinnitus synthesis, there was an SOAE in the region of each component of the imitation tinnitus. However, the subject had more SOAEs than there were components in the imitation tinnitus, suggesting that the SOAEs might not be the sole source of her tinnitus. A similar case study of one subject with two coexisting sources of tinnitus has been previously documented.[22]

CONCLUSION

It has sometimes been reported that matches to tinnitus exhibit minimal variability.[6-10] In such cases, subjects were intentionally instructed to focus on a single component of the tinnitus. For example, Graham and Newby[6] continued matches until the subject had made three consecutive matches within 5% of a central frequency[6] and Goodwin and Johnson[7-8] continued until five settings were within 1% of the center frequency of the bracketed region. By terminating the matching procedure only if the subject repeatedly matched to a narrow frequency region, a strategy similar to that in the FCDS task was conceivably induced.

The data in this paper demonstrate that broadband imitations of tinnitus may be matched reliably in a FCDS task (presumably because all but one component in the imitation was ignored so that the task converged), and conversely, that successive matches to the predominant tinnitus pitch in a MOA task may be unreliable (presumably because disparate components of the imitation were subsequently matched). By demonstrating that the same subject may exhibit either low-or-high-variability matches to tinnitus, we have united disparate results indicating on the one hand, that matches are variable[2-5] and, on the other hand, that matches are stable.[6-10]

In classical psychophysics, much emphasis is placed on the "ideal" observer, a mathematical construct in which a constant criterion is mathematically maintained while the observer detects signals in noise.[23] In matching the predominant pitch of tinnitus, the MOA task does not tend to produce a constant criterion (i.e., a constant listening band). It seems likely that the MOA is, therefore, unable to produce salient information concerning tinnitus pitch which may not be gleaned from direct measures of the range of the tinnitus.

There are two clinical consequences of this work. First, in assessing the effects of medical treatments on tinnitus, direct measures of the range of the tinnitus are desirable so that reported changes in tinnitus reflect changes in more than one component of the tinnitus. Second, the observation that tinnitus is a broad-band stimulus lends support to the use of broad-band tinnitus maskers but unfortunately suggests that it may be difficult to pinpoint the center frequency of the noise masker.

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