An improved model of electrical stimulation of the auditory nerve

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SUMMARY

Mathematical models are a useful means of formally describing and investigating pertinent features of complex systems such as the human auditory system. These features may be deduced from physiological and psychophysical experiments utilising animal models or humans, and from engineering studies. Historically, models of the auditory nerve's (AN) response to electrical stimulation have ignored randomness in single-fiber activity which has been recorded in physiological studies. These models, however, have been unable to accurately predict a number of important psychophysical phenomena. In this study, a model that incorporates random activity of the AN is presented, and is shown to predict psychophysical performance. These results indicate that random activity is indeed an important part of the response of the AN to electrical stimulation.

INTRODUCTION

The AN response to electrical stimulation has be modeled historically using deterministic (non-random) descriptions. These models predict that, for stimulus amplitudes above threshold, single bi-phasic current pulses will produce an action potential in response to every pulse. This behavior can be described by a step-shaped input/output (I/O) function for probability versus intensity. Considering results from physiologically studies, however, the auditory nerve I/O functions are better fit by an integrated-Gaussian "Error Function" (ERF) (Verveen, 1960), rather than a step function. Step-function and integrated-Gaussian fits to AN data from cat (Javel *et al.*, 1987) are shown in Figure 1. The slope, or dynamic range, is determined primarily by the diameter of the fiber (Verveen, 1962) and by the pulse-width (see Figure 2).

MATERIALS AND METHODS

Auditory nerve and psychophysical data were evaluated using the model shown in Figure 3. The model includes current spread which is dependent on the electrode configuration, I/O functions for each AN fiber, and a psychophysical model of loudness. In the neural section of the model, the distribution of single-pulse I/O functions is set to approximate that seen in the cat data from (Javel *et al.*, 1987) and to change with pulse-width as shown in Figure 2 (Dynes, unpublished). Both step-shaped and integrated-Gaussian functions are fitted in order to compare the model's behavior when stochastic activity is included or omitted. From the single-pulse response properties, each fiber's response to specific pulse-trains can be predicted. The output of the neural section of the model is then a set of response probabilities.

A simple counting model is assumed for the psychophysical section of the model. The mean and variance of the AN response to a particular electrical stimulus is predicted by calculating spatial and temporal integration of

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the single-fiber response probabilities. The probability distribution is approximated very well by a Poisson distribution for a mean number of action potentials less than ten and by a Normal distribution for mean counts greater than ten. Signal detection theory is used to predict the model's performance for specific detection/estimation tasks, such as threshold, intensity difference limens and dynamic range.

RESULTS AND CONCLUSIONS

We have used this model to investigate a number of different psychophysical phenomena. In all the cases examined so far, the prediction of the perceptual performance of cochlear implant users is significantly better when stochastic activity is included in the neural section of the model, compared to when it is omitted.

One example is the prediction of auditory threshold versus pulse-width for single bi-phasic pulses. In Figure 4(a) physiological and auditory thresholds are compared. The single-fiber thresholds are significantly higher than the auditory thresholds with which they are compared, and do not change as sharply with pulse-width. The measurement of the physiological thresholds has been conducted assuming a deterministic AN response. In Figure 4(b), the model's prediction of auditory threshold is displayed. The deterministic version of the model predicts an auditory threshold which is very similar in slope and relative position to this physiological data. The range of physiological thresholds can be explained by the variance in single-fiber thresholds and by the uncertainty of placing "threshold" on the I/O curve, that is, by assuming a Pr of 0.5, Pr 1.0 or some value between the two. The stochastic version of the model, in comparison, accurately predicts the slope and relative position of the auditory threshold curves collected from subjects using cochlear implants. Furthermore, the range of auditory thresholds is well explained by the effect of the mode of stimulation (bipolar vs monopolar).

The results obtain with this model have a number of important consequences for investigation of neural sound coding, for physiological studies and for speech processing strategies.

This study indicates that stochastic activity should be included in models of electrical stimulation of the AN. This will have a significant effect on the spatiotemporal patterns of response expected from AN and on the quality and quantity of information coded by these patterns. Additionally, a preliminary investigation of temporal frequency coding has revealed that the discrepancy between physiological data and the auditory percept related to the electrical stimulation rate could be explained by stochastic components of the neural firing patterns.

A simple "threshold" measurement is not a sufficient description of neural response to electrical stimulation, but rather an I/O function describing the neuron's response is required. Secondly, physiological safety studies have usually been conducted at stimulus levels significantly above the single-fiber "threshold". From Figure 4 it can be seen that these stimulus levels could be considerably above the normal operating range of cochlear implants and that levels used routinely in cochlear implants are appropriate for safety studies.

With developments in cochlear implant technology, speech processing strategies are now using higher stimulation rates than had previously been possibly. Some concern has been expressed that AN fibers will be driven beyond their normal physiological discharge rates by such high-rate stimulation. This study suggest, in contrast, that high-rate stimulation does not necessarily produce high discharge-rates. Over most of the operating range of cochlear implants the majority of AN fibers will have a relatively small probability of responding to each pulse in a pulse-train, and will therefore only fire at a fraction of the stimulation rate.

In conclusion, this study has found that stochastic models are needed to describe some aspects of neural response; inclusion of stochastic behavior in psychophysical models can better predict a number of psychophysical results; and the presence of stochastic activity in AN response to electrical stimulation has implications for many areas of cochlear implant research.

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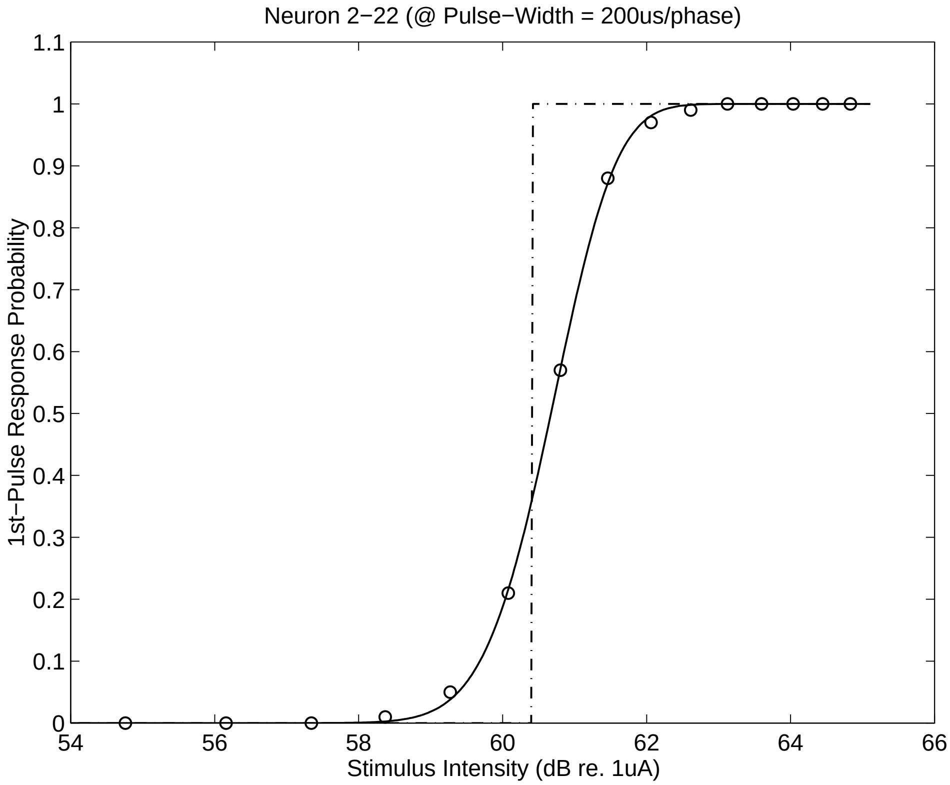
CAPTIONS

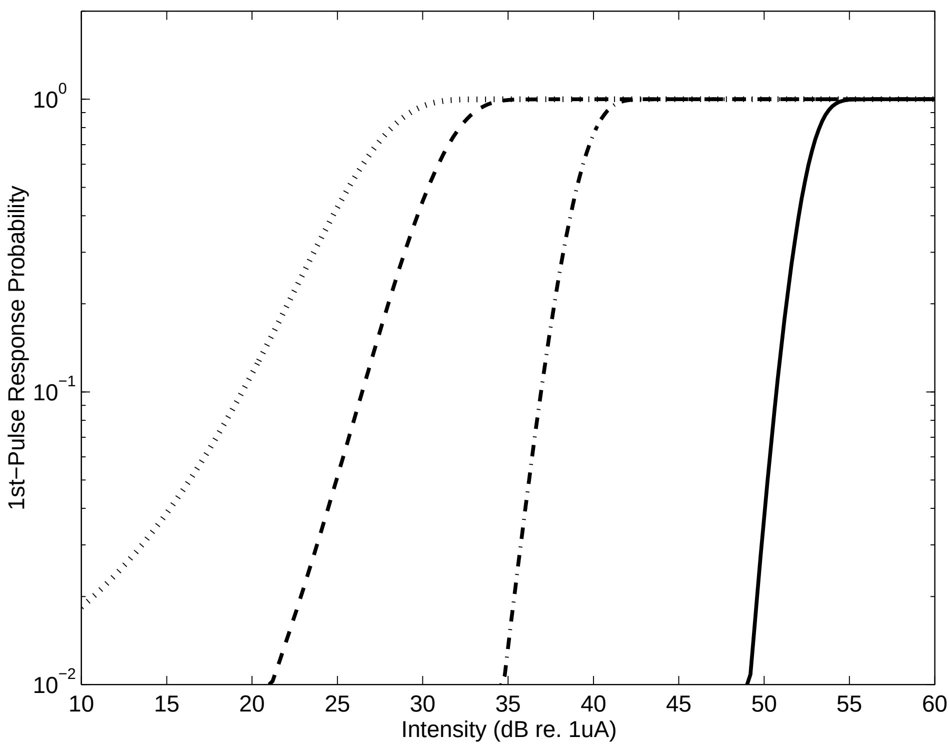
Fig. 1 Best stochastic model (solid line) and deterministic model (dashed line) fits to data (circles) from Neuron 2-22 in (Javel *et al.*, 1987).

Fig. 2 Mean integrated-Gaussian fits to cat data for pulse-widths of 100 (solid line), 500 (dot-dashed line), 2000 (dashed line) and 5000 (dotted line) $\mu sec/phase$.

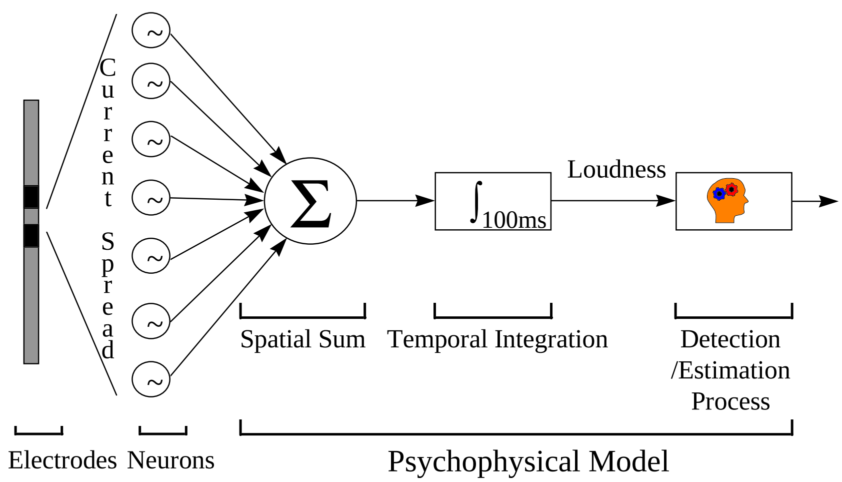
Fig. 3 The cochlear neural/psychophysical model.

Fig. 4 Comparison of physiological and auditory threshold versus pulse-width with predictions of auditory threshold versus pulse-width by the deterministic and stochastic models.

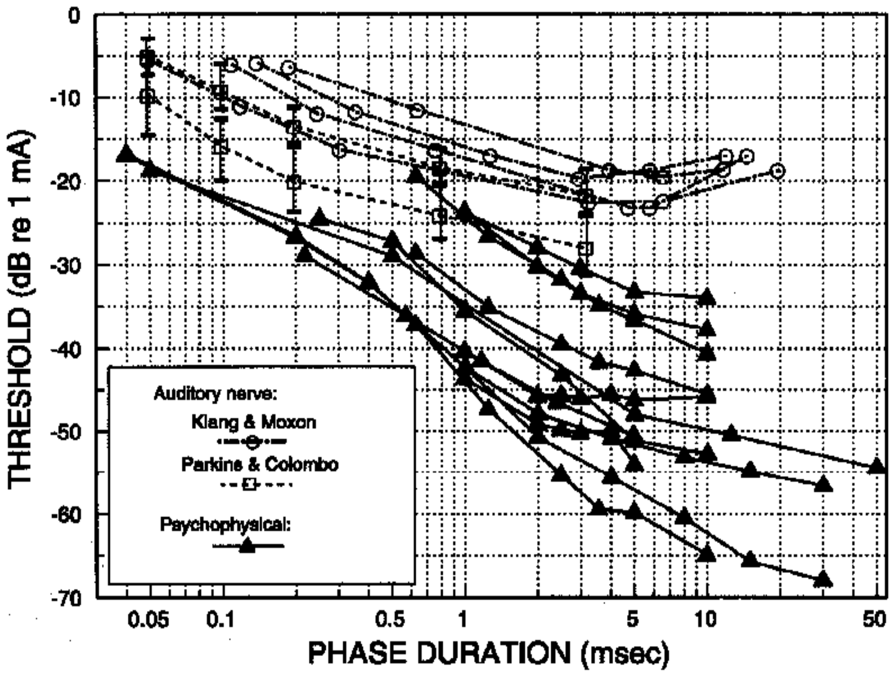

Neuron 2−22 (@ Pulse−Width = 200us/phase)
1st−Pulse Response Probability
Stimulus Intensity (dB re. 1uA)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
54
56
58
60
62
64
66



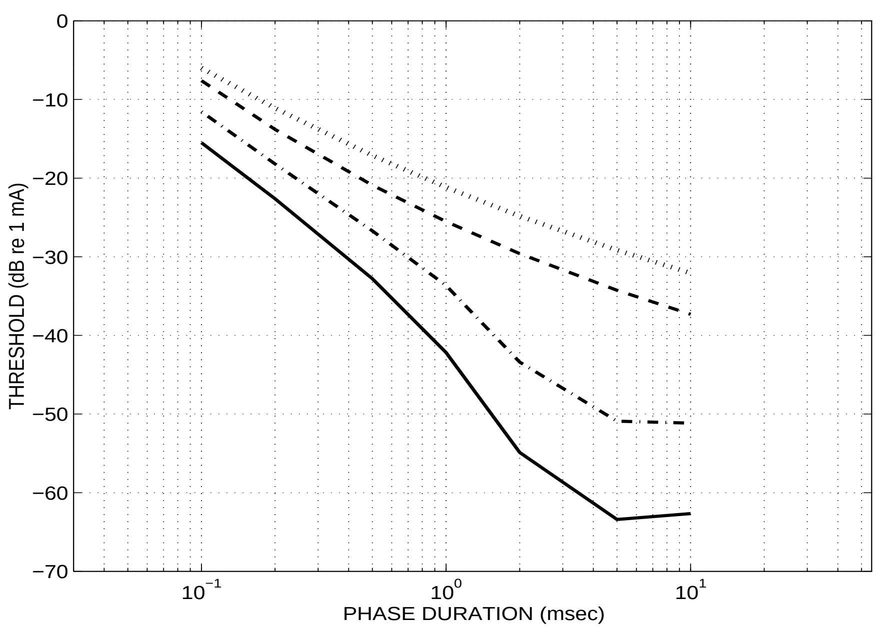
1st−Pulse Response Probability
10^{0}
10^{-1}
10^{-2}
10
15
20
25
30
35
40
45
50
55
60
Intensity (dB re. 1uA)



Current Spread
Σ
∫100ms
Loudness
Spatial Sum
Temporal Integration
Detection /Estimation Process
Electrodes
Neurons
Psychophysical Model



(a) Comparison of physiological and psychophysical thresholds. Reprinted with permission from (Pfingst *et al.*, 1991). Copyright 1991 Acoustical Society of America.



(b) Prediction of auditory threshold versus pulse-width by the deterministic model - threshold at 0.5 (dotted line) and 1.0 (dashed line) firing probability; and by the stochastic model - bipolar (dot-dashed line) and monopolar (solid line) stimulation.