Aliasing of spectral ripples through CI processors: a challenge to the interpretation of correlation with speech recognition scores

UNIVERSITY of WASHINGTON — Listen Lab

Elle O'Brien, M.S.   Matthew B. Winn, Au.D., Ph.D.

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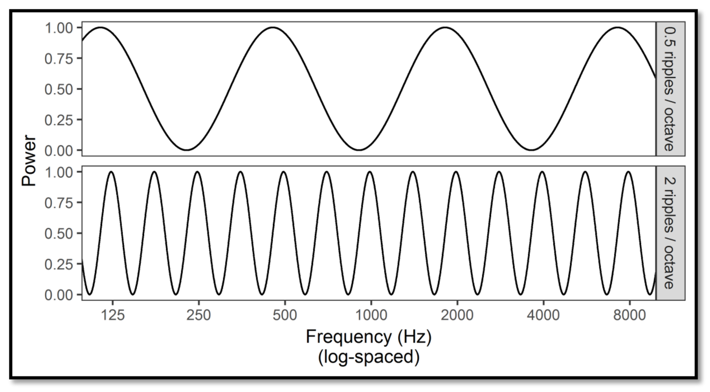
INTRODUCTION

Spectral resolution is an important factor in cochlear implant performance.
It needs to be measured carefully and accurately.

A common, psychophysical test is the **spectral ripple**, in which listeners discriminate between broadband acoustic stimuli with increasingly high spectral densities.

Performance on this test has been shown to correlate with vowel, consonant, and word recognition [1-4].



The problem

CI speech processors have a limited number of frequency channels;
this places an upper limit on the spectral density that can actually be conveyed to a listener.
This is analogous to the Nyquist sampling theorem in the frequency domain.

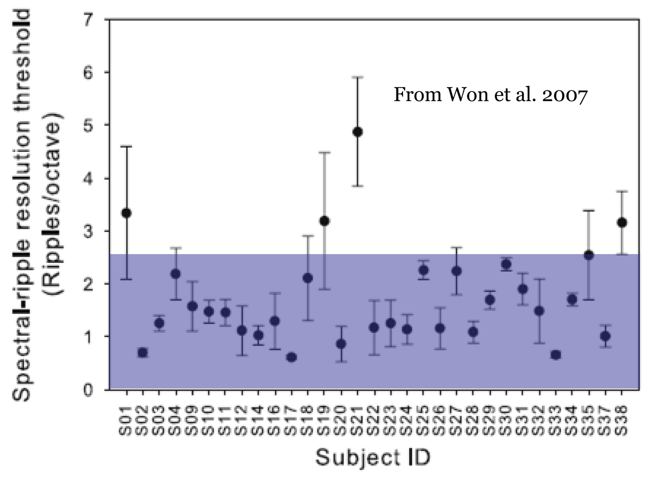
Are we testing ripple densities that the CI processor can't actually convey?

If so, what is the stimulus?
Does it still reflect the intention of the experimenter?

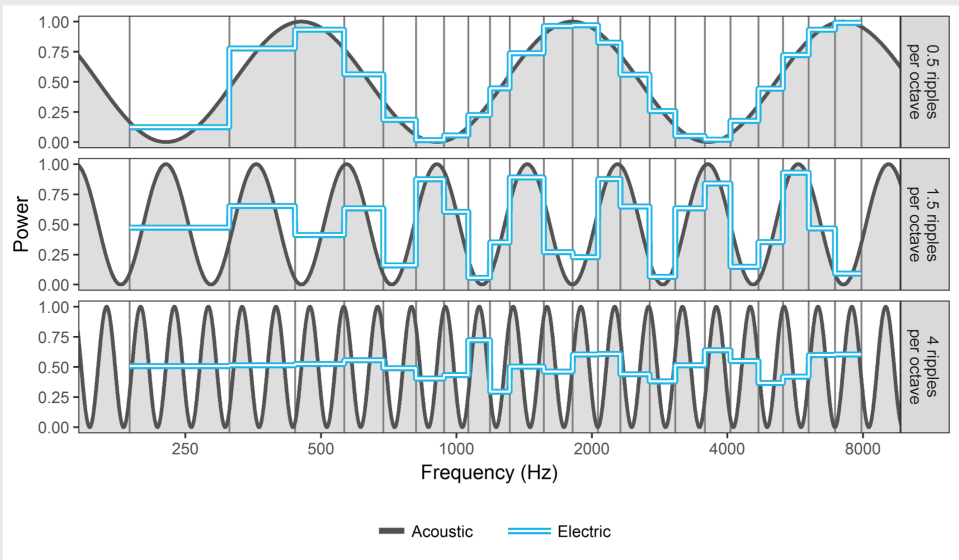
Insight from the literature

Nearly all studies using spectral ripple stimuli show data where most CI listeners perceive at most 2 ripples per octave [1-5].

- **Does this represent the critical upper limit of spectral density that can be possibly be transmitted through the CI?**
- **What about listeners who appear to perceive more than 2 ripples per octave?**



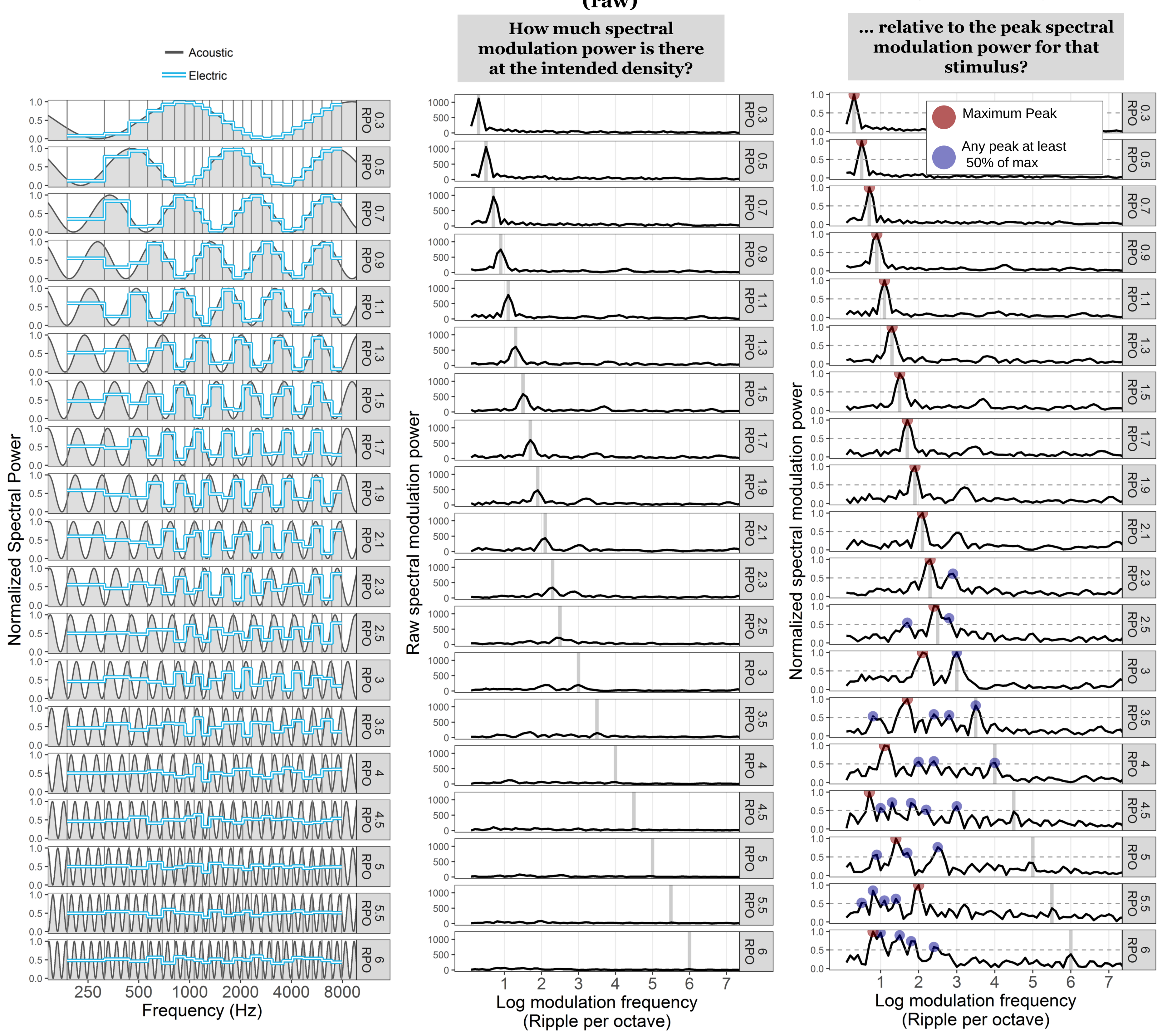
METHOD



We simulated the output of a 22-channel Cochlear "Nucleus" processor using acoustic spectral ripple stimuli as inputs. Channel boundaries were taken from the device frequency allocation table.

The spectral ripple stimuli are periodic in octave-scaled frequency space. We estimated the spectral output of the processor as well as the spectral modulation spectra, which is the FFT of the spectra in $\log_2$ units.

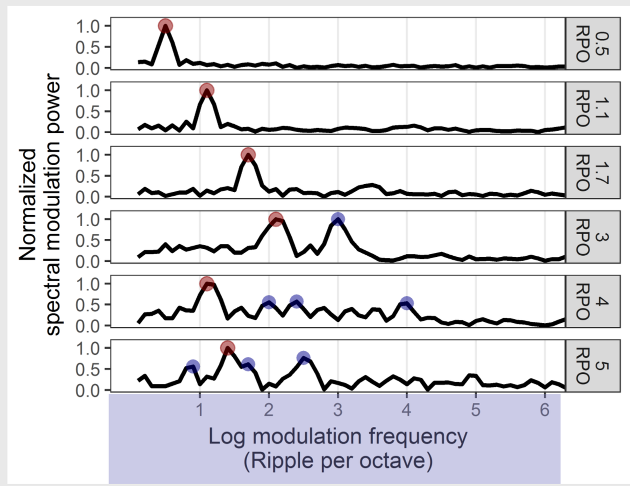
RESULTS

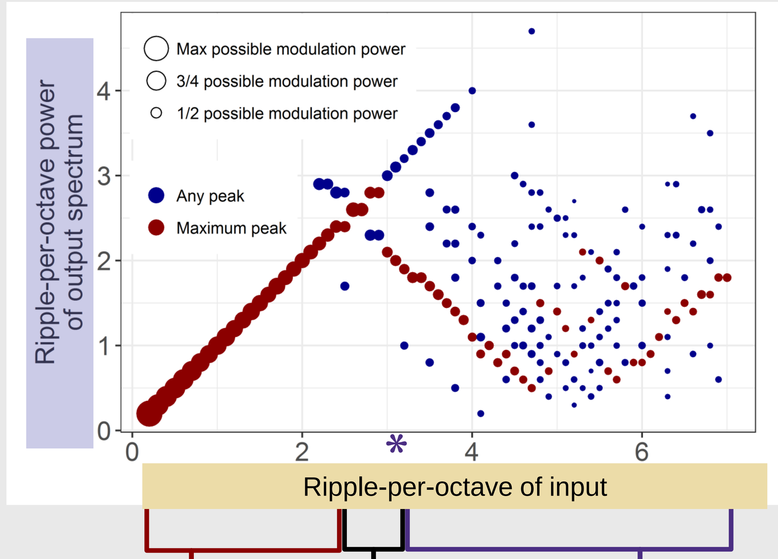


DYNAMICAL ANALYSIS

The processor output as a function of increasing ripple density resembles a classical dynamical (chaotic) system.

- Before a critical point (for very low ripple densities), the processor output is orderly and predictable
- Increasingly complex behavior emerges as the ripple density is increased
- After a critical point, there is little correspondence between ripple density and processor output
- As the input changes monotonically, the output no longer changes monotonically in a single dimension.

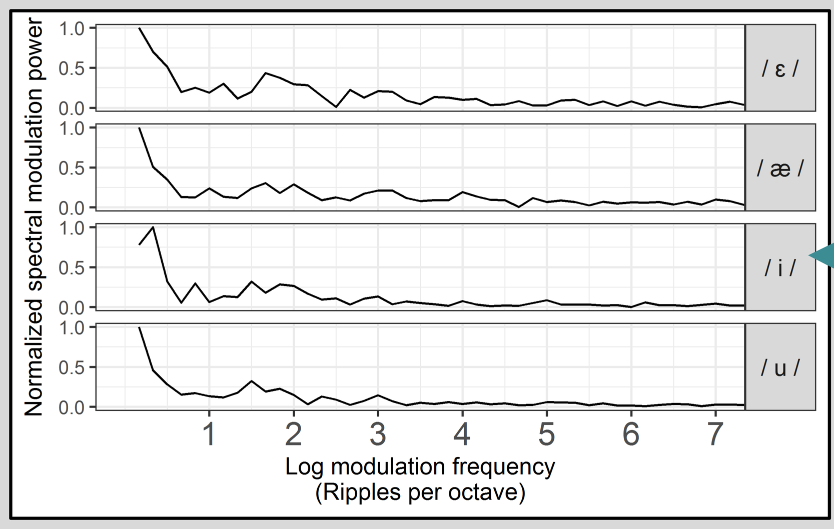




It's not just that CI-processed high-density ripples become distorted, they become unpredictable and non-monotonic, and vary in multiple dimensions

6 RPO is not "more dense" than 4 RPO; It is *different* (*like how* ▲ ● ■ ★ *are different, but not ordered).*

Listeners who can perform well for high-density ripples are probably good at employing a flexible listening strategy. (that's good!)
... but are not necessarily better at perceiving high spectral density



An alternate explanation for the test's apparent success

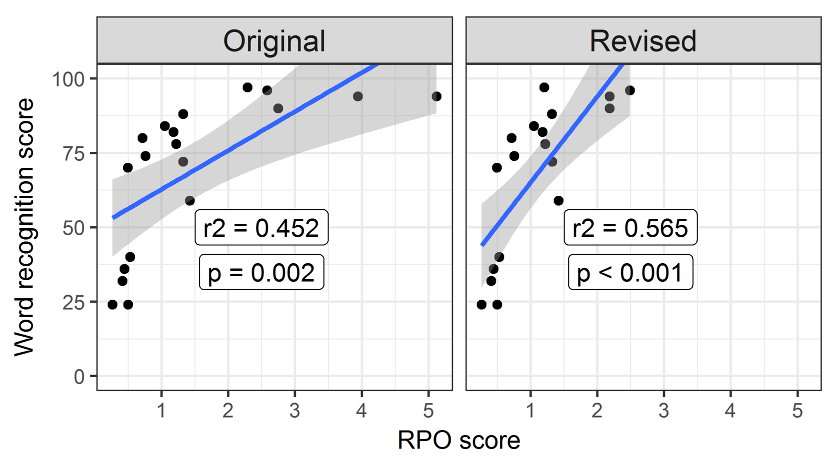
- "High-density" spectral ripples contain almost no high-density spectral information in the output.
- Still, CI users who can reliably discriminate these "high-density" ripples tend to perform well on speech recognition tests. *Why?*

The spectral modulation spectrum of "high-density" spectral ripples doesn't contain high-density spectral modulations, but DOES accidentally bear resemblance to the spectral modulation spectrum of ***vowels***!

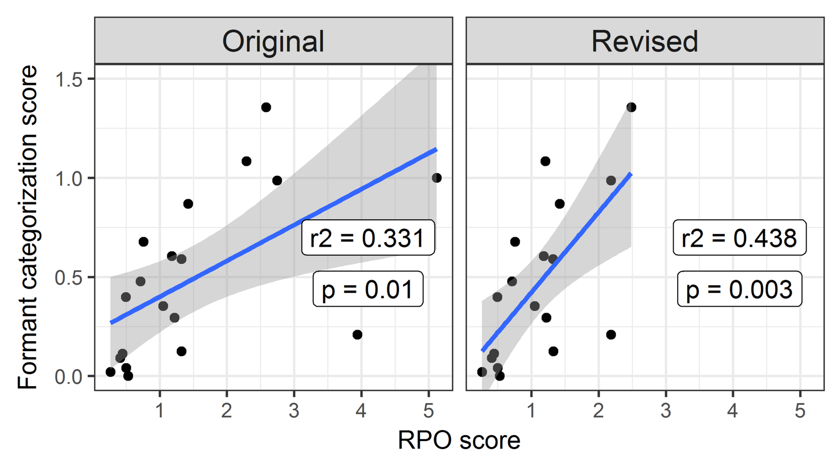
This *does not* imply that listeners are making use of genuine high spectral-density components corresponding to ripple density!

It might imply that listeners broke through the critical limit and then began to discriminate sounds using an entirely different perceptual criterion.

OBSERVING A CRITICAL LIMIT IMPROVES CORRELATIONS WITH SPEECH PERCEPTION SCORES



Method: all individual runs with scores greater than 2.56 were eliminated, average RPO scores [5] are re-calculated and re-correlated with scores for word recognition and formant categorization [6]



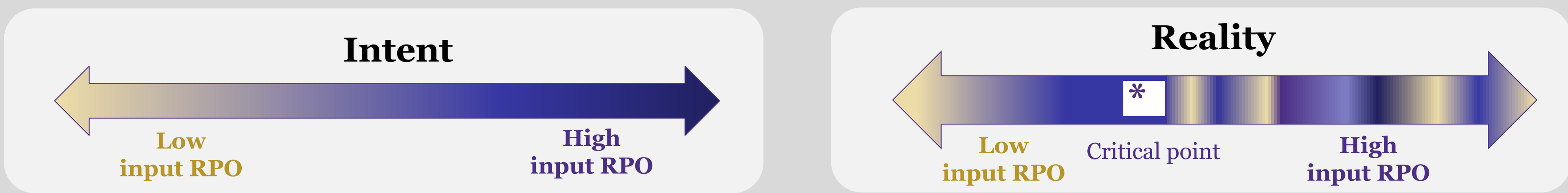
Imposing an upper limit on spectral ripple density IMPROVES p-values and correlations with other speech-based outcome measures

CONCLUSIONS

As spectral ripple density increases, the output of the cochlear implant processor becomes increasingly complex and loses a meaningful correspondence with intended ripple density.

In other words...

For spectral density in a cochlear implant, more dense is not more dense; more dense is *different*
... and an experimenter loses control over the stimulus if it is aliased.



Interpretation: Experimenters should not interpret high and low ripple densities to be testing the same parameter.
... testing low-density ripple modulation depth perception[2] instead of ripple density could potentially solve this problem.

High RPO thresholds on the spectral ripple task might correlate with speech test scores due to accidental resemblance of processed ripples to speech stimuli, or because listeners employ a flexible strategy, not because listeners are detecting the intended ripple density.

Q: "Resemblance to speech spectra - Isn't that good?" A: "It isn't good when we don't know the parameters we are varying."

Phonetically-relevant speech contrasts generally don't contain spectral densities above 1 – 2 peaks per octave anyway, so we are likely going to achieve better success in measuring accurate perception of low-density spectra.

[1] Won, J. H., Drennan, W. R., & Rubinstein, J. T. (2007). Spectral-ripple resolution correlates with speech reception in noise in cochlear implant users. *JARO*
[2] Litvak, L. M., Spahr, A. J., Saoji, A. A., & Fridman, G. Y. (2007). Relationship between perception of spectral ripple and speech recognition in cochlear implant and vocoder listeners. *JASA*
[3] Drennan, W. R., Won, J. H., Timme, A. O., & Rubinstein, J. T. (2016). Nonlinguistic Outcome Measures in Adult Cochlear Implant Users Over the First Year of Implantation. *Ear and Hearing*
[4] Anderson, E. S., Nelson, D. A., Kreft, H., Nelson, P. B., & Oxenham, A. J. (2011). Comparing spatial tuning curves, spectral ripple resolution, and speech perception in cochlear implant users. *JASA*
[5] Winn, M.B., Won, J.H., Moon, I.J. (2016). Assessment of spectral and temporal resolution in cochlear implant users using psychoacoustic discrimination and speech cue categorization. *Ear and Hearing*
[6] Winn, M.B. & Litovsky, R.Y. (2015). Using speech sounds to test functional spectral resolution in listeners with cochlear implants. *JASA*

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