Reverse Correlation Uncovers More Complete Tinnitus Spectra

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Abstract*—*Goal: **This study validates a reverse correlation method for characterizing the sounds experienced by tinnitus patients with potential for characterizing a wider range of sounds than currently possible. *Methods:* Ten normal-hearing subjects assessed the subjective similarity of random auditory stimuli and target tinnitus-like sounds ("buzzing" and "roaring"). Reconstructions of the targets were obtained by regressing subject responses on the stimuli, and were compared for accuracy to the frequency spectra of the targets using Pearson's r. *Results:* Reconstruction accuracy was significantly higher than chance across subjects: buzzing ($M = 0.53$, $SD = 0.27$): $t(9) = 5.766$, $p < 0.001$; roaring ($M = 0.57$, $SD = 0.30$): $t(9) = 5.76$, $p < 0.001$. *Conclusion:* Reverse correlation can accurately reconstruct non-tonal tinnitus-like sounds in normal-hearing subjects, indicating its potential for characterizing the sounds experienced by patients with non-tonal tinnitus.**

***Index Terms*—reverse correlation, tinnitus, behavioral assay**

***Impact Statement*—Characterization of tinnitus can inform tinnitus treatment by allowing for individualized sound therapies, leading to better outcomes for patients suffering from the cognitive and psychological effects of tinnitus.**

I. Introduction

TINNITUS—the perception of sound in the absence of any corresponding external stimulus—affects up to 50 million people in the U.S. [1], [2], a third of whom experience functional cognitive impairment and substantial reduction in quality of life [3]–[5]. Clinical guidelines for tinnitus management frequently involve targeted exposure to tinnitus-like external sounds, either as a form of habituation therapy (termed *sound therapy*), or in the context of Cognitive Behavioral Therapy [6]. Critically, sound therapy is shown to improve with knowledge of the patient's internal tinnitus experience [7]–[14]. However, existing strategies for characterizing tinnitus sounds, such as Pitch Matching (PM) methods, are best suited for patients who experience sounds resembling pure tones (*e.g.*, ringing). This group may represent only between 20-50% of all tinnitus patients [15]–[17], with others experiencing non-tonal (*e.g.*, buzzing, roaring) tinnitus sounds. There is a pressing need for more robust tinnitus characterization methods [18]–[21].

Tinnitus sounds are presumed to be both complex and heterogeneous [18], [22], [23], although little has been firmly established about the specific characteristics. Therefore, we base our approach on *reverse correlation* (RC), an established behavioral method [24]–[26] for probing internal representations of visual and auditory percepts that is unconstrained by prior knowledge about the percepts themselves. RC asks subjects to render subjective judgments (*e.g.*, "does this sound like your tinnitus?") over random stimuli, from which unbiased estimates of the percepts can be produced. RC is closely related to Wiener theory [27], which has also inspired "white-noise" approaches to system characterization in physiology [28], [29] and engineering more broadly [30].

Here, we validate RC as a method for characterizing all component frequencies of non-tonal tinnitus sounds by estimating the full psychoacoustic tinnitus spectrum (PTS). To that end, we asked normal-hearing participants to complete an augmented RC experiment, comparing random stimuli to a target tinnitus-like sound. Target sounds were subsequently used as the basis for validating the quality of the estimated PTS. Our results demonstrate, for the first time, that tinnitus-like sounds with complex spectra can be accurately estimated using RC. This discovery may open the door to developing a clinical assay for characterizing the full range of sounds experienced by tinnitus patients.

II. Materials and Methods

Software code used for the experiments and analysis was written in MATLAB and is freely available at https://github.com/alec-hoyland/tinnitus-reconstruction/.

A. Stimuli

Stimuli were composed of $b = 8$ Mel-spaced frequency bins, which divide the frequency spectrum between $[100,\ 13,000]$ Hz into continuous segments of equal amplitude (*i.e.*, "rectangular" bins). Reconstruction detail increases with b, but $b = 8$ bins provides a good approximation to the chosen target sounds (see Fig. 3).

For each stimulus, $[2, 7]$ bins were randomly "filled" with power 0 dB. "Unfilled" bins were assigned a power of -100

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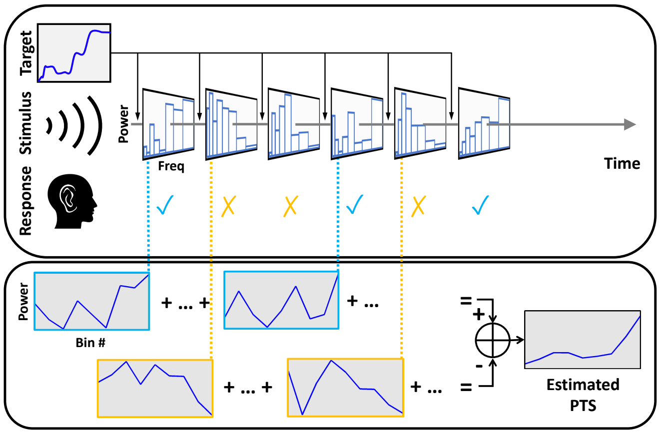

Fig. 1. Diagram of the experimental protocol. Subjects listen to a series of random stimuli, each preceded by a target sound. Subjects compare the stimulus to the target, and respond either "yes" or "no" depending on their perceived similarity. The recorded stimulus-response pairs are used to form an estimate of the target.

dB. Assigning random phase, the inverse Fourier transform of the spectrum yields a 500-ms stimulus waveform.

B. Target Sounds

Two tinnitus-like target sounds ("buzzing" and "roaring") from online examples maintained by the American Tinnitus Association [31] were downloaded and truncated to 500-ms in duration. These sounds were selected for the complexity and complementary nature of their frequency spectra.

C. Experiment

Trials followed an $A-X$ paradigm (Fig. 1), where $n=10$ subjects with self-reported normal hearing listened to the same target sound (A) followed by a random stimulus (X) for each trial. The task is designed to mimic the process by which a tinnitus patient might compare a random stimulus to their own tinnitus percept.

Subjects were told that some stimuli had the target sound embedded in them, and were instructed to respond "yes" to any such stimuli, and "no" otherwise. Subjects performed trials in blocks of 100, with breaks between blocks. Subjects completed two (2) blocks of trials per given target, A. The 400 total trials took subjects 10-20 minutes to complete.

D. Reconstruction

A subject performing n RC trials with b frequency bins produces a stimulus matrix $\Psi \in \mathbb{R}^{b\times n}$ and a response vector $y \in \{1,-1\}^n$, where 1 corresponds to a "yes" response and -1 to a "no." RC classically assumes the subject response model:

$$y = sign(\Psi^{\mathrm{T}} x), \tag{1}$$

where $x \in \mathbb{R}^{\mathrm{b}}$ represents the subject's internal representation of interest (*e.g.*, their tinnitus percept). This model can be inverted, yielding the following formula:

$$\hat{x} = \frac{1}{n}\Psi y \tag{2}$$

This formula is a restricted form of the Normal equation, under the assumption that the stimulus dimensions are uncorrelated [25]. Intuitively, $\hat{x}$ is the sum of all stimuli eliciting a "yes" response, after subtracting all stimuli eliciting a "no."

E. Validation

The $A-X$ paradigm allows for direct validation of the reconstructions $\hat{x}_{buzzing}$ and $\hat{x}_{roaring}$ against their corresponding target sounds. To that end, we represent the power spectra of the target sounds as vectors $s_{buzzing} \in \mathbb{R}^{\mathrm{b}}$ and $s_{roaring} \in \mathbb{R}^{\mathrm{b}}$ using the same $b=8$ frequency bins used in stimulus generation. The power in each bin is set as the mean power level of frequencies within that bin. Pearson's r between $s_{buzzing}$ and $s_{roaring}$ and their corresponding reconstructions ($\hat{x}_{buzzing}$ and $\hat{x}_{roaring}$) represents reconstruction accuracy. One-sample t-tests were performed on the mean Fisher-transformed r values across subjects to assess significant differences from zero.

F. Synthetic and Random Subjects

To establish bounds on human performance, additional experiments were run *in-silico* with two simulated subjects that represent participants who always give either *ideal* or *random* responses. Each experiment ran for $n=200$ trials and was repeated 1000 times.

The *ideal* subject gives responses following:

$$y_i = \begin{cases} 1 & \text{if } \Psi_i s \geq Q(0.5; \Psi s) \\ -1 & \text{otherwise} \end{cases} \tag{3}$$

for $i \in 1,\ldots,n$, where $Q(x,y)$ is the quantile function for $x \in [0,1]$ of the similarity calculation Ψs, and Ψ_i is the i^{th} column of Ψ. The ideal subject represents one who has precise knowledge of every stimulus and where the reconstruction algorithm mirrors 2.

The *random* subject chooses responses at random:

$$r_i = \begin{cases} 1 & \text{if } X > 0.5 \\ -1 & \text{otherwise} \end{cases} \tag{4}$$

where $X \in [0,1]$ is a uniform random variable.

III. Results

Figure 2 shows the distribution of Pearson's r (*i.e.*, reconstruction accuracy) from human, ideal, and random subject responses in the buzzing and roaring experimental conditions. Accuracies from human responses were generally higher than those from random subject responses, with some accuracies approaching those from ideal subject responses. Mean accuracy from the random subject responses was 0 in all conditions, while mean accuracy from human responses was significantly different from 0 in all conditions: buzzing: $t(9)=5.766$, $p<0.001$; roaring: $t(9)=5.76$, $p<0.001$; combined: $t(19)=7.542$, $p<0.001$. The buzzing results vary more than the roaring results. The buzzing ground truth spectrum contains significant high-frequency content, suggesting that the task may be more difficult for subjects with minor high-frequency hearing loss. Figure 3 plots example reconstructions from human responses with the best reconstruction accuracies overlaid on the target sound spectra, showing that those reconstructions capture many of the salient features of the target.

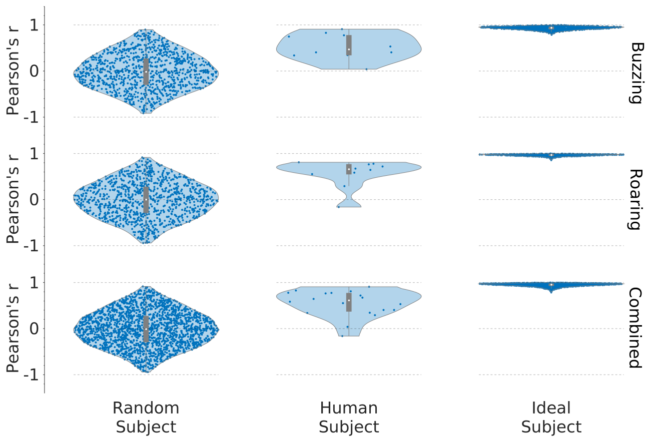

Fig. 2. Reconstruction accuracy for human subjects is significantly above baseline, but is not optimal. Reconstruction accuracies of random, human, and ideal subjects are shown as violin plots with box plots overlaid. The median is a white dot, the ordinate of the blue points are the Pearson's r values.

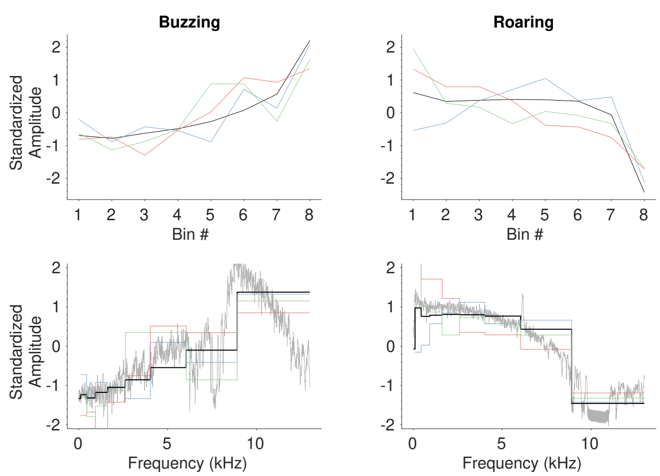

Fig. 3. Reconstructions of the PTS capture many salient features of tinnitus spectra. On each set of axes, the black trace indicates the target, while colored traces plot exemplar reconstructions from human subjects' data. In the top row, the target and reconstructions are shown as standardized power levels within each frequency bin. In the bottom row, those standardized power levels are mapped from the 8-dimensional bin domain to a 11025-dimensional frequency domain. The unbinned power spectral density of the targets is also shown in gray.

IV. Conclusion

Our results show that RC can accurately reconstruct the frequency spectrum of complex, non-tonal tinnitus-like sounds. This indicates that RC may also be useful for developing a clinical assay to characterize a wider variety of tinnitus percepts than currently possible. RC is purely behavioral, requires no specialized equipment, and has marginal setup. Moreover, subjects in the present study were able to complete the required number of trials within 20 minutes, indicating that this procedure could be conducted in a single clinical visit. Future work will focus on validating this approach in patients suffering from tinnitus.

Reconstruction accuracies observed here are well below those provided by an ideal subject's responses, which may be attributed to noisy human response characteristics universally observed in applications of RC. This may be mitigated by optimizing the experimental protocol, stimulus generation, and reconstruction method. For example, recent approaches to improving RC reconstruction methods have been shown to boost efficiency, noise robustness and overall accuracy [32], [33], and may also be applicable in the context of tinnitus.

References

[1] J. M. Bhatt, H. W. Lin, and N. Bhattacharyya, "Prevalence, Severity, Exposures, and Treatment Patterns of Tinnitus in the United States," *JAMA Otolaryngology–Head & Neck Surgery*, vol. 142, no. 10, pp. 959–965, Oct. 2016.

[2] National Institute on Deafness and Other Communication Disorders, "Quick Statistics About Hearing," https://www.nidcd.nih.gov/health/statistics/quick-statistics-hearing.

[3] D. B. Ahmed, A. Ahmed, D. T. Akhtar, and D. S. Salim, "Impact of Tinnitus Perception on Psychological Distress in Male and Female Tinnitus Patients," *Foundation University Journal of Psychology*, vol. 1, no. 1, pp. 01–26, Jan. 2017.

[4] D. M. Nondahl, K. J. Cruickshanks, D. S. Dalton, B. E. K. Klein, R. Klein, C. R. Schubert, T. S. Tweed, and T. L. Wiley, "The Impact of Tinnitus on Quality of Life in Older Adults," *Journal of the American Academy of Audiology*, vol. 18, no. 3, pp. 257–266, Mar. 2007.

[5] S. Tegg-Quinn, R. J. Bennett, R. H. Eikelboom, and D. M. Baguley, "The impact of tinnitus upon cognition in adults: A systematic review," *International Journal of Audiology*, vol. 55, no. 10, pp. 533–540, Oct. 2016.

[6] D. E. Tunkel, C. A. Bauer, G. H. Sun, R. M. Rosenfeld, S. S. Chandrasekhar, E. R. Cunningham, S. M. Archer, B. W. Blakley, J. M. Carter, E. C. Granieri, J. A. Henry, D. Hollingsworth, F. A. Khan, S. Mitchell, A. Monfared, C. W. Newman, F. S. Omole, C. D. Phillips, S. K. Robinson, M. B. Taw, R. S. Tyler, R. Waguespack, and E. J. Whamond, "Clinical Practice Guideline: Tinnitus," *Otolaryngology–Head and Neck Surgery*, vol. 151, no. 2_suppl, pp. S1–S40, Oct. 2014.

[7] P. B. Davis, B. Paki, and P. J. Hanley, "Neuromonics Tinnitus Treatment: Third Clinical Trial," *Ear and Hearing*, vol. 28, no. 2, pp. 242–259, Apr. 2007.

[8] M. Landgrebe, A. Azevedo, D. Baguley, C. Bauer, A. Cacace, C. Coelho, J. Dornhoffer, R. Figueiredo, H. Flor, G. Hajak, P. van de Heyning, W. Hiller, E. Khedr, T. Kleinjung, M. Koller, J. M. Lainez, A. Londero, W. H. Martin, M. Mennemeier, J. Piccirillo, D. De Ridder, R. Rupprecht, G. Searchfield, S. Vanneste, F. Zeman, and B. Langguth, "Methodological aspects of clinical trials in tinnitus: A proposal for an international standard," *Journal of Psychosomatic Research*, vol. 73, no. 2, pp. 112–121, Aug. 2012.

[9] A. K. Nickel, T. Hillecke, H. Argstatter, and H. V. Bolay, "Outcome Research in Music Therapy," *Annals of the New York Academy of Sciences*, vol. 1060, no. 1, pp. 283–293, 2005.

[10] H. Okamoto, H. Stracke, W. Stoll, and C. Pantev, "Listening to tailor-made notched music reduces tinnitus loudness and tinnitus-related auditory cortex activity," *Proceedings of the National Academy of Sciences*, vol. 107, no. 3, pp. 1207–1210, Jan. 2010.

[11] R. Schaette, O. König, D. Hornig, M. Gross, and R. Kempter, "Acoustic stimulation treatments against tinnitus could be most effective when tinnitus pitch is within the stimulated frequency range," *Hearing Research*, vol. 269, no. 1, pp. 95–101, Oct. 2010.

[12] A. Stein, A. Engell, M. Junghoefer, R. Wunderlich, P. Lau, A. Wollbrink, C. Rudack, and C. Pantev, "Inhibition-induced plasticity in tinnitus patients after repetitive exposure to tailor-made notched music," *Clinical Neurophysiology*, vol. 126, no. 5, pp. 1007–1015, May 2015.

[13] P. A. Tass, I. Adamchic, H.-J. Freund, T. von Stackelberg, and C. Hauptmann, "Counteracting tinnitus by acoustic coordinated reset neuromodulation," *Restorative Neurology and Neuroscience*, vol. 30, no. 2, pp. 137–159, Jan. 2012.

[14] H. Wang, D. Tang, Y. Wu, L. Zhou, and S. Sun, "The state of the art of sound therapy for subjective tinnitus in adults," *Therapeutic Advances in Chronic Disease*, vol. 11, p. 2040622320956426, Jan. 2020.

[15] J. S. Turner JR, "Auditory dysfunction: Tinnitus," *Clinical Methods: The History, Physical, and Laboratory Examinations*, 1990.

[16] J. A. Henry, K. E. James, K. Owens, T. Zaugg, E. Porsov, and G. Silaski, "Auditory test result characteristics of subjects with and without tinnitus." *Journal of Rehabilitation Research & Development*, vol. 46, no. 5, 2009.

[17] O. C. Ukaegbe, F. T. Orji, B. C. Ezeanolue, J. O. Akpeh, and I. A. Okorafor, "Tinnitus and its effect on the quality of life of sufferers: A Nigerian cohort study," *Otolaryngology–Head and Neck Surgery*, vol. 157, no. 4, pp. 690–695, 2017.

[18] J. A. Henry, K. M. Reavis, S. E. Griest, E. J. Thielman, S. M. Theodoroff, L. D. Grush, and K. F. Carlson, "Tinnitus: An Epidemiologic Perspective," *Otolaryngologic Clinics of North America*, vol. 53, no. 4, pp. 481–499, Aug. 2020.

[19] J. A. Henry, ""Measurement" of Tinnitus," *Otology & Neurotology*, vol. 37, no. 8, p. e276, Sep. 2016.

[20] A. Noreña, C. Micheyl, S. Chéry-Croze, and L. Collet, "Psychoacoustic Characterization of the Tinnitus Spectrum: Implications for the Underlying Mechanisms of Tinnitus," *Audiology & neuro-otology*, vol. 7, pp. 358–69, Nov. 2002.

[21] L. E. Roberts, G. Moffat, and D. J. Bosnyak, "Residual inhibition functions in relation to tinnitus spectra and auditory threshold shift," *Acta Oto-Laryngologica*, vol. 126, no. sup556, pp. 27–33, 2006.

[22] D. Vajsakovic, M. Maslin, and G. D. Searchfield, "Principles and Methods for Psychoacoustic Evaluation of Tinnitus," *Current Topics in Behavioral Neurosciences*, Feb. 2021.

[23] M. B. Meikle, T. A. Creedon, and S. E. Griest, "Tinnitus Archive: Archive Background and Development," http://www.tinnitusarchive.org/appendix/archiveBackgroundAndDevelopment/, 2004.

[24] A. Ahumada and J. Lovell, "Stimulus Features in Signal Detection," *The Journal of the Acoustical Society of America*, vol. 49, no. 6B, pp. 1751–1756, Jun. 1971.

[25] F. Gosselin and P. G. Schyns, "Superstitious Perceptions Reveal Properties of Internal Representations," *Psychological Science*, vol. 14, no. 5, pp. 505–509, Sep. 2003.

[26] W. O. Brimijoin, M. A. Akeroyd, E. Tilbury, and B. Porr, "The internal representation of vowel spectra investigated using behavioral response-triggered averaging," *The Journal of the Acoustical Society of America*, vol. 133, no. 2, Feb. 2013.

[27] N. Wiener, *Nonlinear Problems in Random Theory*, 1966.

[28] D. Ringach and R. Shapley, "Reverse correlation in neurophysiology," *Cognitive Science*, vol. 28, no. 2, pp. 147–166, 2004.

[29] P. Z. Marmarelis and V. Z. Marmarelis, "The White-Noise Method in System Identification," in *Analysis of Physiological Systems: The White-Noise Approach*, ser. Computers in Biology and Medicine, P. Z. Marmarelis and V. Z. Marmarelis, Eds. Boston, MA: Springer US, 1978, pp. 131–180.

[30] G. M. Ljung and G. E. P. Box, "On a measure of lack of fit in time series models," *Biometrika*, vol. 65, no. 2, pp. 297–303, Aug. 1978.

[31] "Measuring Tinnitus — American Tinnitus Association," Aug. 2022.

[32] B. W. Roop, B. Parrell, and A. C. Lammert, "A Compressive Sensing Approach for Inferring Cognitive Representations with Reverse Correlation," *bioRxiv*, 2021.

[33] A. Compton, B. W. Roop, B. Parrell, and A. C. Lammert, "Stimulus whitening improves the efficiency of reverse correlation," *Behavior Research Methods*, Aug. 2022.