Chapter 1

INTRODUCTION

Cochlear implants have been developed to stimulate the auditory systems of deaf individuals to create a hearing sensation (Clark, 1993;Clark, 1996;Clark, Tong, and Patrick 1990). Cochlear implants are intended to elicit firing patterns on the auditory nerve that are faithful replicas of firing patterns found in normal hearing. Many thousands of deaf people worldwide use cochlear implants with varying degrees of success (Kou, Shipp, and Nedzelski, 1994).

1 ISSUES IN COCHLEAR IMPLANT RESEARCH

A primary problem with cochlear implants is the large variability in speech recognition performance across users (Clark, 1996). This is also reflected in inter-subject performance variability in psychoacoustic experiments. Most implant listeners cannot appreciate music (Fujita and Ito, 1999) and many users cannot use a telephone or struggle to follow speech in noisy environments (Hirsch, 1993). Auditory sensations vary as a result of complex interactions between several patient and device related factors, among others electrode distance from nerve fibres, surviving nerve fibre distribution (Zimmerman, Burgess, and Nadol, 1995), and current distribution in the cochlea due to non-homogeneous cochlear impedance (Ifukube and White, 1987).

Initially, cochlear implant research was driven by clinical objectives. Safety and reliability issues, like biocompatibility of electrodes and implantable electronics, needed to be solved. Design and development of the external speech processors, the implantable stimulator, electrode arrays and communication protocols between the stimulator and the speech processor required attention. Stimulation parameters (currents and waveforms) and stimulation strategies needed to be developed.

Medical-ethical aspects, including animal experiments to prove safety and functionality, proving that deaf people would benefit from cochlear implants and determining which segment of the deaf population (including children) would benefit needed to be addressed and regulatory body approval had to be obtained.

After this initial phase, research focus shifted to more fundamental issues. Many of the issues identified in chapter 25 of (Miller and Spelman, 1990) are still topics of active research. Progress has been made in finite element modelling to predict current flow through excitable tissue in the cochlea (Frijns, de Snoo, and Schoonhoven, 1995; Hanekom, 2001). New and more selective electrode designs have been introduced. Methods to limit channel interaction and current spread is a topic of current research (Kral et al., 1998). Techniques are being researched to determine channel interaction in individual cochlear implant users (Fu, 1997; Hanekom and Shannon, 1998; Shannon, 1985), to enable optimum setting of stimulation parameters. New encoding strategies have been developed (Loizou, 1999), based on improving either spectral or temporal presentation of sound, or both.

Especially important in developing improved cochlear implants is to develop a deeper understanding of the processing of complex speech signals in the central auditory nervous system. This needs to be achieved through neurophysiological animal experiments, psychoacoustic experiments with cochlear implant users, and the development of models of the neurophysiology of the coding and processing of information in the central auditory nervous system in both acoustic and electric hearing. Relating psychoacoustic results to the underlying neurophysiology is essential. Appropriate models can greatly assist in this effort.

2 MODEL BASED RESEARCH

This thesis promotes a model-based research approach. Therefore, it is appropriate to give a more detailed description of the process and value of modelling in cochlear implant research, before the objectives of this thesis are described. The objective of this section is to place the models created in this thesis into context.

Engineers and scientists frequently create mathematical models to represent processes and predict the effects of changes on a system. A model is a mathematical description of a natural phenomenon, in this case a mathematical description of the functioning of the central auditory nervous system under acoustic or electrical stimulation.

Neurophysiological research, psychoacoustic research and modelling research are interrelated and cannot exist in isolation (figure 1.1). Without models to aid interpretation, psychoacoustics research may follow an empirical or trial and error approach, without a clear route to follow to improve cochlear implant designs.

2.1 Types of models

The researcher creates a system of mathematical equations that describes the behaviour of the normal or electrically stimulated auditory system. Modelling equations may be solved with analytical methods (e.g. Siebert, 1970), or with numerical methods (e.g. Finley, Wilson, and White, 1990) or a combination of both (e.g. Bruce et al., 1999b). Numerical solutions can be obtained with computer simulations. It is a requirement that any type of model produce numerical predictions.

Furthermore, models can vary from biology-faithful models to black box models. Biology-faithful models incorporate as much as possible of the existing knowledge about the anatomy and physiology. These models may, for example, represent the function of a specific system in the brain by modelling a large number of nerve fibres and combining these nerve fibres into a larger structure (Bower, 1990). More specifically for the current application, these models may describe each nerve fibre in the model by a full-blown Hodgkin-Huxley model (Rattay and Motz, 1986). The Hodgkin-Huxley model is one of a number of biology-faithful nerve fibre models and uses a number of differential equations to describe the functioning of a single nerve cell. Biology-faithful models can be accurate, but may require substantial computer time for simulation.

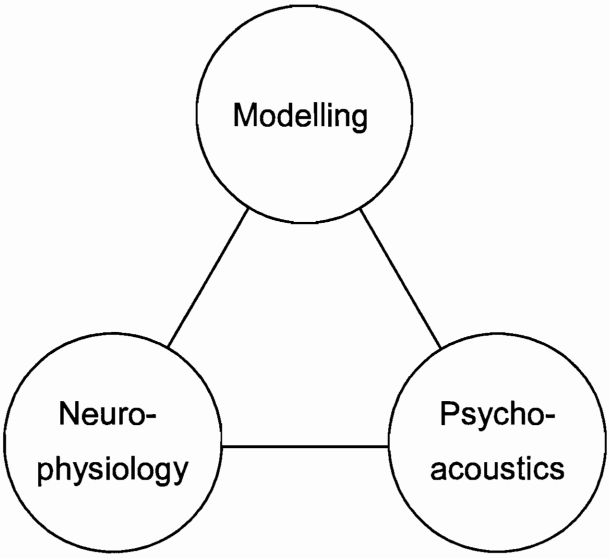

Figure 1.1.

Relationship between neurophysiological research, psychoacoustic research and modelling research.

Black box models are phenomenological models that simply describe input-output data with a mathematical equation without consideration for the biology. Some nerve fibre models model the nerve fibre as a simple generator of neural spikes (e.g. Gabbiani and Koch, 1996). In the simplest form black box models simply fit a curve to the data and assumes no knowledge of the functioning of the system that is modelled. Black box models tend to be very limited in terms of the data sets that can be predicted.

A whole continuum of models that incorporate existing knowledge of the biology to a greater or lesser extent exists between biology-faithful models and black box models. Some models deliberately ignore existing knowledge (thus are more idealized than biology-faithful models) with the objective to exclude extraneous factors (e.g. variations between people or noise in signals) to uncover the core calculations performed by the system that is investigated. Therefore, models sometimes deliberately simplify the real situation to get rid of "noise" that hides the true function that the system under consideration performs. Examples of this approach will be evident in this thesis.

Models are characterized by the model structure and the parameters. Modelling is frequently an iterative process. Based on the researcher's understanding of the processing performed in the system that is modelled, the researcher determines a model structure. Parameters for the model must subsequently be measured and can sometimes be found in the literature. Estimating model parameters is frequently necessary and sometimes it is adequate if the estimate is only roughly correct. With the structure and parameters known, computer simulations can be performed with the model and numerical predictions can be obtained.

If the model is well-behaved, i.e. the model can reproduce measured data accurately (it can predict magnitudes and trends), the choice of structure may be presumed to be appropriate. Sometimes trends are predicted correctly, but the magnitudes of the measured and predicted data do not correspond. This may be because the structure of the model is correct, but parameters have been guessed or measured incorrectly. Or it may happen that the model cannot predict the measured data at all, in which case the model structure may be incorrect.

2.2 The value of models

An important question that should be answered about each model is: can the model explain measured data outside the data set for which the model was created? If not, the model probably requires further development. The wider the data set that a model can explain, the more confident the researcher may be that the functionality of the underlying system is understood and that the model structure is correct. For example, if a model were created to predict frequency discrimination of pure tones, but it can also predict discrimination of complex tones, it gives confidence in the validity of the model. As models are developed, understanding of the system that is modelled grows.

Models cannot predict the effect of stimulation or the behaviour of the auditory system perfectly, since they represent a simplification of the real system. However, an exact representation of reality is not necessarily required, or available, to describe the functioning of a system. The cochlear implant is a good example of this, because development of and improvements to implants have been successful, based on, among others, modelling studies, although the functioning of the auditory system is not fully understood (Clark, 1996). If a model can predict the most important characteristics of a system accurately enough, the model may be useful.

Finally, models may be regarded as part of the measuring tools in psychoacoustic and neurophysiological research. Models enable the researcher to test some concepts in computer simulations rather than performing experiments directly on humans or animals. Models summarize knowledge and show gaps in knowledge, but perhaps most important, they build understanding. This will be demonstrated in the various models discussed in this thesis. Many conclusions of this thesis (see the ends of the chapters) are based on discoveries made during the process of deriving numerical predictions that mimic measured data.

3 OBJECTIVES OF THIS THESIS

The absence of comprehensive, anatomically and physiologically faithful models to predict the effect of electrical stimulation on the auditory system is a primary deficiency in cochlear implant research. The creation of new, more comprehensive models, to incorporate a broader base of data is crucial for the further development of cochlear implants. Specifically, many gaps exists in our knowledge of the relationship between electrical stimuli and the perceived sound. It is unclear why certain stimuli elicit certain perceived sounds (perception is measured psychoacoustically).

The primary objective of this thesis is to build understanding of the functioning of the peripheral and central auditory system in acoustic and electric hearing, through measurement and modelling. The study of auditory electrical stimulation provides a window on the auditory system that provides new perspectives on how the auditory system functions.

4 HYPOTHESES OF THIS THESIS

Four hypotheses are investigated in this thesis, as described here. Although not all of these can be proven conclusively, they are proven qualitatively by examples.

4.1 Hypothesis 1

Psychoacoustic data for electric hearing can be predicted by models for acoustic hearing

A lack of an integrated interpretation of different psychoacoustic results exists in literature. Throughout, the models in this thesis aim to reconcile psychoacoustic and neurophysiological data. An important assumption in this thesis is that the same underlying processes (in the central auditory nervous system) are responsible for the perception of electrical and normal acoustic stimulation. The primary hypothesis of this thesis is that appropriate models for normal acoustic hearing should be able to predict psychoacoustic data from electric hearing when the model input is changed from acoustic to electrical stimulation (figure 1.2). Chapters 3 and 4 (that describe models of acoustic and electric gap detection) and 6 and 7 (that describe models of acoustic and electric frequency discrimination) investigate this hypothesis.

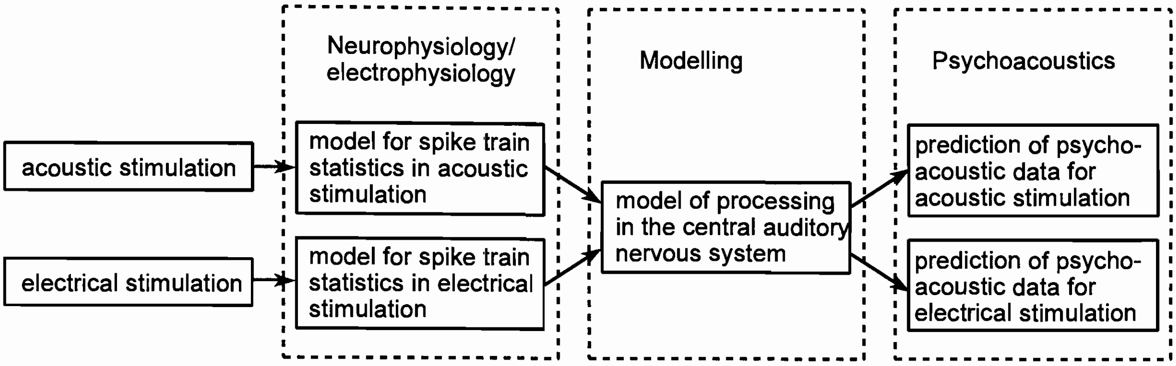

Figure 1.2.

The same underlying model of the central auditory nervous system is used to predict psychoacoustic data for both acoustic and electric hearing.

4.2 Hypothesis 2

The auditory system employs an internal model to interpret sounds

Classical detection and estimation theory as applied to auditory research asserts that the auditory system has no prior knowledge of the type of signals (speech, music, environmental sounds) that it receives. But evidence exists that the brain does use its prior knowledge to aid it in estimating input signals. A secondary hypothesis of this thesis is that the auditory system employs an internal model or an analysis-by-synthesis mechanism to estimate sounds impinging on the ear. This hypothesis is investigated in chapters 5 and 6.

4.3 Hypothesis 3

Temporal and spatial mechanisms can be explained by the same underlying neurophysiology

Mechanisms that neurophysiologists and psychophysicists interpret as "temporal mechanisms", and "frequency" or "spatial mechanisms", are based on and should therefore be explained by the same underlying neuroanatomy and neurophysiology. This hypothesis is investigated in this thesis. This is important in cochlear implants, where a trade-off between temporal and spectral resolution exists. If fewer electrodes are stimulated, higher stimulation rates may be achieved. Thus it is necessary to know what information transmitted to the electrically stimulated cochlear nerve is perceptually significant. Strategies used in current cochlear implant systems reflect different approaches. In the Spectral Peak (SPEAK) strategy (Skinner et al., 1994; Loizou, 1999), which relies on the existence of a rate-place mechanism, spectral peaks are extracted and presented to electrodes that are arranged tonotopically. In contrast, the Continuous Interleaved Sampling (CIS) strategy (Wilson et al., 1991; Loizou, 1999) assumes that it is important to conserve temporal waveform information and therefore employs high pulse-rate stimulation.

Chapters 3 and 4 employ a spatial model to predict psychoacoustic data for temporal gap detection. Chapters 5 and 6 employ spatial and temporal models respectively to obtain predictions for frequency discrimination.

4.4 Hypothesis 4

Electrode interaction in cochlear implants can be measured with gap detection

Multiple-electrode stimulation is preferred in cochlear implants, because it is generally accepted that the tonotopic organization found along the length of the cochlea in the healthy auditory system is retained to some degree for electrical hearing. Many research studies, including earlier work by Eddington (1980) and more recent studies by Nelson et al. (1995) and Donaldson and Nelson (2000), have shown that electrodes stimulating the more basal areas of the cochlea result in higher perceived pitches (or sharper tonal quality) and stimulation closer to the apex results in lower perceived pitches.

Assuming that tonotopic organization in electrical hearing is retained by multiple electrodes selectively stimulating discrete neural populations would be natural. However, the assumption that discrete neural populations can be excited is not always true. When electrodes are closely spaced, considerable overlap occurs in the neural populations excited by the stimulation current. This electrode interaction problem was addressed by (among others) Townshend and

White (1987). This is the result of spread of electrical current in the biological medium of the cochlea.

The implication of electrode interaction is that, if two electrodes stimulate the same neural population or overlapping neural populations, sound sensations elicited by the two stimuli might be confused or might even be indistinguishable. This reduces the number of independent channels of information that can be conveyed to the cochlear implant user's auditory system. Realizing that the number of independent channels of information is not equal to the number of electrodes is important in the design of processors for cochlear implants. Chapters 2 and 4 investigates the hypothesis that electrode interaction can be measured with gap detection, and shows that estimates can be obtained for the current distribution in the cochlea.

5 THESIS OUTLINE

The hypotheses summarized in 4.1 to 4.4 above is reflected in the layout of this thesis. The chapters are entirely self-contained and some of them have been published.

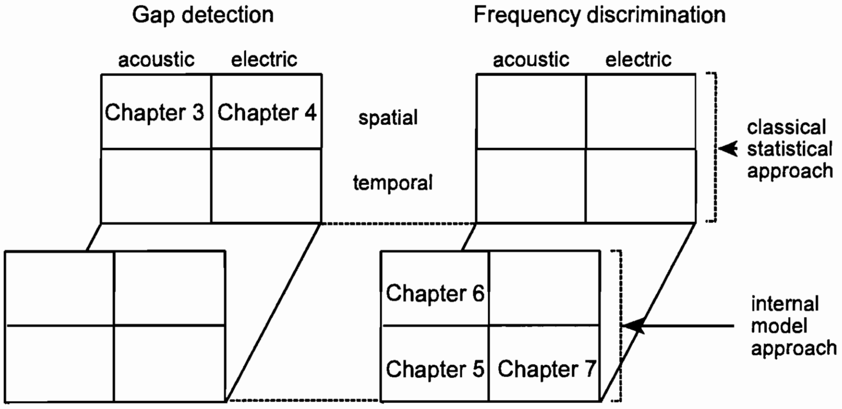

Figure 1.3.

Illustration of the multidimensional problem addressed in this thesis, and an indication of where each chapter fits in.

Figure 1.3 summarizes the layout of the thesis. The figure shows that in some chapters model are created using a classical statistical approach, while in other chapters an internal model approach is followed. Temporal and spatial models of acoustic and electric hearing are investigated, and psychoacoustic experiments that use frequency and time signals are modelled.

Chapter 2 describes psychoacoustic data for gap detection, a technique usually used for probing the temporal ability of the auditory system, but used here to measure spatial characteristics in auditory electrical stimulation. The material in this chapter has been published in Hanekom and Shannon (1998).

Chapter 3 creates a model of gap detection in acoustic hearing and shows that gap detection data can be explained in terms of spatial mechanisms.

Chapter 4 expands the model of chapter 3 for electric hearing to predict the data of chapter 2. This chapter shows that the same model used for acoustic hearing may be applied to electric hearing if the inputs are appropriate. The chapter also shows that current distribution in the cochlea influences channel interaction.

In addition, chapter 4 shows how predictions for current distributions in the cochlea may be obtained from gap detection data. Predicted current distributions (based on the gap detection data in chapter 2) are then used to predict electrode discriminability. These predictions are compared with electrode discriminability data measured in the same subjects (previously published in Hanekom and Shannon, 1996).

Chapter 5 develops a spatial model for frequency discrimination in acoustic hearing. The model is built on the concept of an internal model. A priori knowledge about spike train statistics and possible frequencies that may exist in the "external world" is used in a Markov model for the signal. A non-linear frequency estimator that observes a spatial spike train pattern then estimates the frequency of a pure tone impinging on the auditory system. The material in this chapter has been published in Hanekom (1999).

Chapter 6 develops a model for frequency discrimination in acoustic hearing, based on temporal mechanisms. This model uses a Kalman filter to estimate the pure tone auditory input frequency from temporal information in spike trains. The Kalman filter incorporates an internal model of the system that generates the spike trains and uses an analysis-by-synthesis mechanism to arrive at frequency estimates. The material in this chapter has been published in Hanekom and Krüger (2001).

Chapter 7 extends the temporal model for frequency discrimination in acoustic hearing (chapter 6) to electric hearing. The chapter then interprets psychoacoustic data obtained with cochlear implants in terms of spatial and temporal mechanisms for the coding of frequency information in the auditory system. The material in this chapter has been published in Hanekom (2000).

The thesis is concluded in chapter 8 with a summary and discussion of the main results and findings. It is shown there that the four hypotheses have been proven in a qualitative fashion.