THEORETICAL PREDICTION OF DYNAMIC RANGE AND INTENSITY DISCRIMINATION FOR ELECTRICAL NOISE-MODULATED PULSE-TRAIN STIMULI

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ABSTRACT

This work investigates dynamic range and intensity discrimination for electrical noise-modulated pulse-train stimuli using a stochastic auditory nerve model [1]. Based on a hypothesized monotonic relationship between loudness and the number of spikes, theoretical prediction of the most uncomfortable level was determined by comparing spike counts to a fixed threshold [2]. However, no specific rule for determining this fixed number has previously been suggested. Our work determines the most uncomfortable level based on the excitation pattern of the basilar membrane in a normal ear. The number of fibers corresponding to the portion of the basilar membrane driven at an uncomfortable stimulus level in a normal ear is related to the most uncomfortable spiking number. The intensity discrimination limens are predicted using signal detection theory via the probability mass function (PMF) of the neural response and via experimental simulations. The results show that the uncomfortable level for a pulse-train stimulus increases slightly as noise level increases. Combining this with our previous threshold predictions [3], we hypothesize that the dynamic range for noise-modulated pulse-train stimuli increases with additive noise. However, since our predictions indicate that intensity discrimination under noise degrades, the overall intensity coding performance does not improve significantly.

1. INTRODUCTION

One issue being studied in cochlear implants is the difference in the neural response to electrical and acoustic stimuli, with much higher levels of synchrony observed in response to electrical stimulation. The incorporation of low levels of noise into an electrical stimulus is a mechanism by which to desynchronize the neural response [4]. It had been shown that adding noise to an electrical vowel stimulus improves formant representation [5]. Some psychophysical studies have also indicated improved threshold and frequency discrimination performance as a result of adding noise [6]. Bruce $et\ al.$ [1] proposed a stochastic input/output (I/O) response model of auditory nerve fibers under pulsatile electric stimulation. This model is computationally inexpensive and provides a link between theoretical predictions and psychophysical measurements. Its accuracy has been demonstrated by its agreement with physiological data [7] as well as psychophysical data [8]. In preliminary studies using Bruce's stochastic AN model, we demonstrated the effect of noise on threshold for electrical noise-modulated pulse-train stimuli [3]. Theoretical predictions have suggested that threshold decreases as noise level increases. It is instructive to investigate how noise affects other psychophysical measurements that may be related to speech recognition performance.

In this study, we investigated the effect of noise on dynamic range (DR) and intensity discrimination for pulse-train stimuli. These psychophysical measurements are essential because they are related to speech coding in cochlear implants. A new method of determining the most uncomfortable level (UCL) is proposed. Based on the PMF of the neural response derived in our previous work [3], intensity discrimination limens (IDLs) are predicted using signal detection theory. The number of just noticeable differences (JNDs) across the DR is calculated to quantitatively demonstrate the intensity coding performance.

This research has been supported by NSF grant NSF-BES-00-85370.

2. METHODS

Pulse-train threshold (THL) has been studied in detail [3]. This work proposes a method to determine the most uncomfortable level. With predicted dynamic range, intensity discrimination is also predicted using signal detection theory.

2.1. Stimuli

The electrical stimulus considered is a bi-phasic pulse train with phase duration of 200 μs/ph, pulse rate of 125 pulses per second (pps), and duration of 300 ms. These parameters are the same as used in a psychophysical IDL study for electrical pulse-train stimuli [9]. We aim to predict the psychophysical data through our modeling study. The stimulus is applied at the central electrode and the current decays spatially as predicted for a bi-polar (BP) electrode configuration. The addition of noise varies the stimulus amplitude of individual pulses within the pulse train, or essentially jitters the pulse amplitude across the pulse train. The jitter is dependent across nerve fibers within a single pulse, but independent across pulses. The auditory nerve (AN) model and the statistics of the accumulated neural response to the pulse-train stimulus are described in [3].

2.2. Prediction of the most uncomfortable level

We assume that the mechanism underlying the most uncomfortable loudness is similar whether or not the subject has normal hearing or a cochlear implant. Once an electrical stimulus generates the same excitation extent along the basilar membrane as an uncomfortable acoustic stimulus in a normal ear, this stimulus level is considered to be the UCL for the cochlear implant subject. To obtain the excitation pattern along the basilar membrane for the

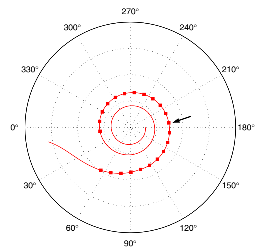

Fig. 1. Electrode positions in the cochlea. The arrow indicates where the simulated current stimulus is inserted.

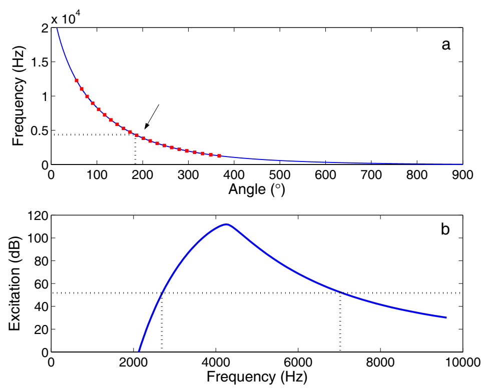

Fig. 2. a) Characteristic frequency associated with the position of each electrode. The arrow indicates the central electrode. b) Excitation pattern at most uncomfortable level in normal hearing subjects. Dotted lines illustrate the half attenuation points of the excitation pattern. The portion between the two dotted lines on the abscissa corresponds to the excited portion that contributes to the UCL.

cochlear implant, the position of the stimulus electrode must be known. The cochlear implant insertion and physical properties varies across devices, so to illustrate our approach, we consider a Nucleus 22 device. There are 22 electrodes along the cochlea and Fig. 1 shows the customary electrode position in the cochlea [10]. The 35 mm cochlea has three and a half turns and the electrodes are inserted through approximately one turn. According to the Greenwood function [11], the characteristic frequency at the position of each electrode is illustrated in Fig. 2a. The stimulus is applied to the central electrode as in our previous study [3]. The arrow indicates the characteristic frequency of 4267 Hz where the central electrode is located. The UCL for normal hearing is approximately 112 dB SPL at this frequency [12]. The excitation pattern at this normal hearing UCL is shown in Fig. 2b [13]. We assume that the portion of the basilar membrane encompassed by the half attenuation of the peak value contributes to the UCL of the ear. This region is from 2758 Hz through 6747 Hz along the frequency axis as shown in Fig. 2b. The length of the arc in the cochlea corresponds to 6.28 mm. The percentage of the cochlea thus excited is $6.28/35\times100=18\%$. We choose N_{ucl}=18% $\times\, F$, where F indicates the total number of fibers, and N_{ucl} represents the number of responding fibers that determines the UCL. The stimulus level achieves the UCL when the convergent spike number exceeds N_{ucl} at 70.7% correct discrimination.

2.3. Prediction of intensity discrimination limens

We adopted the same rule for IDL as used in [2], i.e., comparing the overall spike number generated by the exciting stimulus to that generated by the reference stimulus. The IDL is predicted based on the discrimination statistic d' as given in [14], which is,

$$d' = \frac{\mu_1 - \mu_0}{0.5(\sigma_1 + \sigma_0)}. \tag{1}$$

Here, μ_1 and σ_1 are the mean and the standard deviation of the total spike numbers for the exciting stimulus at a level of I_1 in μA, and μ_0 and σ_0 are the mean and the standard deviation of the total spike numbers for the reference stimulus at a level of I_0 in μA. The IDL is $\Delta I = I_1 - I_0$ in μA. Bruce et al. [15] have derived the statistics for the total spike number for the noise-free pulse-train stimulus but have not provided any analytic solution for the noise-modulated pulse-train stimulus. We have derived the PMF of the convergent neural response to successive pulses in a pulse-train stimulus for both noise-free and noise-modulated cases [3]. The means of the total spike number, u_i, $i = 1, 2$ in (1), are obtained by multiplying the number of pulses in the stimulus and the mean of the convergent neural response obtained by (22) in [3]. A similar procedure is used to obtain the standard deviations, σ_i, $i = 1, 2$. This is appropriate assuming an independent approximation since the refractory effect at 125 pps is not significant. The Weber fraction is a commonly-used metric for intensity discrimination, where

$$Wf = 10\log_{10}\frac{(I_0+\Delta I)^2 - I_0^2}{I_0^2} \overset{(\frac{\Delta I}{I_0})^2\to 0}{\simeq} 10\log_{10}\frac{2\Delta I}{I_0}. \tag{2}$$

2.4. Calculation of the number of JNDs

To quantitatively analyze the intensity coding performance resulting from adding noise, the total number of discriminable steps across the dynamic range are calculated. We adopted the method used in [9]. Calculations of consecutive ΔI began at threshold and continued to the most uncomfortable level. For example, if the ΔI at THL is 2 μA then the next ΔI was calculated at THL+2 μA.

3. RESULTS

3.1. Dynamic range

Table 1 provides theoretical predictions of UCL and THL for the noise-free pulse-train stimulus as described in Section 2.1. The threshold is predicted by a logarithmic rule [3]. Table 1.a shows the predictions for constant model parameters. Table 1.b shows the predictions for random model parameters. Constant model parameters, while not physiologically accurate, simplified model simulation and theoretical prediction of single-fiber I/O functions. The distribution of the model parameters was described in [1]. From Table 1.a and Table 1.b respectively, we observe that dynamic range increases as the total number of fibers, F, increases mainly due to the decrease in threshold. Comparing Table 1.a and Table 1.b, random model parameters result in predictions of a wider dynamic range. For comparison, Table 1.c shows the prediction obtained by Bruce et al.'s method [2], in which N_{ucl} is an arbitrarily chosen constant number. Dynamic ranges predicted by our

Table 1. UCL and THL (dB re 1μA) for the noise-free stimulus

a. Constant model parameters

Fibers	F=100	F=300	F=1000	F=10000
UCL	58.49	58.57	58.63	58.59
THL	48.84	46.85	45.62	43.89

b. Random model parameters

Fibers	F=100	F=300	F=1000	F=10000
UCL	58.59	58.55	58.55	58.50
THL	47.59	44.67	42.77	39.91

c. Bruce et al. prediction [2], F=10000

N_{ucl}s	N_{ucl}=100	N_{ucl}=300	N_{ucl}=1000
UCL	39.30	41.33	42.17
THL	28.06		

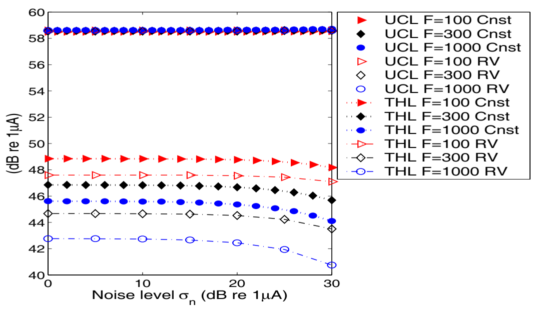

Fig. 3. Prediction of UCL and THL for the noise-modulated pulse trains. "Cnst" and "'RV"' indicate predictions for constant and random model parameters respectively.

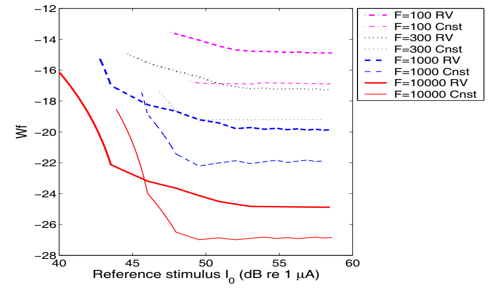

Fig. 4. Weber fraction for the noise-free pulse-train stimuli as a function of reference stimulus level.

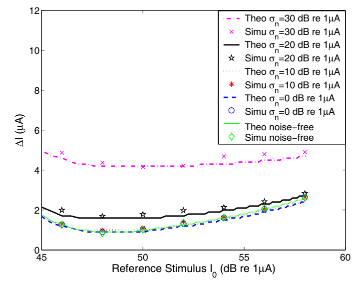

Fig. 5. Intensity discrimination for the pulse train stimuli at F=1000 with constant model parameters. Lines, labeled by "Theo", represent theoretical predictions. Symbols, labeled by "Simu", represent the model simulation results.

method and Bruce's method are both in the range of $10-20$ dB. These predictions are close to psychophysical data for sinusoidal stimuli with human and monkey subjects, which is around 23 dB [16].

Fig. 3 shows the predictions of dynamic range for the noise-modulated pulse-train stimulus. As noise increases, UCLs change slightly but no significant difference is observed as a function of the total number of fibers and the variability of the model parameters. This is similar to the results from the UCL for the noise-free stimulus as shown in Table 1. Threshold decreases with noise level [3], and the dynamic range increases as noise level increases. Random model parameters result in larger dynamic range since the dynamic range of each fiber is larger. The increase in dynamic range is mainly due to decrease in threshold for the noise-modulated stimulus.

3.2. Intensity discrimination

In Section 3.1, we predicted that adding noise to the stimulus increases dynamic range. It remains to be determined whether the wider dynamic range allows more accurate intensity representation. We predicted IDLs within the dynamic range. In this section, we determined ΔI for d'=0.78 corresponding to 70.7% correct in a two-down one-up (2D1U) adaptive measurement procedure [17]. Fig. 4 shows the predictions of Weber fractions for the noise-free pulse-train stimuli for different numbers of fibers and model parameter assumptions. The predictions indicate that a smaller number of fibers results in shallower Weber fraction improvement across the dynamic range. Models with random parameters have flatter Weber fraction curves across the dynamic range. Comparing these results with the psychophysical data, some subjects demonstrate obvious improvement while others do not [9]. The number of fibers and the variability of the model parameters affect the slope of the Weber fraction. This may be related to performance variability in subjects. Our prediction for IDL at F=10000 with random model parameters is consistent with the psychophysical observation of a -8 dB improvement on average in Weber fraction across dynamic range [9].

Psychophysical data of IDL for noise-modulated pulse-train stimuli are not yet available. The 2D1U simulations are performed via the auditory nerve model to verify the theoretical predictions. Fig. 5 shows theoretical predictions of IDL compared to model simulations at F=1000 for constant model parameters. The consistency between theoretical predictions and model simulations holds for other combinations of the total number of fibers and assumptions regarding model parameters.

3.3. The number of JNDs across the DR

Psychophysical data suggest that the number of JNDs for the noise-free pulse-train stimuli are between 6.6 and 45.2 [9]. Table 2 shows predictions of the numbers of JNDs for the noise-free pulse-train stimulus at F=100 for both constant model parameters and random model parameters. Three different values for d' are consid-

Table 2. The number of JNDs for the noise-free pulse-train stimulus at F=100

Model parameters	d′=0.78	d′=1	d′=1.63
Constant	116.2	90.7	55.4
Random	72.9	56.7	34.7

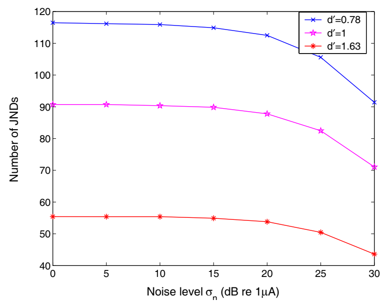

Fig. 6. The number of JNDs within the dynamic range for noise-modulated pulse-train stimulus at F=100 with constant model parameters with different measurement paradigms.

ered. $d'=1$ corresponds to 75% correct, and $d'=1.63$ corresponds to 79.4% correct for the widely used three alternative forced choice (3AFC) measurement paradigm. As expected, the higher the percent correct required, the smaller the number of the JNDs. Random model parameters result in smaller numbers of JNDs. Fig. 6 shows the prediction of the number of JNDs for the noise-modulated pulse-train stimuli at F=100 with constant model parameters. The number of JNDs decreases as the noise level increases. We demonstrate this conclusion only for one parameter combination although the trends of JND versus noise level are similar for other parameter combinations.

4. CONCLUSIONS

This work has proposed a new method of theoretically predicting the most uncomfortable level for electrical pulsatile stimulation. The intensity discrimination limen is theoretically predicted using signal detection theory. Theoretical predictions show that the dynamic range increases as noise level increases. However, the intensity discrimination performance becomes worse as the noise level increases. The total number of JNDs within the dynamic range decreases as noise level increases. The variance of the predicted performance for different number of fibers and model parameter selections may be related to the variability of dynamic range and intensity discrimination in human subjects. This series of theoretical studies may be helpful in designing psychophysical experiments under noise in the future.

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