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Modelling the Response of Neurons to Auditory Stimuli: Differences between Acoustical and Electrical Stimulation

A. N. Burkitt and G. M. Clark

Abstract— There are significant differences in the responses of auditory nerves when they are stimulated acoustically (normal hearing situation) or electrically (with a cochlear implant). This paper addresses the underlying causes of these differences by studying the interspike interval histogram, the synchronization index, and the entrainment (degree of response to successive cycles of the stimulus). The new integrated-input technique is used to analyze the response to periodic synaptic input of integrate-and-fire neurons, in which the randomly arriving synaptic inputs are summed and an action potential is generated when the postsynaptic potential reaches threshold. The synaptic inputs in the model are a sinusoidally modulated inhomogeneous Poisson process, and each input generates a postsynaptic response that subsequently decays according to the membrane decay constant. The results provide a quantitative understanding of both the decrease of the synchronization index with increasing frequency of acoustical stimulation in the auditory pathway and the previously observed enhancement of synchronization in globular bushy cells of the cochlear nucleus. The differences in the responses of neurons in higher stages of the auditory pathway for acoustical and electrical stimulation may be accounted for by the differences in the degree of entrainment that they induce.

Keywords— Integrate-and-fire neurons, synchronization, periodic stimulation.

I. Introduction

The periodic response of neurons in the auditory system to low frequency acoustic stimulation was observed by Gerstein and Kiang [6], who measured neural responses in the cochlear nucleus (the first stage of auditory processing in the brainstem) to auditory stimuli presented to anesthetized cats. They observed a multimodal interspike interval histogram (ISIH), resulting from spikes that tend to fire near the peak of the stimulus and hence cluster around integer multiples of the stimulus period [6]. Rose and collegues [15] analyzed phase-locked responses in the auditory nerve in terms of the phase histogram, in which the responses are plotted in terms of their relation to the phase of the stimulus. This behaviour was simulated using a Monte Carlo simulation of the diffusion equation with a periodically varying drift parameter [7], and ISIHs were obtained that resembled the experimental results.

These temporal response patterns of neurons in the auditory pathway, which have been extensively investigated since the above mentioned studies, play a crucial role in electrical stimulation strategies for cochlear implants (see Clark [5] for a recent review). The aim of the cochlear implant is to use electrical stimuli on electrodes located at different sites along the cochlea in order to generate patterns of neural excitation that encode frequency and intensity of the acoustic stimulus. However it is well known that the neural responses to acoustical and electrical stimulation are quite different [11], [13]. Whereas acoustical stimuli generate a multimodal ISIH, electrical stimuli typically produce a dominant peak, with subsequent peaks (if they exist) of greatly reduced amplitude, indicating that the neural response has a higher degree of *entrainment* to the electrical stimulus (i.e., ability to respond at successive cycles of the stimulus). Moreover the response is more tightly phase-locked to the electrical stimulus, as indicated by the larger synchronization index, which is a measure of the relationship between the phase of the periodic inputs and the resultant output spikes. Our aim here is to examine the underlying causes of this difference in the responses to acoustical and electrical stimulation by investigating the response to periodically varying rates of synaptic input using integrate and fire neurons, in which the randomly arriving synaptic inputs are summed and an action potential is generated when the postsynaptic potential reaches threshold.

Mathematical studies of neural responses to periodic input have typically modelled the intracellular potential as a random walk or diffusion process in which the potential is subject to both decay and time-modulated random inputs, as reviewed by Tuckwell [17]. We have adopted a different approach, namely the new "integrated-input" approach [4] in which the probability density of the intracellular potential is calculated by integrating over the distribution of arrival times of the incoming postsynaptic potentials. This technique has previously been used to study the synchronization problem [2], [3], in which the response to a group of synaptic inputs with temporal dispersion is analyzed. The problem in which we are interested here requires inputs that are periodic with frequency ω, which we parameterize by the time-varying sinusoidal rate

$$\lambda(t) = \lambda_0 (1 + D\cos(\omega t + \phi)) \quad , \qquad 0 \leq D \leq 1, \quad (1)$$

where D is the degree of modulation and ϕ is the initial phase of the stimulus, i.e., the phase of the input at the time when the summation commences. The output spike, which is generated when the potential reaches threshold for the first time (the *first-passage time*), then depends upon the phase of the stimulus at which the summation is initiated. In order to find the average phase distribution that results over the whole time course of the periodic stimulus

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it is necessary to find the *stationary spike-phase distribution*, as recently proposed by Plesser and Geisel [14]. This technique is used to generate the spike output distribution, $\rho(t;\omega)$.

II. Results

We present here results on the dependence of the synchronization index upon the frequency of stimulation for a range of numbers of afferent fibres and degrees of modulation of the sinusoidally varying input rate. The degree of phase locking (or synchronization) of the neural response to the stimulus is measured by the vector strength, also known as the synchronization index [8], [1], [9], which takes values between zero (a flat period histogram) and one (all spikes in one bin of the period histogram).

The interspike interval distribution that we obtain is typically of the form illustrated in Figure 1, which shows the multimodal response and a degree of entrainment considerably less than one (parameter values given in figure caption). The amplitudes of the individual EPSPs in this figure is given by $a = \theta/16$, where θ is the difference between the threshold and reset values of the potential. By contrast, a higher rate of synaptic inputs produces an interspike interval distribution in which the first peak is more pronounced, as illustrated in Figure 2, for which the rate of inputs is 20% higher than in Figure 1 (other parameters unchanged). Frequency (ω) and rate (λ) are measured here in units of the time constant of the membrane (τ), i.e., a frequency (rate) of 1.0 corresponds to one cycle (spike) per τ units of time.

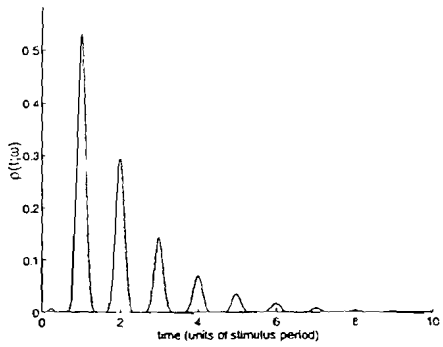

Fig. 1. Plot of the interspike interval distribution, $\rho(t;\omega)$, for $N = 32$ inputs, an input frequency of $\omega = 0.3$, input rate of $\lambda_0 = 0.3$, and the amplitudes of the individual EPSPs $a = \theta/16$, where θ is the difference between the threshold and reset values of the potential. Frequency and rate are given as cycles (spikes) per unit of τ.

The dependence of the synchronization index upon the frequency is illustrated in Figure 3, which shows that the synchronization index decreases for increasing frequencies. The average rate of the inputs, λ_0, is the same as the frequency in all cases, i.e., there is on average one incoming spike per fibre per cycle of the stimulus. For each value of N the amplitude of the individual postsynaptic potentials

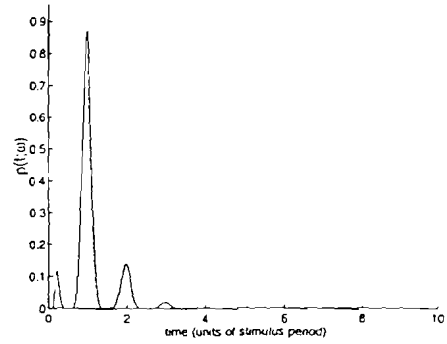

Fig. 2. Plot of the interspike interval distribution, $\rho(t;\omega)$, for $N = 32$ inputs, an input frequency of $\omega = 0.3$, input rate of $\lambda_0 = 0.36$, and the amplitudes of the individual EPSPs $a = \theta/16$ (with frequency and rate in units of τ^{-1}).

is given by $a = 2\theta/N$. The synchronization index is large for all cases in this plot and closest to one when the number of inputs is greatest (the case $N = 128$ in Figure 3). Note that the synchronization index of the sinusoidal input is 0.5, so that the outputs represent an *enhancement* of the synchronization relative to the input. The cutoff on the low frequency side of the plot is determined by the vanishing of the probability of firing (i.e., no output spike being produced), and on the high frequency side values are plotted up to where the entrainment approaches 100% (i.e., output spikes always being generated in the first cycle of the stimulus).

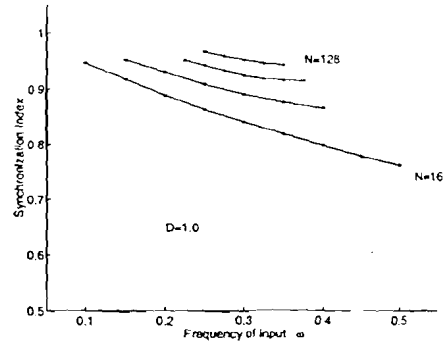

Fig. 3. The synchronization index is plotted against the frequency, ω, (measured in units with $\tau = 1$), for a value of the modulation of the input rate $D = 1.0$. The amplitude of individual EPSPs is $a = 2\theta/N$. The average input rate, λ_0, is the same as the frequency in all cases and the numbers of inputs on the plot are $N = 16, 32, 64, 128$.

In Figure 4 the dependence of the synchronization index upon the degree of modulation of the input, D, is illustrated for a frequency of $\omega = 0.35$ and an average input

rate of $\lambda_0 = 0.35$ (i.e., one spike per input fibre per cycle). The synchronization index of the input is a linear function of the modulation, D, and varies from 0.5 (at $D = 1.0$) to zero (at $D = 0$), so that all points on the plot show a great degree of synchronization of the output than is evident in the input. This enhancement of synchronization is more pronounced for large numbers of inputs.

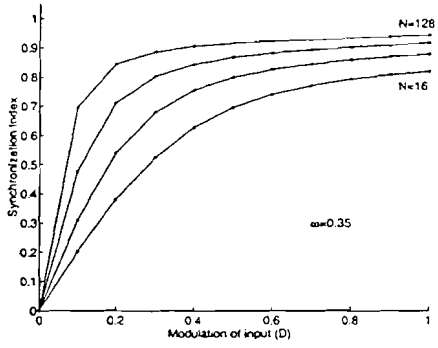

Fig. 4. The synchronization index is plotted as a function of the modulation of the input rate, D, for a frequency of $\omega = 0.35$ and average input rate $\lambda_0 = 0.35$ (in units with $\tau = 1$). The amplitude of individual EPSPs is $a = 2\theta/N$. The number of inputs on the plot are $N = 16, 32, 64, 128$ (bottom to top plots respectively).

III. Discussion

The ISIHs that are observed in neurons in the early stages of the auditory pathway (such as the cochlear nucleus) under acoustical stimulation typically have a multimodal distribution, such as that illustrated in Figure 1. However the same neurons under electrical stimulation typically display a single predominant peak in the ISIH. The preliminary results of our studies presented here appear to indicate that the predominant factor in explaining these different responses is the greater entrainment (and the resulting increase in input rate) that electrical stimulation generates. Electrical stimulation typically causes auditory nerve fibres to fire with substantially higher degrees of entrainment than acoustical stimuli [5], [13], and this is sufficient to explain the predominant first peak in the resulting ISIHs of neurons in higher stages of the auditory pathway, as illustrated in Figure 2.

The results of our studies of the dependence of the synchronization index upon the input frequency and degree of modulation are in accord with the enhancement of synchronization observed by Joris *et al.* [10] in their recordings from neurons in the cat cochlear nucleus, namely that the synchronization index of the spikes generated is greater than that of the inputs for low frequencies. Moreover, the observed decrease of the synchronization index with increasing frequency [10] is also evident in our studies, as shown in Figure 3.

While the present model captures the principal features of the neuronal response, there remain a number of features that need to be incorporated and studied in order to gain a more thorough understanding of the experimentally observed responses. One important factor is the effect of axonal propagation times, which will introduce temporal jitter between the outputs that are generated at any stage of the auditory pathway and their subsequent arrival as synaptic input to the next stage of processing. The effect of these delays is to reduce the synchronization index, and it is expected that they will have a more pronounced effect upon the synchronization index at higher frequencies. There are also a number of features of the neural model that require further analysis, such as the study of the effect of inhibitory inputs and the role of neuronal reversal potentials, the inclusion of refractory effects, as well as habituation and adaptation effects in the neural response. It is also necessary to take into account the timing jitter that fluctuations and differences in individual thresholds cause to the output spike distribution. The effect of pulsatile electrical stimulation (in contrast to sinusoidal stimulation) also needs to be investigated.

The study presented here addresses only the differences in single-fibre responses to electrical and acoustical stimulation. A more complete understanding of the resulting differences in psychophysical and speech processing capabilities under both sets of stimulation requires a consideration of the connectivity of neurons in the auditory pathway, since it is the collective behaviour of the entire network of neurons that determines their functional properties.

Nevertheless, an understanding of the single neuron response is central to the development of a number of proposed electrical stimulation strategies for the cochlear implant [5]. One such scheme is the addition of noise [12], which has been shown to enhance distinguishing features of the vowels in the fine time structure of neural discharges. The addition of noise may seem counter-intuitive from the stand point of traditional signal processing, since noise generally degrades the detectability of a signal. The rationale is based upon the principles of stochastic resonance [18], in which small amounts of noise actually enhance the detectability of a signal near its threshold. By introducing a high-rate subthreshold electrical stimulus it may be possible to introduce both more within-fibre jitter and across-fibre asynchrony in the responses of the auditory nerve [16]. Such a response would more closely resemble that produced by the inner-hair cells in the normal hearing situation and eliminate one of the major differences between normal hearing (acoustical stimulation) and hearing with a cochlear implant (electrical stimulation).

IV. Conclusions

The different ISIHs for neurons at higher stages of the auditory pathway (cochlear nucleus and above) that result from acoustical and electrical stimulation may be accounted for by the increased entrainment that electrical stimulation produces in auditory nerve fibres. The results are also in agreement with experimental observations [10] which indicate that an enhancement of synchronization is

to be expected and that this will be most pronounced for low frequencies. An understanding of these individual fibre responses is important for the development of new electrical stimulation strategies for cochlear implants.

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REFERENCES

[1] D. J. Anderson. Quantitative model for the effects of stimulus frequency upon synchronization of auditory nerve discharges. *J. Acoust. Soc. Am.*, 54:361–4, 1973.

[2] A. N. Burkitt and G. M. Clark. New method for analyzing the synchronization of synaptic input and spike output in neural systems. In T. Downs, M. Frean, and M. Gallagher, editors, *Proceedings of the Ninth Australian Conference on Neural Networks*, 1998.

[3] A. N. Burkitt and G. M. Clark. Analysis of the synchronization of synaptic input and spike output in neural systems, 1998. To appear in Neural Computation.

[4] A. N. Burkitt and G. M. Clark. New technique for analyzing integrate and fire neurons. In *Proceedings of the Computational Neuroscience Meeting 1998*, 1998. (to appear in Neurocomputing, 1999).

[5] G. M. Clark. Electrical stimulation of the auditory nerve: The coding of frequency, the perception of pitch and the development of cochlear implant speech processing strategies for profoundly deaf people. *Clinical and Experimental Pharmacology and Physiology*, 23:766–776, 1996.

[6] G. L. Gerstein and N. Y.-S. Kiang. An approach to the quantitative analysis of electrophysiological data from single neurons. *Biophys. J.*, 1:15–28, 1960.

[7] G. L. Gerstein and B. Mandelbrot. Random walk models for the spike activity of a single neuron. *Biophys. J.*, 4:41–68, 1964.

[8] J. M. Goldberg and P. B. Brown. Response of binaural neurons of dog superior olivary comples to dichotic tonal stimuli: Some physiological mechanisms of sound localization. *J. Neurophysiol.*, 32:613–636, 1969.

[9] D. H. Johnson. The relationship between spike rate and synchrony in responses of auditory-nerve fibers to single tones. *J. Acoust. Soc. Am.*, 68:1115–1122, 1980.

[10] P. X. Joris, L. H. Carney, P. H. Smith, and T. C. T. Yin. Enhancement of neural synchronization in the anteroventral cochlear nucleus. I.responses to tones at the characteristic frequency. *J. Neurophysiol.*, 71:1022–1036, 1994.

[11] Nelson Y. S. Kiang and Edwin C. Moxon. Physiological considerations in artificial stimulus of the inner ear. *Ann. Otol. Rhinol. Laryngol.*, 81:714–730, 1972.

[12] R. P. Morse and E. F. Evans. Enhancement of vowel coding for cochlear implants by addition of noise. *Nature Medicine*, 2:928–932, 1996.

[13] C. W. Parkins. Temporal response patterns of auditory nerve fibers to electrical stimulation in deafened squirrel monkeys. *Hearing Research*, 41:137–168, 1989.

[14] H. E. Plesser and T. Geisel. Markov analysis of stochastic resonance in a periodically driven integrate-fire neuron. preprint, 1998.

[15] J. E. Rose, J. F. Brugge, D. J. Anderson, and J. E. Hind. Phase-locked response to low-frequency tones in single auditory nerve fibers of the squirrel monkey. *J. Neurophysiol.*, 30:769–793, 1967.

[16] J. T. Rubinstein, B. S. Wilson, C. C. Finley, and P. J. Abbas. Pseudospontaneous activity: Stochastic independence of auditory nerve fibers with electrical stimulation, 1998. preprint.

[17] H. C. Tuckwell. *Stochastic Processes in the Neurosciences*. Society for Industrial and Applied Mathematics, Philadelphia, 1989.

[18] K. Wiesenfeld and F. Moss. Stochastic resonance and the benefits of noise: From ice ages to crayfish and squids. *Nature*, 373:33–36, 1995.

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