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Abstract	Computer models of the auditory periphery provide a tool for formulating theories concerning the relationship between the physiology of the auditory system and the perception of sounds both in normal and impaired hearing. However, the time-consuming nature of their construction constitutes a major impediment to their use, and it is important that transparent models be available on an ‘off-the-shelf’ basis to researchers. The MATLAB Auditory Periphery (MAP) model aims to meet these requirements and be freely available. The model can be used to simulate simple psychophysical tasks such as absolute threshold, pitch matching and forward masking and those used to measure compression and frequency selectivity. It can be used as a front end to automatic speech recognisers for the study of speech in quiet and in noise. The model can also simulate theories of hearing impairment and be used to make predictions about the efficacy of hearing aids. The use of the software will be described along with illustrations of its application in the study of the psychology of hearing.

Chapter 2
A Computer Model of the Auditory Periphery and Its Application to the Study of Hearing

[AU3] **Raymond Meddis, W. Lecluyse, N.R. Clark, T. Jürgens, C.M. Tan, M.R. Panda, and G.J. Brown**

1 Introduction

Auditory models come in various flavours. The model to be described aims to be a faithful simulation of physiological processes in the auditory periphery with two added layers of neurons in the auditory brainstem to make detection decisions. As such, it is an anatomical/physiological model, but the aim is to use it to help understand psychophysical phenomena such as threshold, pitch processing, speech recognition and hearing impairment.

2 Model Description

The architecture of the model is shown in Fig. 2.1. A number of features are important. The model consists of many channels each with their own best frequency (BF). This reflects the tonotopic arrangement of the auditory periphery. It also consists of a cascade of stages that reflect the sequence of successive nonlinear signal processing operations in the cochlea. It also contains feedback loops representing the acoustic reflex and medial olivocochlear (MOC) efferent suppression. Nonlinear feedback systems are difficult to approach intuitively. The model therefore acts as a visualisation tool.

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[AU2]

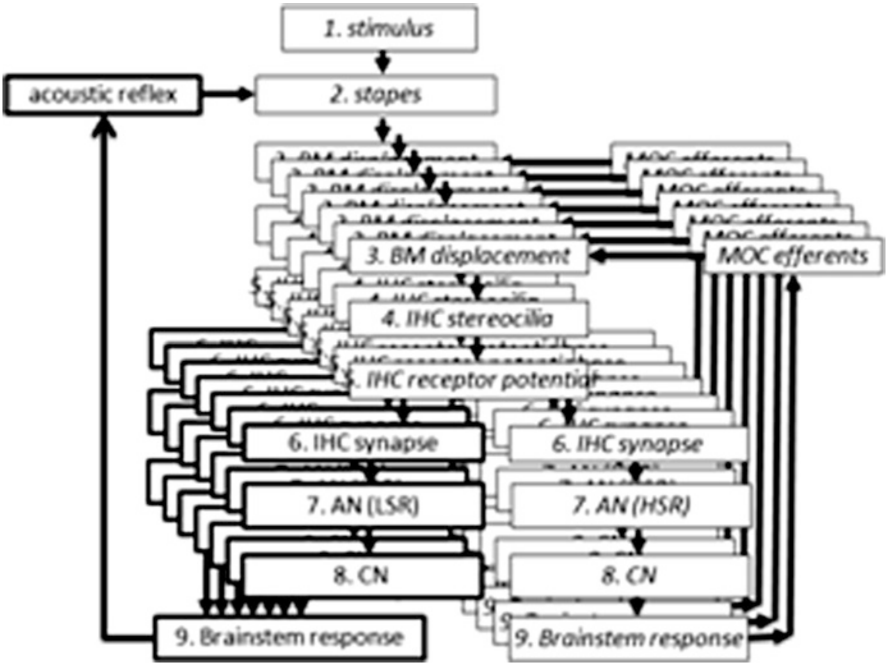


Fig. 2.1 Flow diagram of the MATLAB Auditory Periphery (MAP) model. The lower boxes on the left refer to activity driven by low spontaneous rate (LSR) fibres and forming (speculatively) part of the acoustic reflex (AR) circuit. The boxes on the right are driven by high spontaneous rate (HSR) fibres and form part of the MOC efferent circuit. *CN* cochlear nucleus

Of course, such a model is only as good as its components. Fortunately, the output of individual modules can be evaluated against published physiological data. The output of each stage is expressed in terms of measurable variables such as stapes displacement, basilar membrane (BM) displacement, inner hair cell (IHC) receptor potential, auditory nerve (AN) firing rate and the pattern of firing in individual brain stem neuronal units. The architecture of the model allows us to carry out pseudo physiological experiments by applying acoustic stimulation while measuring the response at the output of a particular stage and then checking against corresponding published data.

Figure 2.2 shows the output of the model at a number of stages in response to the word ‘twister’ presented at 50 dB SPL. Successive panels show the stimulus, the stapes response, a 21-channel BM response as well as three levels of neuronal response; the AN, cochlear nucleus (CN) chopper response and a second-level brainstem response. Figure 2.2b shows the multichannel activity in the MOC efferent. The AR is not activated at this stimulus intensity. Each panel represents an ‘inspection window’ for the corresponding stage.

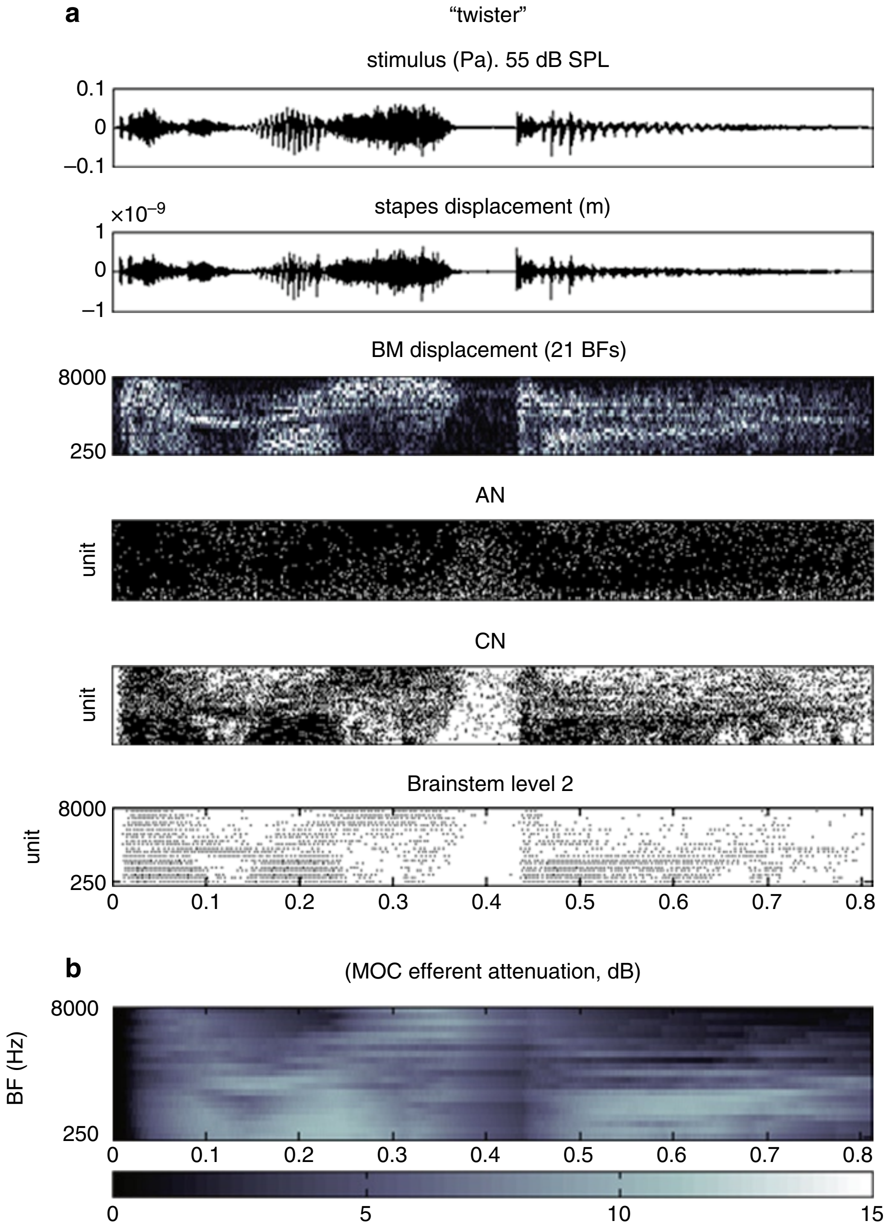


Fig. 2.2 Output from the auditory model. (**a**) Stimulus and output from five stages of the afferent part of the model (stapes, BM, AN, CN chopper, 2nd-level brainstem units). *X*-axis is time. (**b**) Activity in the efferent pathway of the model; time x channel attenuation of nonlinear DRNL input

3 Model Applications

The model is not just a computerised visual display. It has a number of applications. One is to use the AN spiking pattern as the 'front end' to another system that represents a theory of how sensory decisions are made. In the past we have used it as the input to an autocorrelation model of pitch processing and segregation of simultaneous vowels presented with different pitches. Indeed, the majority of requests from potential users of the model concern the need for a front end of this type.

One might expect that a good auditory model should make an ideal front end to an automatic speech recogniser with recognition performance close to human levels. Good performance can be achieved for speech presented in quiet but performance declines substantially in the presence of background noise. This has led us to include a simulation of the peripheral efferent system in the model because it moderates the strength of the system's response in proportion to the intensity of the background. This reduces the spread of excitation across frequency channels and produces a more stable representation. The model components representing the efferent system were first evaluated against the physiological data and then tested in studies using automatic speech recognition (ASR) techniques. The modelled efferent system includes both a MOC arrangement and a simulation of the acoustic reflex. It was possible to compare speech recognition as a function of signal-to-noise ratio (SNR) both with and without the benefit of the closed-loop multichannel efferent reflex. The unfilled squares in Fig. 2.3 show how poorly the unimproved model works as an auditory front end. A 50 % recognition rate requires 15-dB SNR. However, when the efferent pathway is enabled, performance is greatly improved. At 10-dB SNR the recognition rate rises from 30 to 90 %. The modelling exercise does not prove that the MOC is critical for perception of speech in noise, but it does illustrate how modelling can be used to explore the hypothesis. The results also show that human performance remains much better than that of the model!

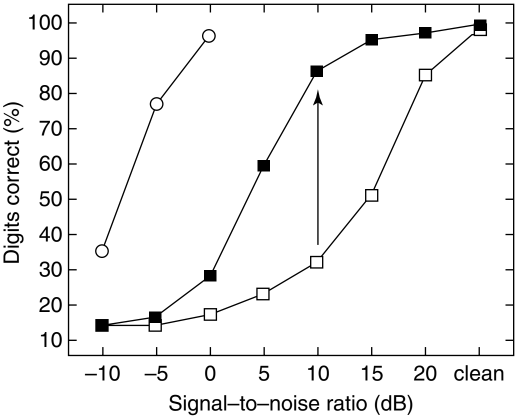


Fig. 2.3 ASR performance (% correct) as a function of SNR. The speech was connected digit triplets using both male and female talkers. The 'noise' is 20-talker babble. Representative human performance on the same test is shown as *unfilled circles*. Model performance without the efferent system is shown as *unfilled squares*. Improved performance using the efferent system is shown as *filled squares*

4 Psychophysics

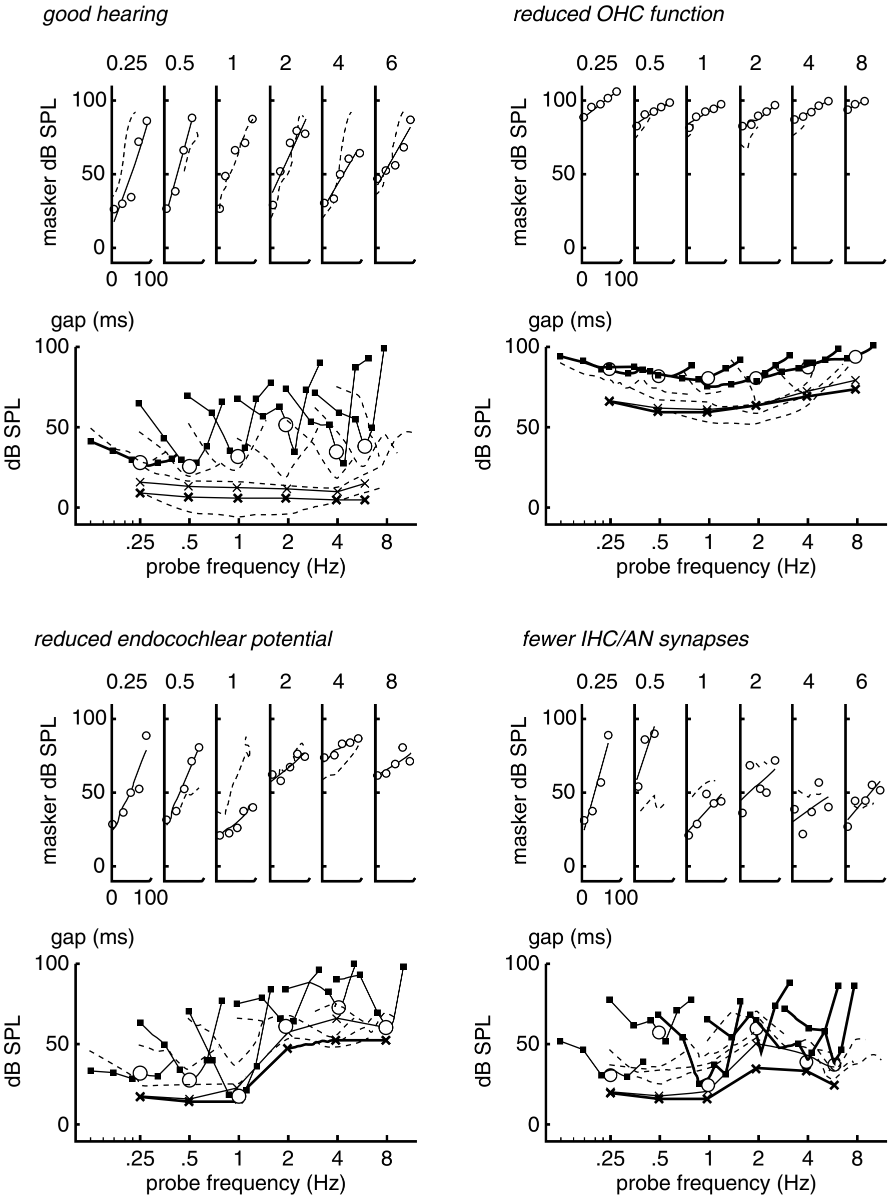
Models can help understand the relationship between hearing and the underlying physiology by comparing model performance with that of human listeners in psychophysical experiments. Of course, some principle must first be established to convert the model multichannel output to a simple psychophysical response. For example, in a single-interval, adaptive tracking paradigm, the output must be converted to a 'yes' or 'no' response. Simple tasks such as detecting a tone against a silent background can be performed by creating neuronal units that never (or very rarely) spike in silence. Any response in any one of them can, therefore, be used to indicate that something has been detected.

The psychophysics of the model has been studied using three tasks: absolute thresholds, temporal masking curves (TMCs) to assess compression and psychophysical tuning curves (PTCs) to assess frequency selectivity. The latter two measurements use a forward-masking procedure where a target tone is presented *in silence* after the end of a pure-tone masker and therefore meets the basic requirement for using the model. In this way both human listeners and the MAP model can be tested using the same adaptive tracking software. All three tests were repeated in six different frequency regions. The complete set of measurements is called the hearing 'profile'. Figure 2.4 compares examples of profiles obtained using models and individual listeners. Figure 2.4a shows a profile of a young man with good hearing (dashed lines) and compares it with a profile obtained with the model. This 'good-hearing' model can then be used as a starting point for examining the consequences of different kinds of physiological pathology. Figure 2.4b shows the effect of reducing the contribution of outer hair cells (OHCs). A reduction of endocochlear potential has the effect shown in Fig. 2.4c, while Fig. 2.4d shows the effect of a reduction in the density of IHC/AN fibre synapses.

In each case, the pathology is simulated by changing only *one* parameter value relative to the 'good-hearing' model. In all cases, the pattern of response contains surprises that take some time to understand. This applies particularly to how the same parameter change can produce different responses at different frequencies. The profiles often have marked similarities to some of the auditory profiles measured in our hearing impaired volunteers. In each case, a real profile is presented for comparison (shown as dashed lines). A similarity between the pathological model and the individual's profile does not prove that the human subject has that particular pathology, but it is a working hypothesis supplied by the model.

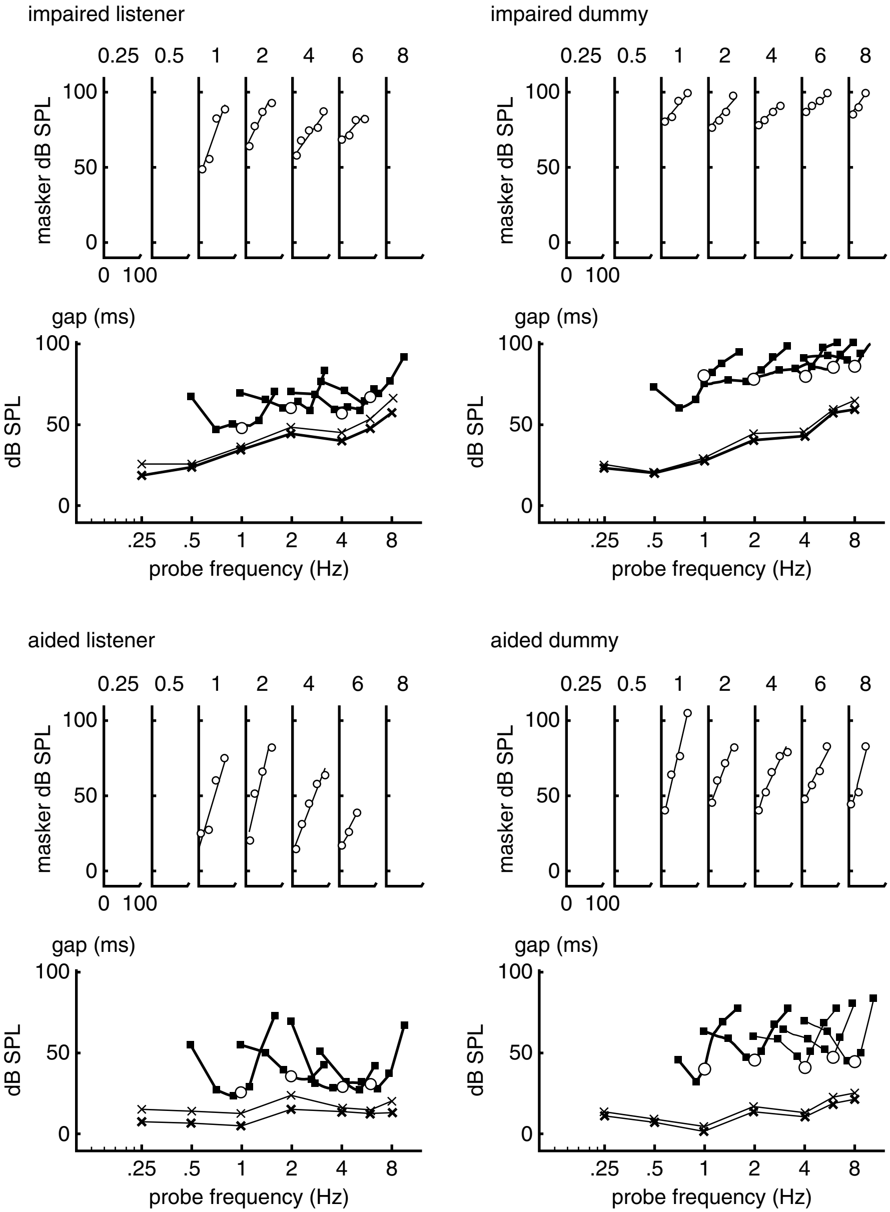
5 Hearing Dummies

The original motivation for measuring patient profiles was to establish 'hearing dummy', models of the hearing of individuals with specific hearing impairments. The idea is to use these dummies for optimising the tuning of hearing aids for a given individual and to study the benefits of different hearing aid designs. The example illustrated in Fig. 2.5 shows the profile for an impaired listener (Fig. 2.5a)



[AU4]

Fig. 2.4 Hearing dummies. (**a**) Good hearing. (**b**) Reduced OHC function (nonlinear path gain reduced to 6 % of original gain). (**c**) Reduced endocochlear potential (−65 mV, reduced from −100 mV). (**d**) Reduced IHC/AN synapses (reduced to 40 % of original density). In each panel, the *top row* shows TMCs at each probe frequency (in kHz). The *lower panel* shows PTCs and, below them, absolute thresholds for 16- and 250-ms tones. The continuous lines are model data. The *dashed lines* are profiles from human listeners (‘NH83_R’, ‘IH11_R’, ‘IH19_R’ and ‘IH73_R’) with profiles similar to the dummies



[AU4]

Fig. 2.5 (**a**) Auditory profile for a listener with a high-frequency hearing loss. (**b**) Profile for a corresponding hearing dummy. (**c**) Profile for the impaired listener when using the hearing aid. (**d**) Profile for the dummy when the hearing aid was used at the input to the dummy and the corresponding hearing dummy (Fig. 2.5b). When a new kind of hearing aid algorithm is used at the input to the dummy, the aided-model profile (Fig. 2.5d) becomes more similar to the good-hearing profile (see Fig. 2.4a). When the impaired listener is tested again (Fig. 2.5c) with the same aid settings as the model, the measured profile moves closer to the profile for good hearing.

An interesting feature of this example concerns the restoration of narrow V-shaped PTCs. The hearing aid used here was configured to restore natural instantaneous compression. The aid's algorithm is based on the architecture of the MAP model itself and represents a spin-off from the modelling exercise. However, the restoration of narrow V-shaped PTCs was not anticipated. On reflection, it could be explained by the fact that low-intensity maskers are compressed less than high-intensity maskers. There is, of course, no suggestion that the resonance characteristics of the impaired BM have been changed at all.

6 Discussion

While it is tempting to ask which one of the many auditory models now in existence is the best one, it would be a mistake to choose one and disregard the rest. Different auditory models are not just different theories; they also serve very different purposes. Each model should be judged both in terms of how well it reflects reality and how well it serves its purpose. The special function of the MAP model is to assist visualisation of what might be happening during hearing at a physiological level in the auditory periphery.

With the MAP model much of the modelling effort is concentrated on perfecting the individual physiological modules and using realistic values for the parameters where these are known. The aim is to understand good and impaired hearing in terms of the underlying physiology and, where appropriate, its pathology. To a large extent the psychophysiological properties of the MAP model are emergent properties and sometimes come as a surprise. This was certainly the case when narrower V-shaped PTCs resulted from the application of the hearing aid algorithm (Fig. 2.5d). The selective loss of high-frequency sensitivity when the endocochlear potential was reduced (Fig. 2.4c) was also unexpected, and its explanation is subtle. The cookie-bite pattern resulting from a reduction in the number of IHC/AN synapses in Fig. 2.4d is a recent finding that remains puzzling.

Equally surprising was the finding that the MAP model had lower psychophysical thresholds for longer tones even though the model contained no component resembling an integrator.

The effect can be seen clearly in Fig. 2.4a where thresholds for a 16-ms tone (thin upper line) are consistently higher than those for a 250-ms tone (thick lower line). An integrator would be required by traditional explanations of this effect. On reflection, it was found that the reduced thresholds could be understood in terms of the probabilistic nature of the response of the decision neuron.

The software for general auditory modelling, measuring auditory profiles and running hearing dummies can be downloaded from the internet at http://www.essex.ac.uk/psychology/department/HearingLab/Welcome.html.

7 Conclusion

Computer models of the physiology of the auditory periphery can be used to explore normal and impaired hearing and sometimes spring surprises.

Author Queries

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Queries	Details Required	Author's Response
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AU2	Please provide better quality figure.	
AU3	Please provide full given names in W. Lecluyse, N.R. Clark, T. Jürgens, C.M. Tan, M.R. Panda, and G.J. Brown	
AU4	Please provide part labels in artwork of Figures 2.4 and 2.5.	