



UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Models and psychophysics of acoustic and electric hearing

by

Johannes Jurgens Hanekom

Submitted as partial fulfilment of the requirements for the degree

Philosophiae Doctor

in the

Faculty of Engineering, Built Environment and Information Technology

University of Pretoria, Pretoria

November 2001

Models and psychophysics of acoustic and electric hearing

by

Johannes Jurgens Hanekom

Advisor : Prof Johann J Krüger
Department : Electrical, Electronic and Computer Engineering
Degree : Philosophiae Doctor

KEY WORDS

Cochlear implants, electrical stimulation, modelling, phase-lock coding, frequency discrimination, gap detection, channel interaction, central auditory nervous system

ABSTRACT

Especially important in developing improved cochlear implants is to develop a deeper understanding of the processing of sound in the central auditory nervous system, for both acoustic and electrical stimulation of the auditory system. This thesis contributes to this objective through cochlear implant psychoacoustic research and modelling of auditory system sound processing.

The primary hypothesis of the thesis was that the same underlying mechanisms are responsible for sound perception in both electric and acoustic hearing. Thus, if appropriate models are created for normal acoustic hearing, they should be able to predict psychoacoustic data from electric hearing when the model input is changed from acoustic to electrical stimulation. A second hypothesis was that electrode interaction could be measured by gap detection and that predictions of current spread in the cochlea could be obtained from gap detection data.

Measured gap detection thresholds in three cochlear implant users were a function of the physical separation of electrode pairs used for the two stimuli that bound the gap, resulting in

a U-shaped "tuning curve" for this across-channel condition. Models of gap detection in acoustic and electric hearing were created to explain these U-shaped curves. A technique was developed to obtain estimates of cochlear current spread from gap detection data. Predictions of electrode discrimination were obtained from the current spread estimates, and these were compared to data measured in cochlear implant users.

The model for acoustic hearing could predict the U-shaped curves found in acoustic hearing, and when the input spike train statistics were adapted appropriately, the same model could also predict gap detection data for electric hearing. Predictions of current spread exhibited current peaks close to the electrodes and had length constants between 0.5 mm and 3 mm, similar to measured data quoted in literature. Predictions of electrode discrimination correlated well with measured data in one subject, but not in two others.

The primary conclusion from the modelling results is that if the mechanisms of central auditory nervous system signal processing of acoustic stimulation are understood, these same mechanisms may be applied to understand the signal processing in auditory electrical stimulation and to predict psychoacoustic data for electrical stimulation. A second conclusion is that spatial mechanisms, as opposed to temporal mechanisms, may determine gap detection thresholds in the across-channel condition. This is important in cochlear electrical stimulation, where spike trains are strongly phase-locked to the stimulus and temporal mechanisms cannot predict gap detection thresholds. A third conclusion is that gap detection can be used to measure channel interaction and to predict current distributions in the cochlea, although there is still uncertainty about the accuracy of these predictions. However, the gap detection data and predictions for current distributions indicate that electrodes are not discriminable when they are closer than 1.5 mm. The implication of these last two conclusions taken together is that research should focus on obtaining better spatial resolution in cochlear implants.



Modelle en psigofisika van akoestiese en elektriese gehoor

deur

Johannes Jurgens Hanekom

Promotor : Prof Johann J Krüger
Departement : Elektriese, Elektroniese en Rekenaar-Ingenieurswese
Graad : Philosophiae Doctor

SLEUTELWOORDE

Kogleêre inplantings, elektriese stimulasie, modellering, fase-sluit kodering, frekwensiediskriminasie, gapingsdeteksie, kanaalinteraksie, sentrale ouditiewe sensuweestelsel

OPSOMMING

Tydens die ontwikkeling van beter kogleêre inplantings is dit besonder belangrik om 'n dieper begrip van die verwerking van klank in die sentrale ouditiewe sensuweestelsel te ontwikkel, beide vir akoestiese en elektriese stimulasie van die ouditiewe stelsel. Hierdie proefskrif dra by tot hierdie oogmerk deur psigoakoestiese navorsing en modellering van klankverwerking deur die ouditiewe stelsel.

Die primêre hipotese is dat dieselfde onderliggende meganismes verantwoordelik is vir klankpersepsie in beide elektriese en akoestiese gehoor. Dus, indien toepaslike modelle vir normale akoestiese gehoor geskep word, behoort hulle psigoakoestiese data van elektriese gehoor te kan voorspel indien die modelinset verander word vanaf akoestiese na elektriese stimulasie. 'n Tweede hipotese is dat elektrode-interaksie gemeet kan word met gapingsdeteksie en dat voorspellings van die stroomverspreiding in die koglea verkry kan word uit gapingsdeteksiedata.



Gemete gapingsdeteksiedrempels in drie gebruikers van kogleêre inplantings was 'n funksie van die fisiese afstand tussen elektrodepare wat gebruik is vir die twee stimuli aan weerskante van die gaping en het gelei tot 'n U-vormige "stemkromme" vir hierdie inter-kanaal geval. Modelle van gapingsdeteksie in akoestiese en elektriese gehoor is geskep om hierdie U-vormige krommes te verduidelik. 'n Tegniek is ontwikkel om skattings van stroomverspreiding in die koglea te verkry vanuit gapingsdeteksiedata. Voorspellings van elektrodediskriminasie is verkry uit die stroomverspreidingskattings en is met gemete data van kogleêre inplantinggebruikers vergelyk.

Die model vir akoestiese gehoor kan die U-vormige gapingsdeteksielokrommes van akoestiese gehoor voorspel, en met gepaste aanpassing van die statistieke van die senuwee-impulsreeks op die modelinset kan dieselfde model ook gapingsdeteksiedata vir elektriese gehoor voorspel. Voorspellings vir stroomverspreidings toon pieke naby die elektrodes en het lengtekonstantes van 0.5 mm tot 3 mm, soortgelyk aan data waarna in die literatuur verwys word. Voorspellings van elektrodediskriminasie korreleer goed met gemete data in een proefpersoon, maar dieselfde geld nie in twee ander proefpersone nie.

Die primêre gevolgtrekking uit die resultate van die modellering is dat indien die meganismes van seinverwerking in die sentrale ouditiewe senuweestelsel verstaan word, kan hierdie meganismes toegepas word om seinprosessering in die elektries-gestimuleerde gehoorstelsel te verstaan en om psigoakoestiese data vir elektriese gehoor te voorspel. 'n Tweede gevolgtrekking is dat ruimtelike meganismes eerder as temporale meganismes verantwoordelik kan wees vir gapingsdeteksiedrempels in die inter-kanaal geval. Dit is belangrik in kogleêre elektriese stimulasie waar senuwee-impulsreekse sterk fasegesluit is aan die stimulus en waar temporale meganismes nie gapingsdeteksiedrempels kan voorspel nie. 'n Derde gevolgtrekking is dat gapingsdeteksie gebruik kan word om kanaalinteraksie te meet en om stroomverspreidings in die koglea te voorspel, alhoewel onsekerheid bestaan oor die akkuraatheid van hierdie voorspellings. Nietemin, die gapingsdeteksiedata en voorspellings vir stroomverspreiding wys dat elektrodes nie diskrimineerbaar is as hulle nader as 1.5 mm aan mekaar is nie. Die implikasie van die laaste twee gevolgtrekkings is dat dit nodig is dat navorsing fokus op die verkryging van beter ruimtelike resolusie in kogleêre inplantings.

CONTENTS

| | |
|---|----------|
| Abstract | i |
| Opsomming | iii |
| Chapter 1: INTRODUCTION | 1 |
| 1 ISSUES IN COCHLEAR IMPLANT RESEARCH | 1 |
| 2 MODEL BASED RESEARCH | 3 |
| 2.1 Types of models | 3 |
| 2.2 The value of models | 5 |
| 3 OBJECTIVES OF THIS THESIS | 6 |
| 4 HYPOTHESES OF THIS THESIS | 7 |
| 4.1 Hypothesis 1: Psychoacoustic data for electric hearing can be predicted by models for acoustic hearing | 7 |
| 4.2 Hypothesis 2: The auditory system employs an internal model to interpret sounds | 8 |
| 4.3 Hypothesis 3: Temporal and spatial mechanisms can be explained by the same underlying neurophysiology | 8 |
| 4.4 Hypothesis 4: Electrode interaction in cochlear implants can be measured with gap detection | 9 |
| 5 THESIS OUTLINE | 10 |



Chapter 2: GAP DETECTION AS A MEASURE OF ELECTRODE INTERACTION IN COCHLEAR IMPLANTS 13

1 INTRODUCTION 13

1.1 The number of information channels in an implant 14

1.2 Physical factors affecting electrode interaction 15

1.2.1 Electrode placement. 16

1.2.2 Nerve survival. 17

1.3 Gap detection as a measure of tonotopic spread 17

2 METHODS 19

2.1 Subjects 19

2.2 Electrode parameters 19

2.3 Stimulus parameters 21

2.4 Psychophysical procedure 22

3 RESULTS 22

3.1 Gap threshold as a function of electrode separation 22

3.2 Gap thresholds as a function of level of stimulation 28

3.3 Gap threshold as a function of mode of stimulation 30

4 DISCUSSION 32

4.1 Relation between spatial selectivity and gap detection thresholds 32

4.2 Relation between stimulation level and spatial selectivity 35

4.3 Relation between stimulation mode and spatial selectivity 35

4.4 Channel characteristics 37

4.5 Implications for cochlear implants 41

4.5.1 Comparison of electrode designs. 41

4.5.2 Reduced electrode processors. 41

4.5.3 Choice of electrodes for a reduced electrode processor 41

4.5.4 Choice of electrode pair separation (stimulation mode) 42



| | | |
|-------|---|-----------|
| 5 | CONCLUSIONS | 42 |
| | APPENDIX 2.A. SUMMARY OF ELECTRODE DISCRIMINATION STUDY | 43 |
| | Chapter 3: MODELS OF GAP DETECTION IN ACOUSTIC HEARING | 45 |
| 1 | INTRODUCTION | 45 |
| 1.1 | Models of gap detection in acoustic auditory stimulation | 45 |
| 1.2 | Extension of previous models | 47 |
| 1.3 | Objectives of this chapter | 48 |
| 2 | A MODEL FOR GAP DETECTION IN ACOUSTIC HEARING | 48 |
| 2.1 | Assumptions about the acoustically evoked spike train | 48 |
| 2.2 | Nerve fibre model | 49 |
| 2.2.1 | Nature of the nerve fibre model | 50 |
| 2.2.2 | Nerve fibre model equations | 50 |
| 2.3 | Cramer-Rao Lower Bound for the Poisson change-point problem | 52 |
| 2.4 | Bounds on the gap detection and discrimination thresholds as a function of ΔF | 61 |
| 2.5 | Measurement of gap length with a Poissonian timer | 65 |
| 2.6 | Gap detection | 66 |
| 3 | RESULTS | 69 |
| 4 | DISCUSSION | 73 |
| 4.1 | Strengths and shortcomings of the model | 73 |
| 4.2 | Parameter sensitivity and the origin of the shape of the gap detection tuning curves | 74 |
| 4.3 | Temporal and spatial models for gap detection | 75 |
| 4.4 | Interpretation of modelling results | 76 |
| 5 | CONCLUSIONS | 77 |



| | |
|---|-----------|
| Chapter 4: MODELS OF GAP DETECTION IN ELECTRIC HEARING | 79 |
| 1 INTRODUCTION | 79 |
| 1.1 Information available to the central detector in acoustic and electric gap detection | 81 |
| 1.1.1 Temporal response properties | 81 |
| 1.1.2 Spatial excitation patterns | 83 |
| 1.2 Differences in the gap detection task between acoustic and electric hearing . . . | 84 |
| 1.3 Models for gap detection | 84 |
| 1.4 Objectives of this chapter | 86 |
| 2 A MODEL FOR GAP DETECTION IN ELECTRIC HEARING | 86 |
| 2.1 Assumptions about the electrically evoked spike train | 86 |
| 2.2 General formulation of a gap detection model for electric hearing | 87 |
| 2.3 Gap detection model structure for electric hearing | 90 |
| 2.3.1 Gap detection based on a single fibre when entrainment is 100% . . . | 91 |
| 2.3.2 Gap detection based on multiple fibres when entrainment is less than 100% | 92 |
| 2.4 Model parameters | 100 |
| 2.4.1 Current distribution | 100 |
| 2.4.2 Distance between electrodes and nerve fibres | 103 |
| 2.4.3 Rate-intensity function of nerve fibres | 104 |
| 2.4.4 Other stimulation parameters | 104 |
| 3 RESULTS | 106 |
| 3.1 Gap detection tuning curves predicted by model | 106 |
| 3.2 Current distributions predicted by model | 113 |
| 3.3 Predictions for electrode discrimination from the predicted current distributions | 119 |
| 4 DISCUSSION | 122 |
| 4.1 Modelling of gap detection data | 122 |



| | | |
|-------|---|-----|
| 4.2 | Modelling of current distributions | 123 |
| 4.3 | Applicability of the model | 125 |
| 4.4 | Free parameters and parameter sensitivity | 125 |
| 4.5 | Strengths and weaknesses of the current model | 126 |
| 4.5.1 | Strengths | 126 |
| 4.5.2 | Weaknesses | 127 |
| 4.5.3 | Other arguments against the model | 128 |
| 4.6 | Future improvements of the model | 128 |
| 5 | CONCLUSION | 129 |
| | APPENDIX 4.A | 131 |

Chapter 5: A SPATIAL MODEL OF FREQUENCY

| | | |
|-----|---|------------|
| | DISCRIMINATION IN ACOUSTIC HEARING | 132 |
| 1 | INTRODUCTION | 132 |
| 2 | POPULATION CODING | 135 |
| 3 | POINT PROCESS DESCRIPTION OF SPIKE TRAINS | 137 |
| 4 | MODELLING AND SIMULATION | 140 |
| 5 | METHODS | 142 |
| 5.1 | Step 1: Generation of auditory spike trains in response to a pure tone stimulus | 143 |
| 5.2 | Step 2: Estimation of the input by a central observer | 145 |
| 6 | RESULTS | 145 |
| 7 | DISCUSSION | 149 |



| | | |
|-----|---|------------|
| 7.1 | Characteristics of the model | 149 |
| 7.2 | Hair cell loss | 150 |
| 8 | CONCLUSIONS | 151 |
| | APPENDIX 5.A. OPTIMAL ESTIMATOR FOR THE INPUT FREQUENCY | 152 |
| | Chapter 6: A MODEL OF FREQUENCY DISCRIMINATION WITH OPTIMAL PROCESSING OF AUDITORY NERVE SPIKE INTERVALS | 155 |
| 1 | INTRODUCTION | 155 |
| 2 | METHODS | 160 |
| 2.1 | Structure of an optimal processor | 160 |
| 2.2 | Model of phase-locking | 161 |
| 2.3 | Model of the pooling of spike trains | 164 |
| 2.4 | Design of the optimal estimator | 170 |
| 2.5 | Choice of Kalman filter parameters | 171 |
| 2.6 | Simulations | 172 |
| 3 | RESULTS | 173 |
| 3.1 | $\Delta f/f$ as a function of frequency | 173 |
| 3.2 | Δf as a function of intensity | 173 |
| 3.3 | $\Delta f/f$ as a function of duration | 175 |
| 3.4 | Performance when the one spike per cycle assumption is violated | 177 |
| 4 | DISCUSSION | 177 |
| 4.1 | Nature of the model | 177 |
| 4.2 | Significance of the Kalman filter model | 178 |
| 4.3 | Comparison between different classes of models of frequency discrimination | 180 |



| | | |
|--|---|-----|
| 4.4 | The influence of ISI histogram mode offsets | 182 |
| 4.5 | The influence of peak splitting | 182 |
| 4.6 | Robustness with respect to the number of spikes per stimulus cycle | 183 |
| 4.7 | Robustness with respect to spike distribution | 183 |
| 4.8 | Parameter sensitivity and the origin of the shape of the $\Delta f/f$ frequency curve | 183 |
| 4.9 | Frequency range | 185 |
| 4.10 | Number of fibres required | 187 |
| 4.11 | Behavior of the model in noise | 188 |
| 4.12 | Comments on the use of cat neurophysiological data to predict human performance | 189 |
| 4.13 | Comments on neural implementation | 189 |
| 5 | CONCLUSIONS | 191 |
| | APPENDIX 6.A. DERIVATION OF EQUATION 6.2. | 192 |
| Chapter 7: WHAT DO COCHLEAR IMPLANTS TEACH US ABOUT THE ENCODING OF FREQUENCY IN THE AUDITORY SYSTEM? 193 | | |
| 1 | INTRODUCTION | 193 |
| 1.1 | Approach | 195 |
| 2 | METHOD | 195 |
| 2.1 | Estimator structure | 196 |
| 2.2 | Number of fibres combined | 197 |
| 2.3 | Model of phase-locking for acoustic stimulation | 197 |
| 2.4 | Model of phase-locking for electrical stimulation | 198 |
| 2.5 | Combination of fibres for electrical stimulation | 200 |
| 2.6 | Implementation of the estimator and simulations | 202 |



| | | |
|-----|--|------------|
| 3 | RESULTS | 203 |
| 3.1 | $\Delta f/f$ as a function of frequency for acoustic stimulation | 203 |
| 3.2 | Δf as a function of frequency for electrical stimulation | 204 |
| 4 | DISCUSSION | 206 |
| 4.1 | Justification of assumptions | 206 |
| 4.2 | The origin of the shape of the $\Delta f/f$ frequency curve | 208 |
| 4.3 | What do cochlear implants teach us about the coding of frequency in the auditory system? | 209 |
| 4.4 | Implications for cochlear implants | 210 |
| 5 | CONCLUSIONS | 211 |
| | Chapter 8: CONCLUSION | 212 |
| 1 | DISCUSSION OF HYPOTHESES | 212 |
| 1.1 | Hypothesis 1 | 212 |
| 1.2 | Hypothesis 2 | 213 |
| 1.3 | Hypothesis 3 | 214 |
| 1.4 | Hypothesis 4 | 214 |
| 2 | RESEARCH CONTRIBUTION | 215 |
| 3 | IMPLICATIONS FOR COCHLEAR IMPLANTS | 218 |
| 3.1 | Speech processors for cochlear implants | 218 |
| 3.2 | Improved individualized programming of cochlear implants | 219 |
| 4 | FUTURE RESEARCH DIRECTIONS | 219 |
| | REFERENCES | 222 |

LIST OF ABBREVIATIONS

| | |
|------------|---|
| 2IFC | two interval forced choice |
| Δf | just noticeable difference in frequency |
| ALSR | average localized synchronized rate |
| ANOVA | analysis of variance |
| AR | apical reference |
| BP | bipolar |
| CF | characteristic frequency |
| CIS | continuous interleaved sampling |
| CN | cochlear nucleus |
| CRLB | Cramer-Rao lower bound |
| dc | direct current |
| DCN | dorsal cochlear nucleus |
| ISI | inter-spike interval |
| jnd | just noticeable difference |
| jndf | just noticeable difference in frequency |
| pdf | probability density function |
| RS | relative spread |
| SL | sensation level |
| SNR | signal-to-noise ratio |
| SPEAK | spectral peak |
| SPL | sound pressure level |
| SR | spontaneous rate |