DTU Library

What affects envelope coding in theelectrically stimulated auditory nerve?

Joshi, Suyash Narendra; Dau, Torsten; Epp, Bastian

Publication date:
2016

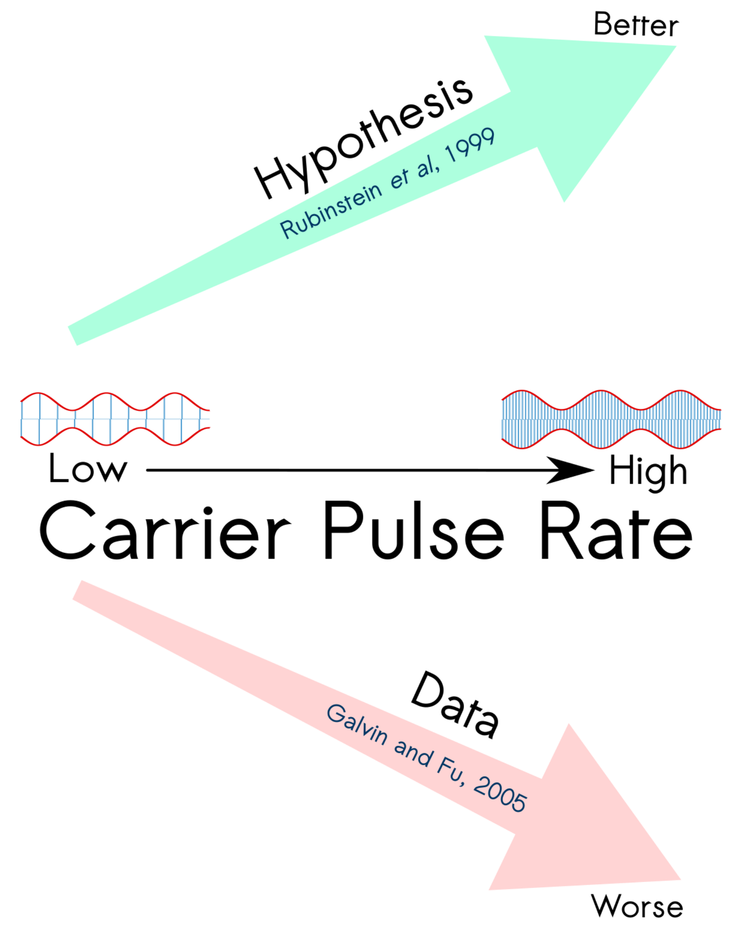
Document Version
Publisher's PDF, also known as Version of record

What affects envelope coding in the electrically stimulated auditory nerve?

Suyash N. Joshi, Torsten Dau, Bastian Epp

Hearing Systems, Technical University of Denmark

Background



- Cochlear implants (CI) electrically stimulate the auditory nerve fibers (ANF) with a train of biphasic pulses modulated with an envelope of a desired acoustic signal.
- It has been suggested that higher pulse rates would reduce phase-locking to the carrier pulse train such that the response will only be dominated by the envelope (Rubinstein et al, 1999).
- However, psychophysical measures of the amplitude modulation detection (AMD) thresholds showed detrimental effects of the higher pulse rate, particularly at low stimulus levels (Galvin and Fu, 2005).

Which potential factors impair the temporal coding in CI listeners?

ANF model

This study explores the factors affecting temporal coding using a model of ANF responses to electrical stimulation (Joshi et al, 2015).

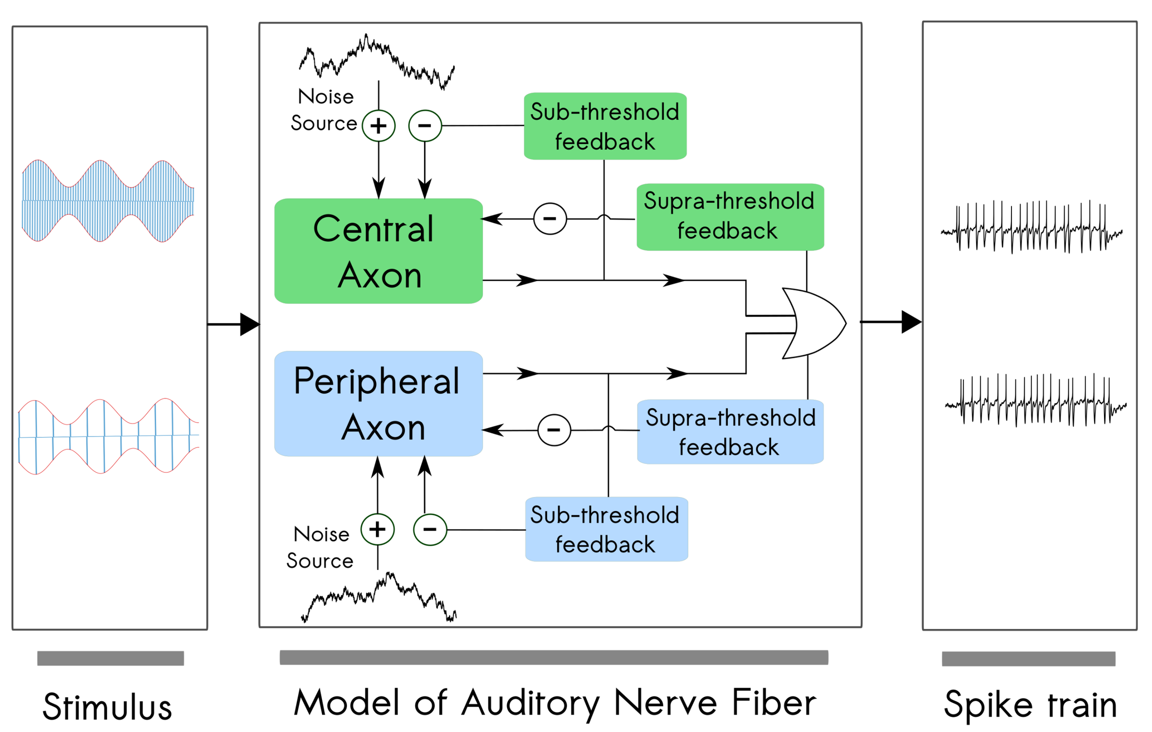


Fig.1 The model of ANF responses proposed by Joshi et al (2015) was used to simulate the ANF responses to modulated and unmodulated pulse trains. The model consists of two neurons, representing a peripheral and a central axon of the AN fiber. The model receives stimulus waveform as an input and provides a spike train output.

This model -

- has been developed based on the observation that the extracellular stimulation with CI can lead to excitation at multiple sites along the ANF.
- The site of excitation largely determines the delay at which a spike arrives at the next processing stage and therefore may be a dominant source in limiting the temporal coding.
- also accounts for the excitation produced by both anodic and cathodic phase of the biphasic pulse and the spike time differences between their responses.
- can also account for sub-threshold adaptation such as facilitation and accommodation as well as the supra-threshold adaptation such as refractoriness and spike-rate adaptation.
- has been shown to predict the correct response statistics including the spike times for various pulse shapes, pulse rates and stimulus levels (Joshi et al, 2015).

Stimuli

- Trains of symmetric biphasic pulses (cathodic-anodic) with a pulse-phase duration of 100 μs/phase and inter-phase gap of 45 μs
- Carrier pulse rates - 250 or 2000 pulses per second
- 20 Hz sinusoidal amplitude modulation was applied using Eq. 1.

$$Stimulus = Pulse\ train \times [1 + m \times (2 \times \pi \times f \times t)] \quad (1)$$

- The modulation depth - from 0 to 100 % modulation
- Stimulation levels that produced firing rates from 20 spikes/second to 230 spikes/second

Analysis

- Vector strength (VS) was used to measure spike time synchrony to the modulation frequency
- The receiver operating characteristic (ROC) was built using distributions of VS for unmodulated and modulated pulse trains
- The area under the ROC was plotted as a function of the modulation depth and was fitted with a logistic function (Fig 2).
- The modulation depth which resulted in 79.7 % correct performance was considered as the AMD threshold.

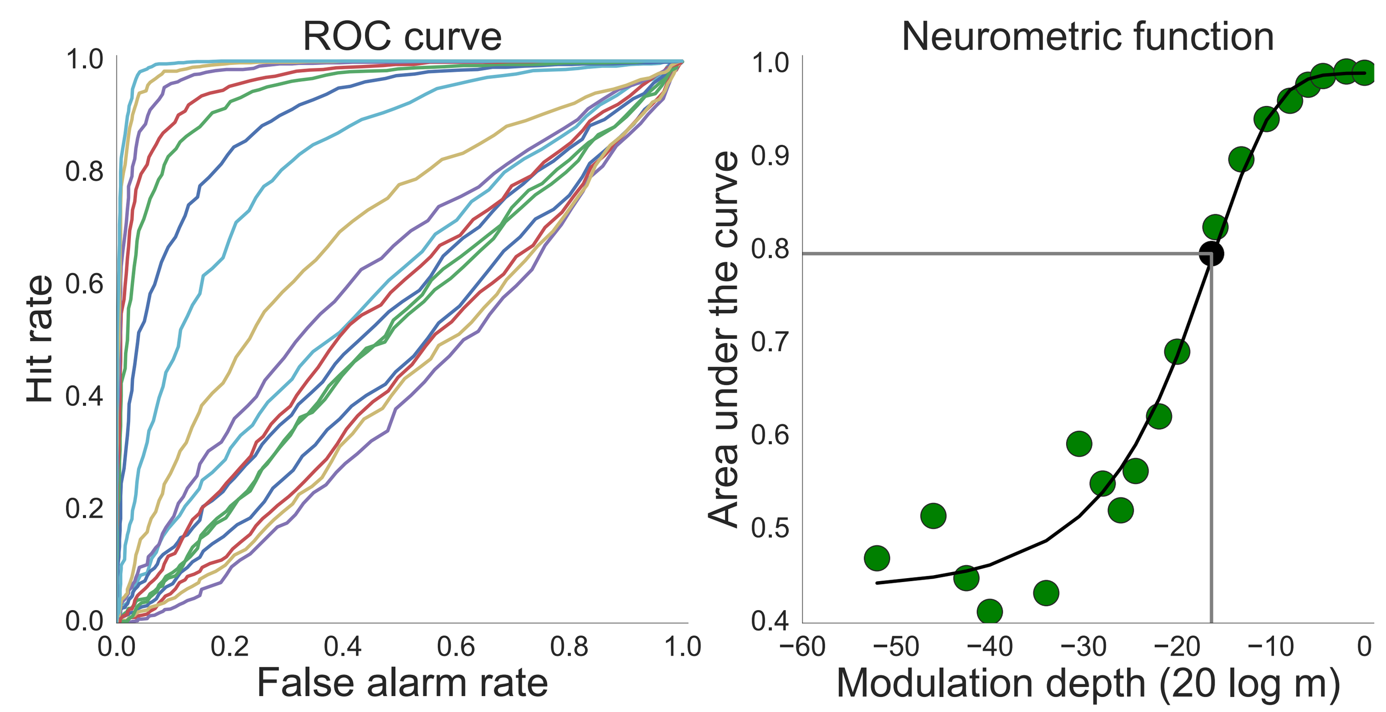


Fig.2 An example of the ROC curves (A) and the neurometric function (B) obtained using the vector strength for modulated and modulated pulse trains at various modulation depths. The area under the ROC curve is equivalent to the percent correct performance of an unbiased observer (Middlebrooks, 2008) and is used to build a neurometric function.

Results

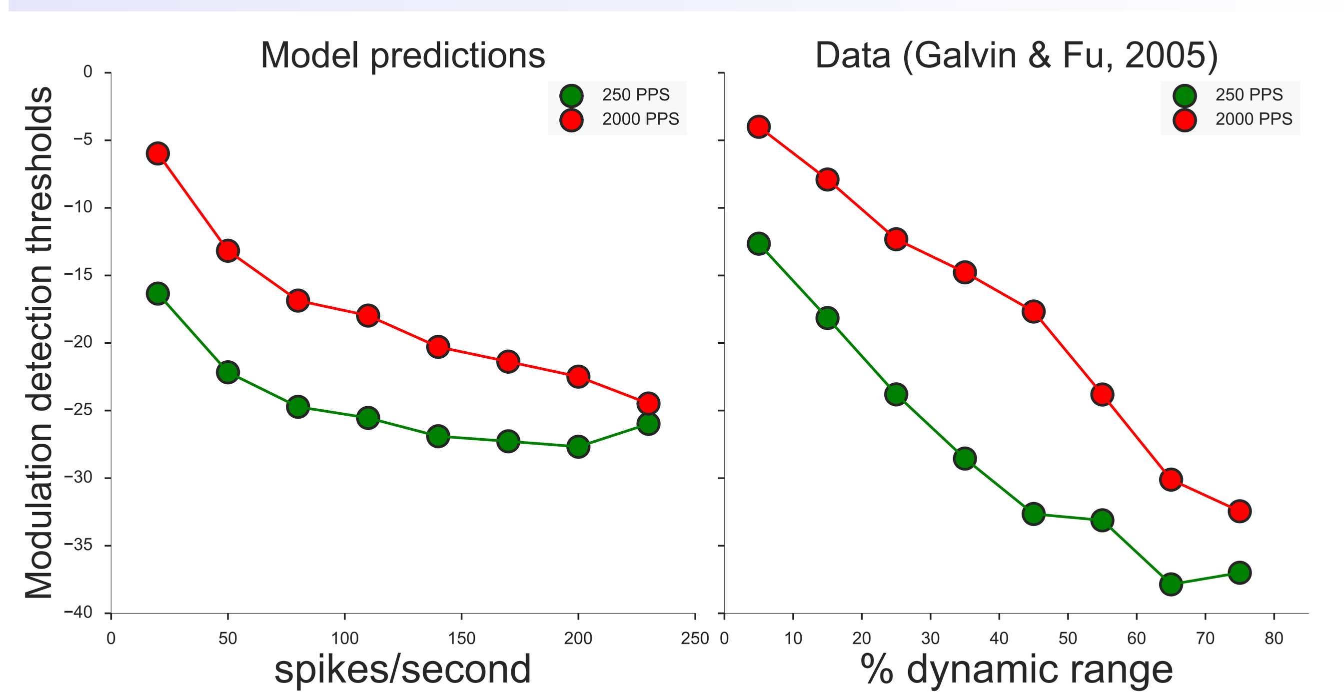


Fig.3 AMD thresholds predicted by the ANF model (A) and from human listener (B) as function of the stimulus level and carrier pulse rate (Subject 1 digitized from Galvin and Fu, 2005). The data shows that AMD thresholds are better for a low carrier pulse rate than for high pulse rate. AMD thresholds get significantly better with increasing stimulus level. Previous models could not predict the effect of pulse rate or stimulus level on AMD thresholds (Goldwyn et al, 2010; 2012).

Contributions of the two axons

Spike time differences between the peripheral and central axons are approximately 250 μs in cats (Miller et al, 1999) and 400 μs in humans (Rattay et al, 2001). **Do multiple sites of excitation limit the precise temporal coding in electrically stimulated ANF?**

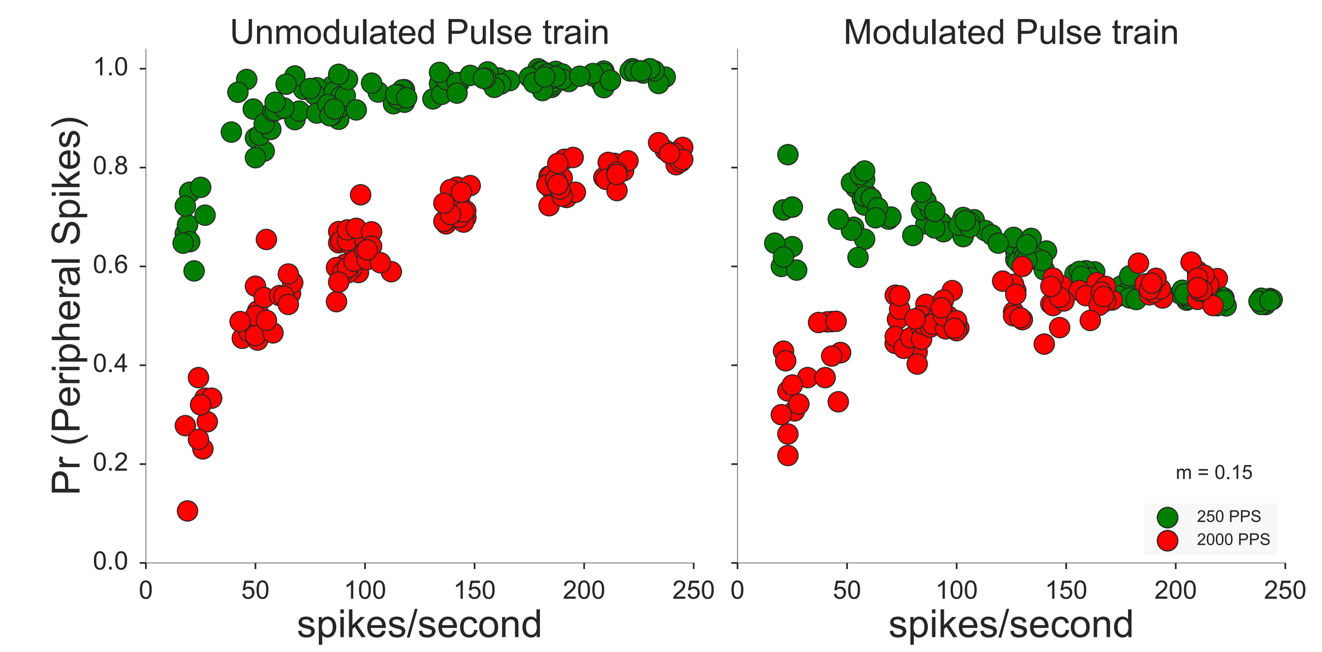


Fig.4 Proportion of total number of spikes produced at peripheral axon measured for unmodulated (A) and modulated (B) pulse train as function of pulse rate. At low stimulus level and high pulse rate, the central axon dominates the response. The increase in stimulus level increases the proportion of spikes produced at the peripheral axon for unmodulated pulse trains. Responses to modulated pulse trains show more uncertainty of the site of excitation. These results indicate that the site of excitation does indeed limit the temporal coding in electrically stimulated ANF.

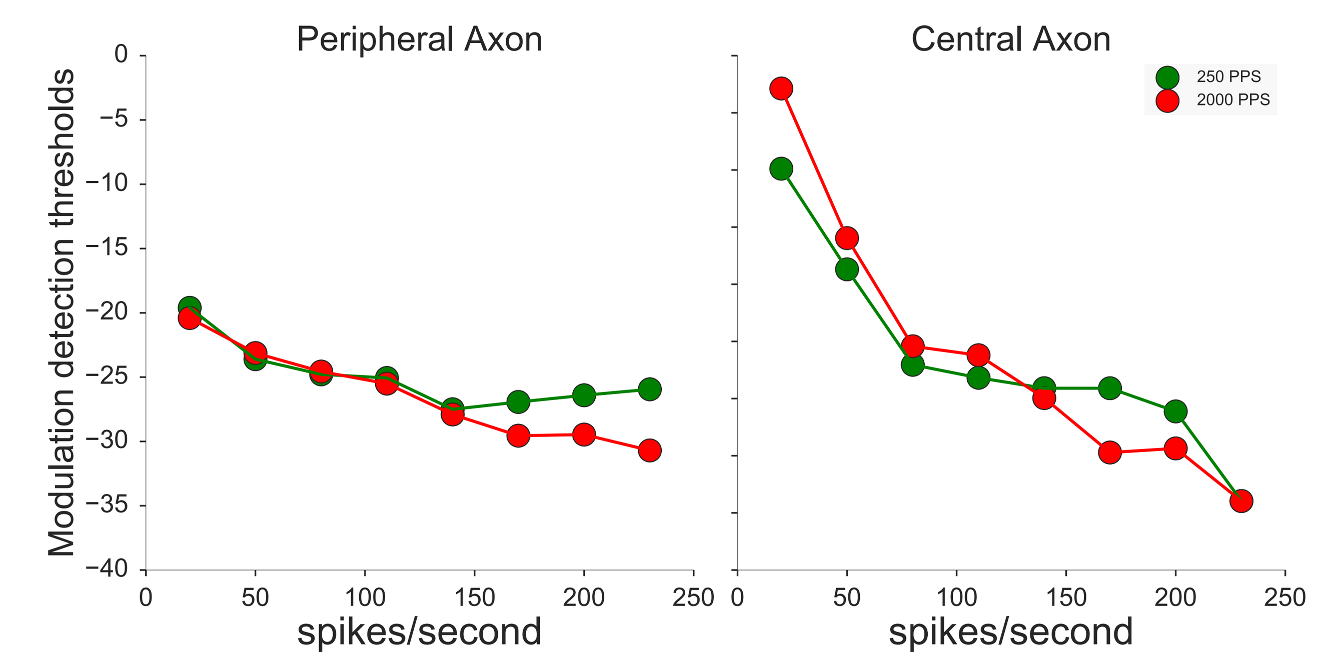


Fig.5 The AMD thresholds obtained from single individual axons of the model. To further test the hypothesis that multiple sites of excitation does contribute to distortions in the temporal coding in ANF, the AMD thresholds were obtained from simulations of only peripheral or the central axon of the model. The results from individual axons do not show any effect of pulse rate on AMD thresholds.

Contribution of stochasticity

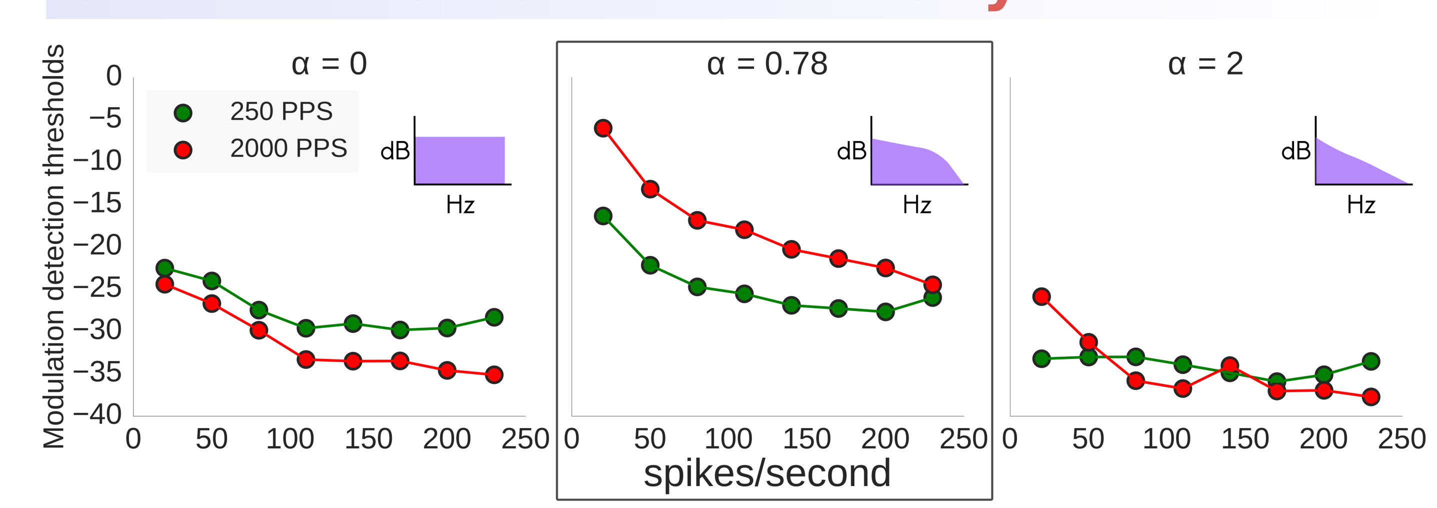


Fig.6 The effect of spectrum of the ion channel noise on predicted AMD thresholds. The spectrum of the noise is shown in the insets. Rubinstein et al (1999) suggested that at high pulse rates, the temporal responses of the ANF will be dominated by ion channel noise and therefore will be better than at low pulse rates. This analysis suggests that the temporal coding at high pulse rate would only improve if the spectrum of the ion channel noise resembles white noise. [The original model uses noise of shape $1/f^{0.78}$.]

Contribution of sub-threshold current

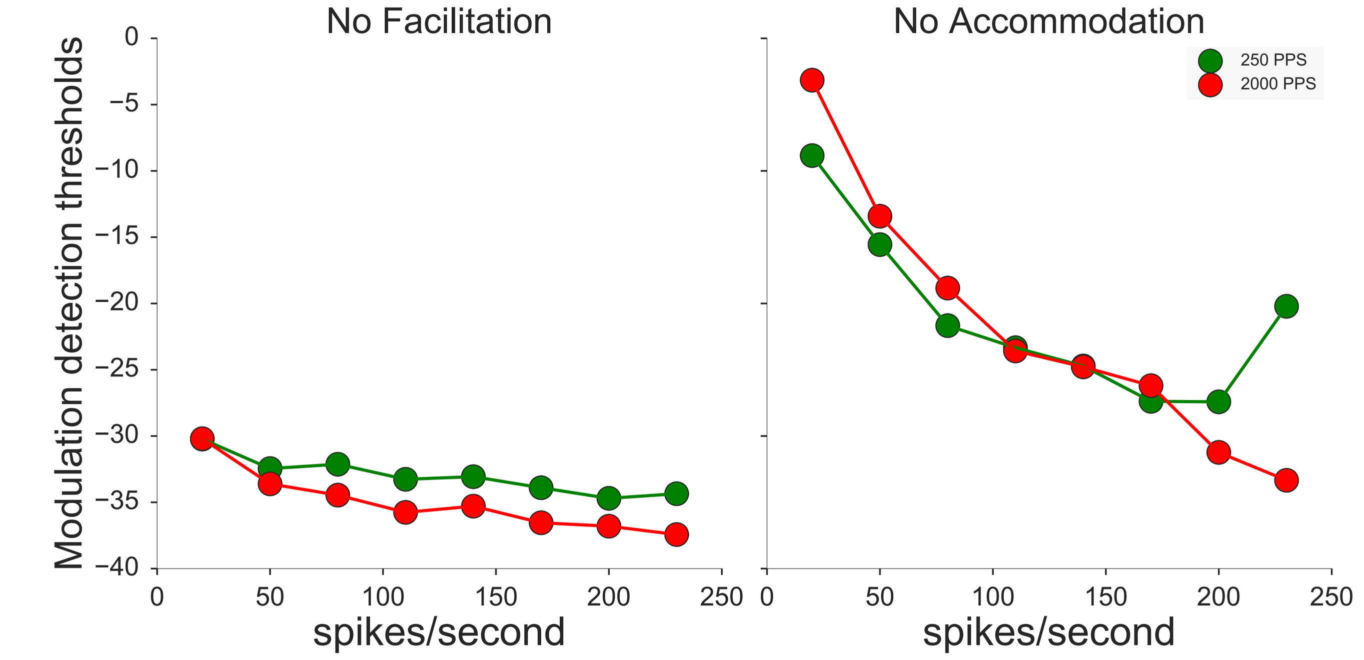


Fig.7 The effect of sub-threshold adaptive current on AMD thresholds predicted by the model. In model version (A), the facilitation (summation of charge of succeeding sub-threshold pulses) was removed. Version (B) of the model was modified to remove any effects of accommodation (masking by sub-threshold pulses). These simulations show that integration of successive sub-threshold pulses (facilitation) impairs the temporal coding at low stimulus levels.

Summary and insights

- The recently proposed model of ANF responses to electrical stimulation (Joshi et al, 2015) can successfully capture the effect of pulse rates on envelope coding in the CI listeners.
- The uncertainty regarding the site of excitation at high pulse rates impairs the temporal coding in electrically stimulated ANF. This might explain why the AMD thresholds of the CI listeners are worse for high pulse rates.
- The spectrum of ion channel noise largely determines the effect of pulse rates on the temporal coding in the ANF.
- The ability of ANF to integrate the charge of successive sub-threshold pulses impairs the temporal coding at low stimulus levels.
- These results suggest that a stimulation strategy that reduces the uncertainty regarding the site of excitation along the ANF will improve the temporal coding in CI listeners.

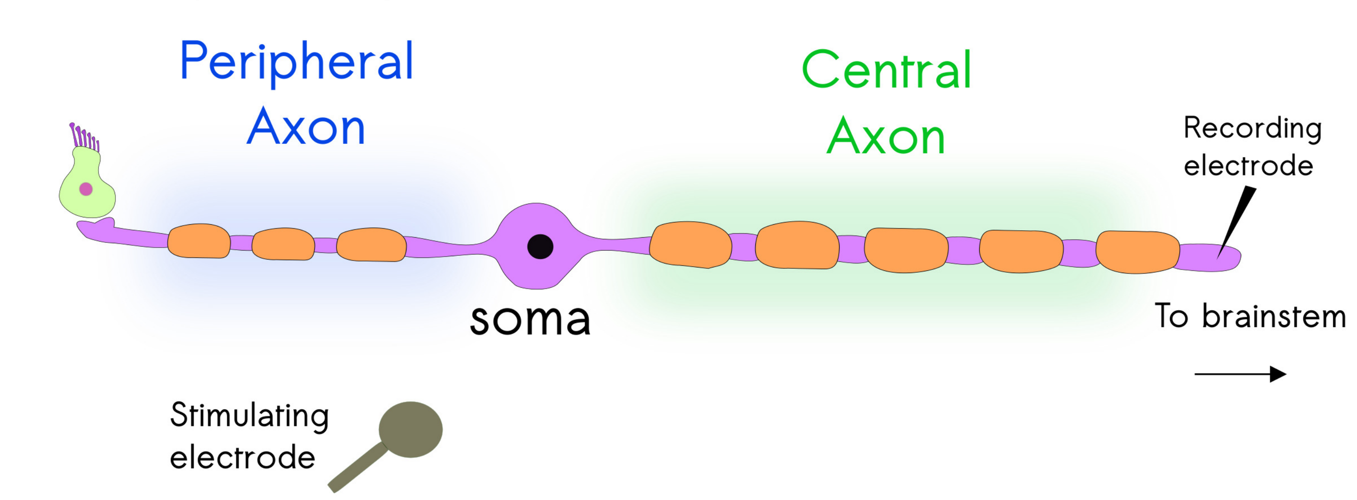


Fig.8 Extra-cellular stimulation of the AN with CI. An electrode inserts the charge in the cochlea and the resulting charge gradient can stimulate multiple sites along the ANF. The spikes produced at the peripheral axon must travel through the soma to reach the brainstem. The spikes produced at the central axon reach the brainstem sooner than those produced at the peripheral axon.

Acknowledgements

The work has been funded by grant from the People Programme (Marie Curie Actions) of the European Union's 7th Framework Programme FP7/2007-2013/ under REA grant agreement number PITN-GA-2012-317521.

References

- Brette and Gerstner (2005) J Neurophysiology, 94, 3637-3642.
- Galvin and Fu (2005) JARO, 6(2), 180-189.
- Goldwyn et al. (2010) J Comp Neurosci, 28, 405-424.
- Goldwyn et al. (2012) J Neurophysiology, 108, 1430-1452.
- Joshi et al. (2015) Mid-winter meeting ARO, Baltimore, MD
- Joshi et al. (2015) CIAP, Lake Tahoe, California.
- Middlebrooks (2008). J Neurophysiology, 100, 92-107.
- Miller et al. (1999) Hear Res, 130, 197-218.
- Rattay et al. (2001) Hear Res, 153, 43-63.
- Rubinstein et al. (1999) Hear Res, 127, 108-118.