Specific Aims

The **objective** of this proposal is to directly and more completely characterize the perceptual experience of tinnitus using the novel application of a primary method for uncovering latent perceptual representations: reverse correlation. Tinnitus is the perception of ringing, buzzing, or hissing in the ears, which can range from mild and transient to debilitating. In the U.S. alone, it affects 45 million people per year, 30% of which report their tinnitus to be moderate to severe. A primary form of treatment habituation therapy that retrains a patients nervous system by habituating it to external sounds that mimic the perceptual experience of the tinnitus sound. Habituation therapies require accurate estimates of patients tinnitus experience in order to promote patient outcomes. There is a pressing need for new approaches to uncovering individuals perceptual experience of tinnitus, because current estimation methods rely on strongly reductionist assumptions concerning the nature of tinnitus sounds, and produce results that are correspondingly biased and incomplete. Reverse correlation holds promise in this regard, as a primary method used to characterize neural tuning that is known to allow for unconstrained and unbiased estimation of latent neural representations (*e.g.,* neural receptive fields) [27, 31], as well as higher-level cognitive representations, including psychophysical kernels that drive the top-down processes of perception (*e.g.,* face or phoneme recognition) [1, 10, 26, 32], and even abstract psychological categories (*e.g.,* male vs. female faces) [6, 22, 30], all on the basis of fairly simple stimulus-response data [20, 23]. Despite its wide acceptance in other areas of inquiry, reverse correlation has not been brought to bear with respect to uncovering tinnitus experience.

Our **long-term goal** is to directly uncover and more completely characterize the perceptual experience of tinnitus using the demonstrated capabilities of the reverse correlation approach. Our guiding hypothesis is that reverse correlation will produce estimates of tinnitus percepts that are substantially more rich, individualized and unbiased than currently possible using existing approaches. The rationale is that high quality characterization of tinnitus percepts can promote detailed assessment of tinnitus, helping to explain individual variability in tinnitus experience, and ultimately informing individualized treatment through enhanced habituation therapies. The proposed work will simultaneously improve the efficiency of the reverse correlation method itself, further enhancing its potential for adoption in clinical settings. We will test our central hypothesis and attain our objective via the following specific aims:

Aim #1: Uncover and reconstruct cognitive representations of tinnitus

Participants will classify white noise stimuli as sounding like their tinnitus or not. We will use reverse correlation to infer an unbiased estimate of each participant's cognitive representation of their tinnitus percept.

Aim #2: Develop efficient reconstruction algorithm for cognitive representations using compressive sensing

The efficiency of this method can be optimized to require fewer samples using advanced signal processing techniques. We will develop an open-source compressive sensing data analysis pipeline to acquire convergent cognitive representations using fewer trials. Our pilot data demonstrates that compressive sensing affords a 90% decrease in number of trials for equivalent resulant latent representation. We will also develop and distribute an open-source software implementation the of the reverse correlation method for speech perception, including the proposed compressive sensing framework, for use by the research community.

Aim #3: Characterize and interpret cognitive representations of tinnitus

Our compressive sensing framework will allow for rapid data acquisition from participants. We will characterize cognitive representations of tinnitus between participants and over time. What is the space of tinnitus cognitive representations? Are there subtypes or clusters on a lower dimensional manifold? We will employ dimensionality reduction and clustering algorithms to represent and visualize the data, providing direct insight into commonalities and variability of tinnitus experience in and between subjects.

A. Significance

Tinnitus, the perception of ringing, buzzing, or hissing in the ears when no external sound is present, is a health condition estimated to affect 10-15% of adults worldwide [16]. The condition is highly heterogeneous and can range from mild and transient to debilitating and constant. In the U.S., tinnitus affects approximately one in ten Americans, with 7.2% of those rating their tinnitus as severe ([3]. Tinnitus can be perceived unilaterally or bilaterally and may differ over time, even within individuals. This heterogeneity in characterization has important implications for research and clinical practice. Identifying patterns in how tinnitus sounds and its relationship to hearing may aid in identifying different forms of tinnitus and revealing their underlying mechanisms. However, the subjective nature of characterizing tinnitus makes it difficult to reliably define and measure [33].

Current methods to determine cognitive representations of tinnitus are inefficient and introduce bias, resulting in a lack of standardization in tinnitus assessment [16]. Alternate forced-choice (AFC) paradigm tasks ask the patient to determine which of two sounds is closer to their tinnitus percept [12, 13, 15, 18]. Recent computer and methodological advances have made the test more portable and efficient, but the AFC paradigm still relies on assumptions about the subject's tinnitus percept. Tinnitus percepts are too heterogeneous to be represented by pure tones or small-envelope waveforms. Adequately sampling the psychoacoustic space of possible tinnitus percepts via an AFC task is unfeasible. Other approaches have attempted to capture the richness of tinnitus percepts using likeness measures, in which the subject rates whether a presented stimulus is part of their tinnitus percept or not [28]. While this method is able to capture more features of cognitive representations of tinnitus, it is time-consuming and limited by the aural skills of the subject [33]. Both these approaches involve the subject comparing an external stimulus to their cognitive representation of the tinnitus percept, however AFC tasks introduce biases by artificially limiting the stimulus space and likeness measures are time-consuming. *We believe that a novel reverse correlation-based approach will produce efficient and unbiased cognitive representations of tinnitus percepts* [10].

Reverse correlation allows for unconstrained and unbiased characterization of latent representations directly from stimulus-response data by eliciting responses to richly varying stimuli, such as white noise [23, 27]. Rich stimuli, by virtue of the fact that they are inherently vague, force the top-down process to exert a clearly measurable influence on responses. Latent representations that drive the top-down process can then be estimated by regressing observed responses against the stimuli over many trials [24]. Reverse correlation, as a method, is powerful enough to characterize any aspect of neurological, cognitive or psychological function that can be modeled as a transductive process [31]. It has become a primary method used to characterize the latent representations encapsulated in neural tuning (*e.g.,* receptive fields; [31]), and is closely related to the widely-used "white noise approach" to characterizing physiological [23] and engineering [20] systems.

Reverse correlation, in addition to its prominence as an important tool relative to lower-level neural mechanisms, has been increasingly used for inferring higher-level cognitive representations, including psychophysical kernels that drive the top-down processes of perception [1, 10, 26, 32], and even abstract psychological categories (*e.g.,* "male" vs. "female" faces; [6, 22, 30]. Recent work in vision has demonstrated that reverse correlation can effectively characterize cognitive representations underlying letter and face recognition (Fig 2A) [10, 19]. One speech study has also estimated steady-state representations of vowels the /a/ and /i/ using a closely-related paradigm to the one proposed here (Fig 2B; [5]). Our proposed use of reverse correlation in the domain of speech expands on classic efforts to understand top-down processing in speech with the presentation of rich, vague stimuli to elicit responses from listeners (Warren & Warren, 1970; Vokey & Read 1985). These studies provide clear evidence that rich stimuli, such as white noise, are sufficient to engage the top-down process, even if they do not attempt to characterize the latent representations.

Incomplete characterizations of cognitive representations impoverish our scientific understanding of tinnitus, weak causal explanations for its etiology, and hinder progress towards effective treatments. Reverse correlation shows promise to provide a more complete characterization of cognitive representations of tinnitus and is applicable to other psychophysical domains as well. Directly characterizing complex representations of tinnitus can enable more effective, targeted treatments, reveal insights about subtypes of the condition, and pave the way for new tinnitus-masking assistive devices. Fully characterizing a high-dimensional representation of tinnitus will improve causal explanations for currently unexplained variability in tinnitus experience both between subjects and within single subjects over time.

A.3. Rigor of the Prior Research

The premise of the proposed work is that reverse correlation will deliver unbiased estimates of cognitive representations of tinnitus. Furthermore, that compressive sensing will dramatically increase the efficiency of experiments, resulting in convergent cognitive representations in a fraction of the samples.

The evidence for this premise is first based on well-established studies using reverse correlation to derive cognitive representations of sounds and symbols. Reverse correlation has been applied to infer cognitive representations from letters [10], vowel sounds [5], and faces [6, 32]. More broadly, it has been applied to infer the shape of receptive fields in linear transducers and spiking neurons [31]. The reverse correlation paradigm makes minimal assumptions about the derived cognitive representation since the subject is presented with high-dimensional random input. A large number of stimulus-response samples are typically required for accurate reconstruction of cognitive representations using conventional techniques. To address this inefficiency, studies often limit the richness of stimuli, or impose strict constraints on the reconstructions, leading to estimates that are biased or incomplete. However, recent advances in signal processing, most notably a techniques known as compressive sensing, are leading to dramatic improvements the efficiency of traditional sampling.

We propose to develop an advanced signal processing pipeline that will enable us to overcome the inefficiencies of existing reverse correlation methods through the use of compressive sensing, a recent advance in signal processing which has led to dramatic improvements the efficiency of traditional sampling and signal estimation methods (Baraniuk, 2007). Compressive sensing has recently gained wide recognition in domains such as medical imaging (Graff & Sidky, 2015; Lustig et al., 2008), where considerations of efficiency and bias reduction are critical. Compressive sensing holds promise to similarly improve the efficiency of reverse correlation, without the drawback of biasing estimates. By dramatically decreasing the number of trials needed for signal reconstruction, this technique will extend the range of perceptual mechanisms that can be estimated. Moreover, compressive sensing can be directly substituted for conventional, regression-based estimation, with no other required changes to existing experimental protocols. Our ultimate objective is to develop and validate a compressive sensing data processing pipeline - culminating in an open-source software tool that will allow for efficient and accurate reconstruction of latent representations using data obtained via the reverse correlation method.

B. Innovation

The proposed project is innovative for several reasons. First, we will leverage interdisciplinary collaboration between engineering (Lammert) and hearing science (Ben) to characterize tinnitus to inform clinical care. Second, we will apply reverse correlation to the tinnitus domain in a novel application, which promises to deliver unbiased, high-dimensional estimates of cognitive representations of tinnitus. Third, we will develop a signal processing pipeline to leverage compressive sensing to acquire accurate estimates of cognitive representations of tinnitus using significantly fewer samples. This pipeline will save experimenters and subjects time and will enable researchers to collect data from more subjects and from individual subjects over time. We will release our open-source software tool online with bindings to popular scientific computing languages.

C. Approach

In the proposed project, we will use reverse correlation to reveal unbiased high-dimensional representations of tinnitus and further characterize the condition using dimensionality-reduction and density-based clustering. In *Aim #1*, we will develop and run an experimental paradigm in which tinnitus patients listen to noisy stimuli and perform an alternate forced-choice task answering the question, "Does this sound like your tinnitus?" Reverse correlation frees us from the methodological constraint of imposing strong *a priori* assumptions about the tinnitus percept. In *Aim #2*, we will develop an open-source signal processing pipeline to reconstruct cognitive representations of tinnitus using compressive sensing. Compressive sensing holds promise to dramatically reduce the number of samples needed for accurate reconstruction, enabling us to run more experimental subjects for Aim #1, and retest subjects to examine the stability of cognitive representations of tinnitus over time. *Aim #3* contextualizes reconstructed cognitive representations of tinnitus by visualizing underlying subtypes or clusters on a lower dimensional manifold. We will employ dimensionality reduction and clustering algorithms to represent and visualize the data, providing direct insight into commonalities and variability of tinnitus experience in and between subjects.

C. Aim #1: Uncover and reconstruct cognitive representations of tinnitus

In this aim, we will identify high-dimensional cognitive representations of tinnitus using reverse correlation. Current methods for estimating cognitive representations of tinnitus fall broadly into three primary categories, each of which has limitations (Table 1). One approach is to use forced-choice selection tasks. In this experimental paradigm, the experimenter presents participants with multiple samples of auditory stimuli that vary in well-characterized and often highly-constrained ways, along specific dimensions (*e.g.,* pure tone frequency, width of spectral envelope) that are known to be, or are hypothesized to be, relevant to tinnitus representation or masking [14, 33]. The subject then makes a choice between stimuli. While new methodological advances in experiment design and technology have streamlined this approach [13, 15, 18], it is still constrained by *a priori* assumptions about the nature of tinnitus percepts. In contrast, likeness approaches use subjective judgment tasks, in which the subject rates how much (if at all) a presented stimulus is part of or masks their tinnitus percept [28]. While likeness measures provide more complete reconstructions of tinnitus cognitive representations, likeness tests are time-consuming and generally not used in clinical practice [33].

The highly-constrained nature of stimuli used in the forced selection approach necessarily results in recovered representations that are correspondingly constrained and typically low-dimensional. It has long been known, however, that representations limited to only a few dimensions are insufficient to account for the full richness of tinnitus experiences [14, 33]. Subjective judgment experiments yield more informative reconstructions but are time-consuming to employ. The nature of subjective judgment approach is such that it is best suited to uncover relations between perceptual categories, rather than characterizing cognitive representations directly, and thus provides limited information about how perceptual similarity comes about. While some of the recovered dimensions along which stimuli differ in these tasks correlate with frequently assumed dimensions of representation (*e.g.,* frequency and pitch to mask tinnitus percept), some recovered dimensions of contrast have no known characterization. Moreover, this approach is fundamentally limited by the precise stimuli presented to participants, and therefore may not systematically explore the entire space of perceptually-meaningful variables.

A third, more recent approach to uncovering cognitive representations is to employ neuroimaging (*e.g.,* fMRI) to identify neural activation patterns indicative of tinnitus. In investigations of functional connectivity in tinnitus patients, resting-state fMRI measures were found to be replicable and reliable, though no explicit representations have been proposed [17]. This approach is also limited, in that it can only uncover representations that have a definite, localized seat in the brain. Cognitive representations, by contrast, are commonly understood to be constructs that need not have such a localized neural seat by definition, and which can best be revealed through analyzing behavior.

In a set of two experiments described below, we propose to implement a reverse correlation approach for recovering cognitive representations of speech which allows for unconstrained, direct characterization of latent representations from yes-no responses to randomly-generated stimuli. Participants will be asked to classify random auditory stimuli as containing or not containing their tinnitus percept. Latent representations that drive the top-down process can then be estimated by regressing observed responses against the stimuli over many trials [24].

Reverse correlation has been applied across multiple fields to reveal underlying representations by application of unconstrained, noisy input. Reverse correlation has been used to characterize low-level latent representations encapsulated in neural tuning (*e.g.,* receptive fields) [31] and has been used to successfully recover cognitive representations underlying visual perception [10] Both existing experimental work (*cf.,* Fig 2B in [5]) and our preliminary simulation experiments (Figure 2) suggest that this method can be successfully translated into the auditory domain. Reverse correlation allows us (1) to uncover more complex, potentially higher-dimensional

Approach	Stimulus	Measurements	Output
Forced selection	Constructed stimuli, constrained variation	Subjective choice	Representation with defined acoustic properties
Likeness measures	Constructed stimuli, constrained variation	Subjective ratings	Frequency spectra
Neural monitoring	N/A	Neural signals (*e.g.*, fMRI)	Correlation maps in localized brain regions, functional connectivity maps
Reverse Correlation	Constructed stimuli, unconstrained variation	Response classification (*e.g.*, present/absent)	Representations best explaining classification behavior

Table 1: Comparison of approaches for estimating cognitive representations. Each approach has benefits and limitations regarding stimuli, measurements, and output. The proposed approach, featured in the final row, is the only approach that can directly uncover a time-frequency map of the cognitive representation that best explains tinnitus percepts.

representations than would be possible using more focused, constrained stimuli, (2) to recover directly the nature of the representations themselves rather than the relation between the tinnitus percept and a masking sound, and (3) to recover cognitive representations of the tinnitus percept directly rather than a neural correlate. In short, reverse correlation will be able to provide deeper understanding of cognitive representations of tinnitus percepts than is possible with conventional methods.

C.1. Method

The proposed method for uncovering perceptual representations can be divided into a sequence of three main parts: (1) construction of vague, "random" stimuli for presentation to subjects, (2) experimental procedure and data collection, and (3) reconstruction of perceptual representations from subject responses.

Stimuli construction Stimuli will be generated randomly, in keeping with prior work in the visual domain [10]. The meaning of "random" with respect to the stimuli presented to subjects refers specifically to the shape of spectral envelope in the frequency domain. This shape will be determined randomly for all stimuli and will not be informed by prior knowledge or statistics over canonical examples of tinnitus. These random spectral envelopes will be used as the basis for building spectrograms that sound like tinnitus percepts.

Our preliminary testing suggests that truly random envelopes often result in the perception of colored noise. Minimal additional spectral-temporal constraints may need to be imposed on stimuli such that participants will interpret the stimuli as intending to be tinnitus percepts. This is similar to the approach taken in some visual domain experiments, where bandlimited random stimuli, or stimuli with partial superimposed templates, are presented [32] (CITE).

What are we doing to create the stimuli?

Experimental procedure Where are we getting our subjects?

How are we evaluating tinnitus in our subjects?

How do we phrase what we want the subjects to do?

Reconstructing representations To reconstruct cognitive representations from subject responses, we will generate a classification spectrogram by taking the difference between a spectrogram generated from the positive labels (the "yes" responses) and a spectrogram generated from the negative labels (the "no" responses) (Figure 1). Such reconstructed representations are the best least-squares fit to the behavioral data [10]. We theorize that the classification spectrogram is used as a template vector against which stimuli were compared in a linear matching model of response generation.

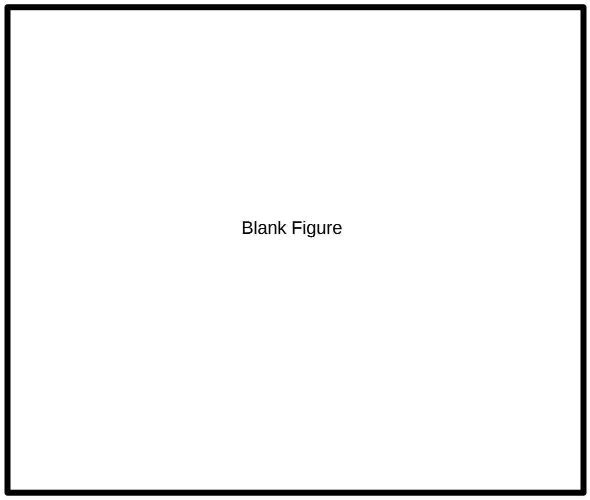

Figure 1: Schematic overview of experiments proposed in Aim #1. Simulation results are shown, demonstrating proof-of-concept for the proposed reverse correlation paradigm.

C.2. Aim #2: Develop an efficient reconstruction algorithm for cognitive representations using compressive sensing

In this aim, we employ advanced signal processing techniques to overcome critical inefficiencies in reverse correlation that limit its scope and impact.

Current attempts to characterize perceptual mechanisms using reverse correlation are limited in scope due to inefficiencies inherent to conventional methods. While reverse correlation allows for relatively unconstrained and unbiased estimation of latent representations using straightforward stimulus-response data [23, 27], the number of stimulus-response samples required for accurate estimation is typically very large [24]. This inefficiency limits the feasibility of applying reverse correlation more broadly, as subject participation must be maintained over long timelines.

The impact of this inefficiency extends well beyond the present proposal. This fundamental sampling problem affects similar efforts to estimate higher-level cognitive representations and psychophysical kernels that drive top-down processes of perception [1, 10, 26, 32]. Since reverse correlation has broad applicability for characterizing any aspect of neurological, cognitive, or psychological function that can be modeled as a transductive process [31], the inefficiencies of reverse correlation impact efforts to characterize phenomena as [word meaning minute, fine-grained, detailed, specific] latent neural representations (*e.g.*, neural receptive fields) [31] and as high-level as abstract psychological categories (*e.g.*, "male" vs. "female" faces) [6, 22, 30]. To combat this efficiency limitation, studies often (*a*) limit the richness of the stimuli (*e.g.*, by only allowing specific aspects of the stimulus to vary) [9], or (*b*) impose some constraints on the inferred representations, for instance by smoothing the raw estimates [10]. The constraints imposed by these approaches ultimately defeat the full power of reverse correlation [25], leading to estimates that are biased or incomplete.

We propose to develop an advanced signal processing pipeline that will enable us to overcome the inefficiencies of existing reverse correlation methods through the use of *compressive sensing*, a recent advance in signal processing which has led to dramatic improvements in efficiency over conventional sampling and signal estimation methods [2]. Compressive sensing has recently gain wide recognition in domains such as medical imaging [11, 21], where considerations of efficiency and bias reduction are critical. Compressive sensing holds promise to similarly improve the efficiency of reverse correlation without the drawback of biasing estimates. Compressive sensing will extend the range of possible cognitive and perceptual mechanisms that can be estimated by dramatically decreases the number of trials needed for signal reconstruction. Since compressive sensing can be directly substituted for conventional, regression-based estimation, it can be directly substituted into eixsting experimental protocols without requiring other changes. Our ultimate objective is to develop and validate a compressive sensing data processing pipeline culminating in an open-source software tool that will allow for efficient and accurate reconstruction of latent representations using data obtained via the reverse correlation method.

Compressive sensing framework Many natural signals, x, including latent representations, are compressible, meaning that they can be represented by a sum of a small number of functions from an appropriately-chosen basis set ($s = \Psi^T x$, for basis Ψ and weights s). A key insight of compressive sensing is that response variables, y, stem from a process of comparing stimuli to latent representations ($y = \Phi x$, for measurement Φ). It is then possible to estimate the latent representation using only a small number of measurements by acquiring the basis function representation directly (*i.e.,* $y = \Phi\Psi s$) via sparse optimization (to find s). The responses can be continuous (*e.g.,* firing rates), ordinal similarity scores [35], or binary [4, 29], as in the proposed experiments here. In practice, sparse representations can be found even when the chosen basis domain is quite general and incorporates no prior knowledge of the signal's characteristics (*e.g.,* the discrete cosine transform or wavelet transform). Critically, it has been shown that using random stimuli to elicit and subsequently observe responses is a highly effective way to ensure accurate reconstruction of latent representations within the compressive sensing framework [7, 8, 34]. In other words, the somewhat unusual model of sampling assumed by compressive sensing maps directly onto reverse correlation.

Simulations and preliminary evidence We have conducted simulation studies to begin validating compressive sensing for improving the efficiency of reverse correlation. Fpr example, using a template time-frequency representation, x, as a proxy for the latent representation of interest, we generate plausible yes/no subject responses, $y \in \{-1, 1\}$), based on the similarity between the template and a random stimuli (*i.e.,* $y = \mathrm{sign}(\phi x)$ for stimuli ϕ). Estimation of the template is performed using (*a*) convention regression-based reverse correlation (*i.e.,* $\hat{x}_c = n^{-1} X^{\mathrm{T}} y$) [10], or (*b*) compressive sensing.

Figure 2 shows example results from our preliminary simulation studies. In this example, we attempt to reconstruct a spectrally-rich signal. Four reconstructions are shown, corresponding to two sample sizes (12,500 and 100,000 samples) and two reconstruction methods (conventional linear regression and compressive sensing). The signal quality obtained using fewer samples via compressive sensing is effectively equivalent to that obtained using eight times more samples via conventional reconstruction. When allowed to operate on the full complement of 100,000 samples, compressive sensing shows +21% improved accuracy over conventional reconstruction. If further simulation studies and validation on real data continue to align with these preliminary results, the number of trials required for accurate estimation using reverse correlation paradigms could be reduced to 12.5% of the current standard. Such a drastic increase in time- and cost-effectiveness would substantially increase the method's potential for widespread use.

Validation of compressive sensing We will validate the proposed use of compressive sensing for relevant cognitive and behavioral data. Validation will be accomplished through simulation studies (*e.g.,* expanding on the simulation results discussed herein) and through analysis of data collected in Aim #1. We will assess outcomes by examining estimation performance as a function of sample size, incuding (*a*) reconstruction accuracy with few samples, (*b*) gains in high-sample reconstruction accuracy, and (*c*) minimal sample size to achieve high-end convergent accuracy. The basis for these assessments will be a comparison with the conventional, full-sample reconstruction as described in Aim #1, since the true gold standard representation is unavailable. Potential improvements of compressive sensing reconstruction will be assessed using signal quality metrics that do not require direct comparison (*e.g.,* peak signal-to-noise ratio). This work will determine optimal parameters for compressive sensing in tinnitus percept reconstruction. We expect these parameters to depend on stimulus type, response noise, and the type of tinnitus experienced by the subject. Considered parameters will include appropriate input/output representations, reconstruction algorithm, and basis type/sparsity.

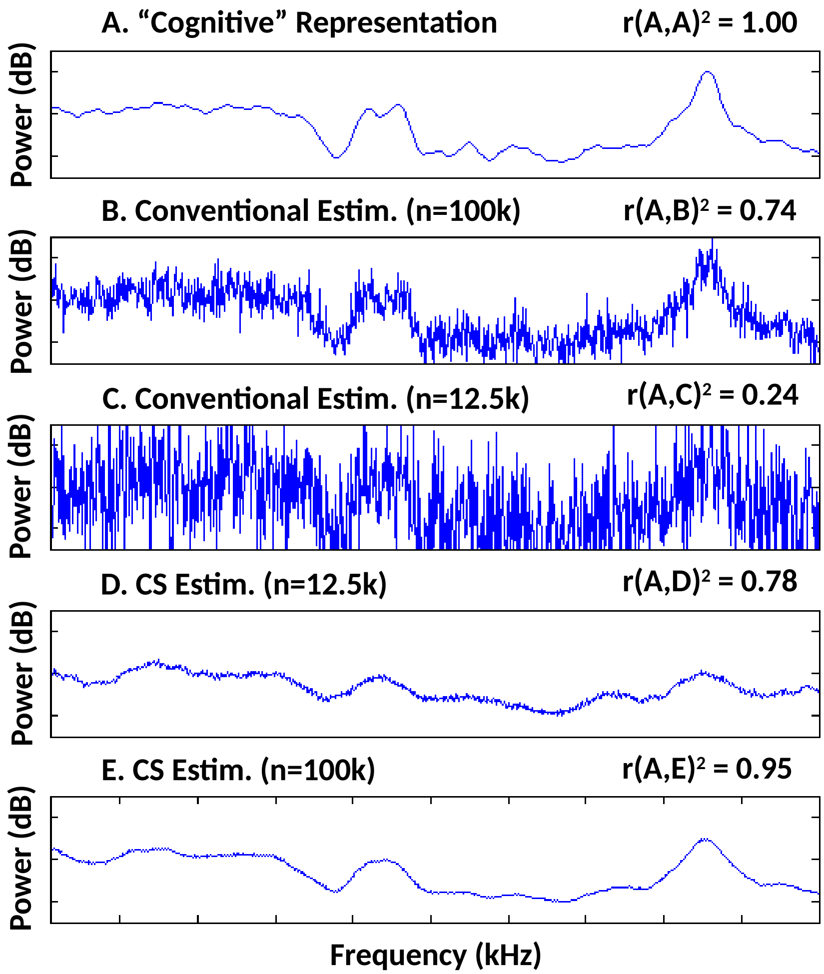

Figure 2: Compressive sensing (CS) delivers accurate signal reconstruction from sampling with a comparatively small number of samples. The latent representation in *A* is estimated in *B-E*. In *B-C* conventional regression-based estimation is used and in *D-E* compressive sensing is used. The number of samples n is displayed along with the correlation coefficient r^2 between the estimated reconstruction and the original signal, as a measure of reconstruction quality.

Development of an open-source software tool We will develop and distribute an open-source software tool for conducting auditory perceptual experiments using reverse correlation, including stimulus presentation, response collection, and representation reconstruction, characterization, and comparison as described in Aim #3. This software package will include both standard reconstruction methods as well as an implementation of the compressive sensing framework, informed by the findings in this Aim, for use by the research community. We will develop interfaces for widely-used programming languages (including MATLAB and Python) in addition to command-line executables. Making the platform open-source provides opportunities for the community to make improvements and enables researchers to tailor these methods to their specific use-cases.

Reverse correlation has the potential to uncover latent representations underlying perception, and transform our understanding of perceptual mechanisms at various levels of investigation: neural, cognitive and psychological. However, in order for this potential to be fully realized, the fundamental inefficiency of reverse correlation paradigms must be overcome. Compressive sensing holds promise to overcome this limitation by dramatically improving the efficiency of reverse correlation, enabling its extension to perceptual mechanisms that are out of reach using current methods. The work proposed here will enable researchers to access the promise of compressive sensing, broadening the impact of reverse correlation.

C.3. Aim #3: Characterize and interpret cognitive representations of tinnitus

1. What is the shape of the manifold of cognitive representations of tinnitus?
2. Is it reducible to fewer dimensions using PCA/t-SNE/UMAP?
3. Can clusters on the manifold/reduced representation be found? What are those clusters?
4. Is this insight clinically useful?

References

[1] Al Ahumada and John Lovell. "Stimulus Features in Signal Detection". In: *The Journal of the Acoustical Society of America* 49 (6B June 1, 1971), pp. 1751–1756. ISSN: 0001-4966. DOI: 10.1121/1.1912577. URL: https://asa.scitation.org/doi/abs/10.1121/1.1912577 (visited on 04/26/2021).

[2] R. G. Baraniuk. "Compressive Sensing [Lecture Notes]". In: *IEEE Signal Processing Magazine* 24.4 (July 2007), pp. 118–121. ISSN: 1558-0792. DOI: 10.1109/MSP.2007.4286571.

[3] Jay M. Bhatt, Harrison W. Lin, and Neil Bhattacharyya. "Prevalence, Severity, Exposures, and Treatment Patterns of Tinnitus in the United States". In: *JAMA OtolaryngologyHead & Neck Surgery* 142.10 (Oct. 1, 2016), pp. 959–965. ISSN: 2168-6181. DOI: 10.1001/jamaoto.2016.1700. URL: https://doi.org/10.1001/jamaoto.2016.1700 (visited on 04/21/2021).

[4] Petros T. Boufounos and Richard G. Baraniuk. "1-Bit Compressive Sensing". In: *2008 42nd Annual Conference on Information Sciences and Systems*. 2008 42nd Annual Conference on Information Sciences and Systems. Mar. 2008, pp. 16–21. DOI: 10.1109/CISS.2008.4558487.

[5] W. Owen Brimijoin et al. "The Internal Representation of Vowel Spectra Investigated Using Behavioral Response-Triggered Averaging". In: *The Journal of the Acoustical Society of America* 133.2 (Feb. 2013). ISSN: 0001-4966. DOI: 10.1121/1.4778264. pmid: 23363191. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3864535/ (visited on 02/23/2021).

[6] L. Brinkman, A. Todorov, and R. Dotsch. "Visualising Mental Representations: A Primer on Noise-Based Reverse Correlation in Social Psychology". In: *European Review of Social Psychology* 28.1 (Jan. 1, 2017), pp. 333–361. ISSN: 1046-3283. DOI: 10.1080/10463283.2017.1381469. URL: https://doi.org/10.1080/10463283.2017.1381469 (visited on 02/23/2021).

[7] E. J. Candes and M. B. Wakin. "An Introduction To Compressive Sampling". In: *IEEE Signal Processing Magazine* 25.2 (Mar. 2008), pp. 21–30. ISSN: 1558-0792. DOI: 10.1109/MSP.2007.914731.

[8] Emmanuel J. Candès. "The Restricted Isometry Property and Its Implications for Compressed Sensing". In: *Comptes Rendus Mathematique* 346.9 (May 1, 2008), pp. 589–592. ISSN: 1631-073X. DOI: 10.1016/j.crma.2008.03.014. URL: https://www.sciencedirect.com/science/article/pii/S1631073X08000964 (visited on 04/27/2021).

[9] Frédéric Gosselin and Philippe G. Schyns. "Bubbles: A Technique to Reveal the Use of Information in Recognition Tasks". In: *Vision Research* 41.17 (Aug. 1, 2001), pp. 2261–2271. ISSN: 0042-6989. DOI: 10.1016/S0042-6989(01)00097-9. URL: https://www.sciencedirect.com/science/article/pii/S0042698901000979 (visited on 04/26/2021).

[10] Frédéric Gosselin and Philippe G. Schyns. "Superstitious Perceptions Reveal Properties of Internal Representations". In: *Psychological Science* 14.5 (Sept. 1, 2003), pp. 505–509. ISSN: 0956-7976. DOI: 10.1111/1467-9280.03452. URL: https://doi.org/10.1111/1467-9280.03452 (visited on 02/23/2021).

[11] Christian G. Graff and Emil Y. Sidky. "Compressive Sensing in Medical Imaging". In: *Applied Optics* 54.8 (Mar. 10, 2015), pp. C23–C44. ISSN: 2155-3165. DOI: 10.1364/AO.54.000C23. URL: https://www.osapublishing.org/ao/abstract.cfm?uri=ao-54-8-C23 (visited on 04/26/2021).

[12] J. A. Henry et al. "Comparison of Two Computer-Automated Procedures for Tinnitus Pitch Matching". In: *Journal of Rehabilitation Research and Development* 38.5 (2001 Sep-Oct), pp. 557–566. ISSN: 0748-7711. pmid: 11732833.

[13] James Henry, Betsy Rheinsburg, and Roger Ellingson. "Computer-Automated Tinnitus Assessment Using Patient Control of Stimulus Parameters". In: *Journal of rehabilitation research and development* 41 (Nov. 1, 2004), pp. 871–88.

[14] James A. Henry. “Measurement of Tinnitus”. In: *Otology & Neurotology* 37.8 (Sept. 2016), e276. ISSN: 1531-7129. DOI: 10.1097/MAO.0000000000001070. URL: https://journals.lww.com/otology-neurotology/Fulltext/2016/09000/_Measurement__of_Tinnitus.43.aspx (visited on 04/24/2021).

[15] James A. Henry et al. “Computer-Automated Tinnitus Assessment: Noise-Band Matching, Maskability, and Residual Inhibition”. In: *Journal of the American Academy of Audiology* 24.6 (June 2013), pp. 486–504. ISSN: 1050-0545. DOI: 10.3766/jaaa.24.6.5. pmid: 23886426.

[16] James A. Henry et al. “Tinnitus: An Epidemiologic Perspective”. In: *Otolaryngologic Clinics of North America*. Tinnitus 53.4 (Aug. 1, 2020), pp. 481–499. ISSN: 0030-6665. DOI: 10.1016/j.otc.2020.03.002. URL: https://www.sciencedirect.com/science/article/pii/S0030666520300384 (visited on 04/21/2021).

[17] Fatima T. Husain et al. “Replicability of Neural and Behavioral Measures of Tinnitus Handicap in Civilian and Military Populations: Preliminary Results”. In: *American Journal of Audiology* 28 (1S Apr. 22, 2019), pp. 191–208. ISSN: 1558-9137. DOI: 10.1044/2019_AJA-TTR17-18-0039. pmid: 31022364.

[18] Daniela Korth et al. “One Step Closer towards a Reliable Tinnitus Pitch-Match Frequency Determination Using Repetitive Recursive Matching”. In: *Audiology & Neuro-Otology* 25.4 (2020), pp. 190–199. ISSN: 1421-9700. DOI: 10.1159/000505308. pmid: 32106112.

[19] Jiangang Liu et al. “Seeing Jesus in Toast: Neural and Behavioral Correlates of Face Pareidolia”. In: *Cortex* 53 (Apr. 1, 2014), pp. 60–77. ISSN: 0010-9452. DOI: 10.1016/j.cortex.2014.01.013. URL: https://www.sciencedirect.com/science/article/pii/S0010945214000288 (visited on 04/29/2021).

[20] G. M. LJUNG and G. E. P. BOX. “On a Measure of Lack of Fit in Time Series Models”. In: *Biometrika* 65.2 (Aug. 1, 1978), pp. 297–303. ISSN: 0006-3444. DOI: 10.1093/biomet/65.2.297. URL: https://doi.org/10.1093/biomet/65.2.297 (visited on 04/29/2021).

[21] Michael Lustig et al. “Compressed Sensing MRI”. In: *IEEE Signal Processing Magazine* 25.2 (Mar. 2008), pp. 72–82. ISSN: 1558-0792. DOI: 10.1109/MSP.2007.914728.

[22] Michael C. Mangini and Irving Biederman. “Making the Ineffable Explicit: Estimating the Information Employed for Face Classifications”. In: *Cognitive Science* 28.2 (2004), pp. 209–226. ISSN: 1551-6709. DOI: 10.1207/s15516709cog2802_4. URL: https://onlinelibrary.wiley.com/doi/abs/10.1207/s15516709cog2802_4 (visited on 04/26/2021).

[23] Panos Z. Marmarelis and Vasilis Z. Marmarelis. “The White-Noise Method in System Identification”. In: *Analysis of Physiological Systems: The White-Noise Approach*. Ed. by Panos Z. Marmarelis and Vasilis Z. Marmarelis. Computers in Biology and Medicine. Boston, MA: Springer US, 1978, pp. 131–180. ISBN: 978-1-4613-3970-0. DOI: 10.1007/978-1-4613-3970-0_4. URL: https://doi.org/10.1007/978-1-4613-3970-0_4 (visited on 04/26/2021).

[24] Patrick J. Mineault, Simon Barthelmé, and Christopher C. Pack. “Improved Classification Images with Sparse Priors in a Smooth Basis”. In: *Journal of Vision* 9.10 (Sept. 1, 2009), pp. 17–17. ISSN: 1534-7362. DOI: 10.1167/9.10.17. URL: http://jov.arvojournals.org/article.aspx?articleid=2122177 (visited on 03/11/2021).

[25] Richard F. Murray and Jason M. Gold. “Troubles with Bubbles”. In: *Vision Research* 44.5 (Mar. 1, 2004), pp. 461–470. ISSN: 0042-6989. DOI: 10.1016/j.visres.2003.10.006. URL: https://www.sciencedirect.com/science/article/pii/S0042698903006540 (visited on 04/26/2021).

[26] Peter Neri and Dennis M. Levi. “Receptive versus Perceptive Fields from the Reverse-Correlation Viewpoint”. In: *Vision Research* 46.16 (Aug. 1, 2006), pp. 2465–2474. ISSN: 0042-6989. DOI: 10.1016/j.visres.2006.02.002. URL: https://www.sciencedirect.com/science/article/pii/S0042698906000733 (visited on 04/26/2021).

[27] Shinji Nishimoto, Tsugitaka Ishida, and Izumi Ohzawa. "Receptive Field Properties of Neurons in the Early Visual Cortex Revealed by Local Spectral Reverse Correlation". In: *The Journal of neuroscience : the official journal of the Society for Neuroscience* 26 (Apr. 1, 2006), pp. 3269–80. DOI: 10.1523/JNEUROSCI.4558-05.2006.

[28] Arnaud Noreña et al. "Psychoacoustic Characterization of the Tinnitus Spectrum: Implications for the Underlying Mechanisms of Tinnitus". In: *Audiology & neuro-otology* 7 (Nov. 1, 2002), pp. 358–69. DOI: 10.1159/000066156.

[29] Yaniv Plan and Roman Vershynin. "One-Bit Compressed Sensing by Linear Programming". In: *Communications on Pure and Applied Mathematics* 66.8 (2013), pp. 1275–1297. ISSN: 1097-0312. DOI: 10.1002/cpa.21442. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/cpa.21442 (visited on 04/27/2021).

[30] Emmanuel Ponsot et al. "Cracking the Social Code of Speech Prosody Using Reverse Correlation". In: *Proceedings of the National Academy of Sciences* 115.15 (Apr. 10, 2018), pp. 3972–3977. ISSN: 0027-8424, 1091-6490. DOI: 10.1073/pnas.1716090115. pmid: 29581266. URL: https://www.pnas.org/content/115/15/3972 (visited on 04/26/2021).

[31] Dario Ringach and Robert Shapley. "Reverse Correlation in Neurophysiology". In: *Cognitive Science* 28.2 (2004), pp. 147–166. ISSN: 1551-6709. DOI: 10.1207/s15516709cog2802_2. URL: https://onlinelibrary.wiley.com/doi/abs/10.1207/s15516709cog2802_2 (visited on 02/23/2021).

[32] Marie L. Smith, Frédéric Gosselin, and Philippe G. Schyns. "Measuring Internal Representations from Behavioral and Brain Data". In: *Current Biology* 22.3 (Feb. 7, 2012), pp. 191–196. ISSN: 0960-9822. DOI: 10.1016/j.cub.2011.11.061. URL: https://www.sciencedirect.com/science/article/pii/S0960982211013947 (visited on 02/23/2021).

[33] Dunja Vajsakovic, Michael Maslin, and Grant D. Searchfield. "Principles and Methods for Psychoacoustic Evaluation of Tinnitus". In: *Current Topics in Behavioral Neurosciences* (Feb. 7, 2021). ISSN: 1866-3370. DOI: 10.1007/7854_2020_211. pmid: 33550568.

[34] P. Wojtaszczyk. "Stability and Instance Optimality for Gaussian Measurements in Compressed Sensing". In: *Foundations of Computational Mathematics* 10.1 (Feb. 1, 2010), pp. 1–13. ISSN: 1615-3383. DOI: 10.1007/s10208-009-9046-4. URL: https://doi.org/10.1007/s10208-009-9046-4 (visited on 04/27/2021).

[35] Argyrios Zymnis, Stephen Boyd, and Emmanuel Candes. "Compressed Sensing With Quantized Measurements". In: *IEEE Signal Processing Letters* 17.2 (Feb. 2010), pp. 149–152. ISSN: 1558-2361. DOI: 10.1109/LSP.2009.2035667.