EXPERIMENTS IN HEARING

Georg von Békésy

TRANSLATED AND EDITED BY

E. G. Wever

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PREFACE

This book brings together in one volume the chief results of a series of experimental studies on hearing and related problems extending over a period of 34 years. The earlier experiments, from 1924 to 1946, were carried out in the Royal Hungarian Institute for Research in Telegraphy in Budapest, those in 1947 in the Department of Telegraphy and Telephony of the Royal Institute of Technology in Stockholm, and the ones since that time in the Psycho-acoustic Laboratory of Harvard University. I am deeply grateful to the directors and staffs of all these institutions, and especially to Professor S. S. Stevens and Professor E. B. Newman, for their generous provision of facilities and technical help. In my work at the Psycho-acoustic Laboratory I am especially indebted to Mr. Ralph Gerbrands and Mr. Rufus L. Grason for their assistance in the development of mechanical and electrical equipment, to Miss Geraldine Stone for aid in the preparation of the papers published in English, and to Mrs. Elizabeth Gardner for her work in the production of drawings. Research in hearing is of such a complex and exacting nature that it would be difficult to proceed without advantage of the knowledge and skills of many other persons.

The original articles appeared in numerous technical journals, access to many of which is now difficult. More than half of them were written in German, the others in English, and all necessarily adhered to the special requirements of the various journals and editors. For this book the German articles have been translated into English, and all have been edited to produce a uniform style.

For this work I am indebted to Professor E. G. Wever, and it is proper to say that this presentation was made possible by his willingness to assume the task. Probably many persons cannot appreciate the labor that is involved in an undertaking of this kind to the extent that I do, who have shifted about in this troubled world to so many countries and have learned and forgotten so many languages. It is almost a unique privilege to have this aid from someone working in the same field of research and conversant with its problems and technicalities.

It should be emphasized that the presentations adhere to the original articles, and the interpretations of problems and results reflect the evidence at hand when the research was carried out. In one or two instances, when later work has led to a change in viewpoint, this fact is pointed out in a footnote. Also a few typographical and other errors have been corrected.

The articles are grouped by subject, and the arrangement bears only a limited relation to the temporal order in which the experiments were performed. Part 1 is introductory. It presents two short chapters of new material on the nature of auditory problems and the historical development of our knowledge about the anatomy of the ear, and then includes two other chapters on anatomical techniques and experimental methods. The technical material of these last two chapters has been extracted from the experimental articles and assembled here so as to avoid needless repetition later on. The remainder of the book consists of the articles in their original form except for the extractions just mentioned and a few other deletions that are referred to at the proper places. Part 2 is concerned with the process of sound conduction in the ear, Part 3 with several aspects of the psychology of hearing, and Part 4 with the mechanical and physiological processes of the cochlea and its associated nervous system.

I should like to express my deepest gratitude to Sũzanne Wever for the typing of the manuscript. The care and precision with which she performed this task contributed greatly to reduce the number of errors.

Georg von Békésy

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PREFACE

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Columbus, Ohio

CONTENTS

PART 1

INTRODUCTION

CHAPTER 1

THE PROBLEMS OF AUDITORY RESEARCH

The experiments with which this book is concerned were begun when the field of acoustics was just approaching its modern period. The rapidly growing science of electronics was providing new and precise instruments for the production and measurement of sounds, and many new methods were being worked out for registering the effects of sounds on the ear. Some of these methods were physical, others were physiological or electrophysiological, and still others were psychological, involving the observations of human subjects. All three types were utilized in the experiments that are reproduced here, and often all of

FIG. 1-1. A Persian miniature painting of the fifteenth century.

them were applied to the solution of a single problem. Because results always flow from the procedure that is used, and because there has been almost a revolutionary development of techniques in acoustics during the decades covered by these studies, this chapter will be devoted to a discussion of auditory problems in relation to methodology.

A primary consideration is the problem to be investigated, how it is approached, and how it is envisaged in relation to what is already known. It is possible to distinguish two forms of approach to a problem. One, which may be called the theoretical approach, is to formulate the problem in relation to what is already known, to make predictions or extensions on the basis of accepted principles, and then to proceed to test these hypotheses experimentally. Another, which may be called the mosaic approach, takes each problem for itself with little reference to the field in which it lies, and seeks to discover relations and principles that hold within the circumscribed area.

A close analogy to these two approaches may be found in the field of art. In the period between the eleventh and seventeenth centuries the Arabs and Persians developed a high mastery of the arts of description and portrayal, and they used the mosaic style. An example is given in Fig. 1-1, which shows a Persian miniature painting of a betrothal. The various persons and objects are represented individually, spread out as though on a carpet, and with little perspective or relation to one another.

Later, during the Renaissance, a new form of representation was developed in which the attempt was made to give unity and perspective to the picture and to represent the atmosphere. An example of this form of art is shown in Fig. 1-2.

When in a field of science a great deal of progress has been made and most of the pertinent variables are known, a new problem may most readily be handled by trying to fit it into the existing framework. When, however, the framework is uncertain and the number of variables is large the mosaic approach is much the easier.

Many of the experiments to be described in this book employed the mosaic approach, but when considered in connection with other experiments carried out subsequently by the author and by many other workers in this field they take on a broader meaning and perhaps now may be woven into a more general structure.

Of great importance in any field of research is the selection of problems to be investigated and a determination of the particular variables to be given attention. No doubt the verdict of history will be that the able scientists were those who picked out the significant problems and pursued them in the proper ways, and yet these scientists themselves would probably agree that in this phase of their work fortune played a highly important role. When a field is in its early stage of development the selection of good problems is a more hazardous matter than later on, when some general principles have begun to be developed. Still later, when the broad framework of the science has been well established, a problem will often consist of a series of minor issues.

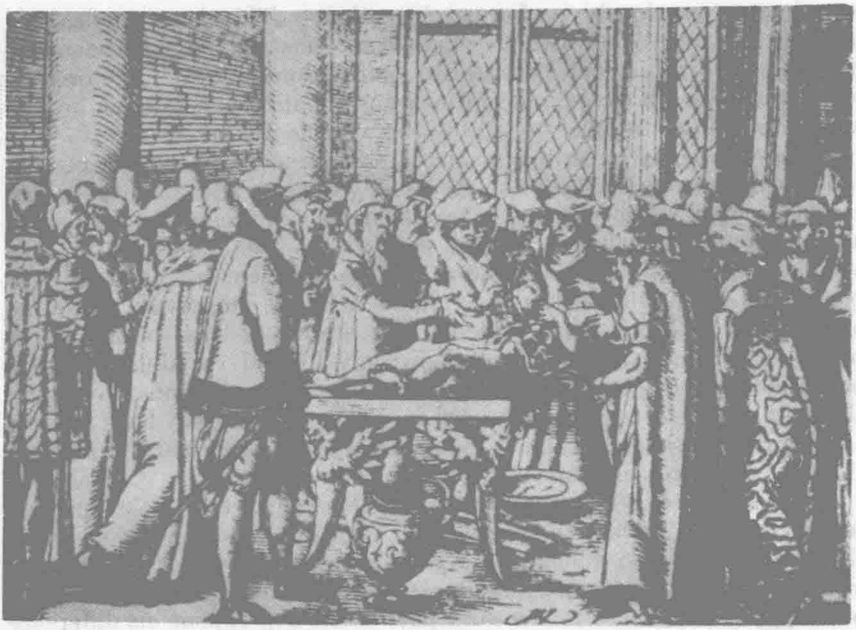

FIG. 1-2. A woodcut of the Renaissance period, sixteenth century.

Problems arise in a variety of ways, and it is often worthwhile to list the forms that they may take. Thus we can distinguish the following:

1. The classical problem, which has had much effort expended upon it, but without any acceptable solution.

2. The premature problem, which often is poorly formulated, or is not susceptible to attack.

3. The strategic problem, which seeks data on which a choice may be made between two or more basic assumptions or principles.

4. The stimulating problem, which may lead to a reexamination of accepted principles and may open up new areas for exploration.

5. The statistical question, which may be only a survey of possibilities.

6. The unimportant problem, which is easy to formulate and easy to solve.

7. The embarrassing question, commonly arising at meetings in the discussion of a paper, and rarely serving any useful purpose.

8. The pseudo problem, usually the consequence of different definitions or methods of approach. Another form of pseudo problem is a statement made in the form of a question. It also is often the result of discussions in meetings.

It is frequently helpful to attempt to place a given problem in this array of possibilities, for such a classification may provide a hint as to the problem's significance, the difficulties involved in its attack, and the sort of solution that may be expected.

A considerable amount of scientific work consists in the repetition of experiments previously performed by others. This is a particularly onerous task, partly because the conditions of the original experiment are not described in full, and because the motivation is poor. The original work was done with care and enthusiasm, but its repetition can be dull and uninspiring. Almost inevitably the work is rushed through.

In psychological experiments an important matter is the type and number of subjects. These two are usually related, and the investigator can use a small number of highly trained subjects for extended periods or a large number of slightly trained subjects for brief times. Both procedures have their uses according to the problem at hand. When basic phenomena have to be explored and the important variables identified it is best to use subjects that are trained as thoroughly as possible. A trained subject will show only limited variability, largely because he is able to keep his attention on the phenomena under investigation and to ignore irrelevancies. On the other hand, it may be of interest to discover the range of capacities in a population, and then it is obvious that a great many subjects are needed.

In any event, it is necessary to train every subject to some extent and to instruct him in the phenomena that are to be reported. Sometimes there are unexpected difficulties in this regard, as an example will make clear. In the experiments on loudness discrimination one of the subjects was a gypsy violinist. In the early part of the experiment his difference limens were enormous, far out of the range of the other subjects. His pitch limens, however, had about the usual values. After much probing it finally developed that he was paying little attention to loudness changes, and the reason for this was that in gypsy music only the pitch is considered an important variable and the loudness is kept relatively uniform. After this situation was understood by the subject, and deliberate training in loudness perception was carried out, his loudness limens fell to normal values.

In the research described in the following chapters the emphasis is upon obtaining numerical values. When such values are lacking it is hardly possible to make a decision among competing hypotheses. An example will make this point clear. Perhaps the most significant measurement in relation to the operation of the cochlea is that of the volume elasticity of the basilar membrane. This value alone can determine whether the basilar membrane vibrates according to a standing-wave theory, a traveling-wave theory, a resonance theory, or a telephone theory. It is not always easy, however, to decide what numerical values are of real importance. Usually a great deal of preliminary work is necessary to discover what variables or constants are of essential value.

There is also the question of the time to be expended in the obtaining of numerical values. One way of increasing precision and also of saving time is to make the presentations as automatic as possible. Of course a certain balance has to be struck between the time saved by automation and the time and effort that have to be expended in setting up the special equipment. However, there is an added gain in many experiments, especially those involving psychological judgments, because the automatic arrangement helps in generating a stabilized atmosphere. In the writer's experience it is good practice in psychological investigations to have a subject in a room alone with the apparatus, with the instruction to press a button when he is ready to make an observation. The system is designed to make the presentation, record the subject's judgment on a paper strip, and then stop until the button is pressed once more. Under these conditions there is no distraction from the presence of another person, and the subject is able to choose the moment when he can give the task his full attention.

A real difficulty with automatic equipment is that it increases the number of data. As a consequence there is a pressure to use statistical methods in evaluating the results. This procedure can greatly alter the problem, or even transform it to something out of all resemblance to the original one.

In scientific work there is always a difficulty in deciding when an experiment should be considered as completed. Most experiments are begun with a definite goal in mind, and there is a strong impulse to stop when this goal is reached. If the goal is not reached on the first attempt the procedure is altered and improved, and this activity continues until the expected results are obtained. It is obvious that this behavior operates so as to bias the investigation in a certain direction. Mistakes that lead away from the goal are corrected; those that lead to it are unnoticed. If the variance of the experiment is large this procedure almost surely leads to wrong conclusions. The writer has found it profitable to carry on a series of experiments for a month or so beyond the point where everything seemed complete and ready for publication. Almost invariably this somewhat aimless working with the equipment has brought out new aspects of the problem and rounded out the final conceptions. Sometimes it has led to new kinds of observations.

It is particularly difficult to determine when a negative experiment should be concluded. It is hardly ever possible to prove the negative of a proposition, and it has come to be a rule of thumb to bring a piece of work to a close after negative results have been obtained ten times in succession. Yet someone has pointed out that ten consecutive failures to circumnavigate the globe did not prove that the earth was flat. Perhaps the most interesting negative experiment in the field of physics was the one concerned with perpetual motion. Hundreds of failures did not seem to be convincing. Yet out of these failures came the development of the three laws of thermodynamics. On the basis of these laws it became possible to make positive statements that could be either proved or disproved with a single experiment, and the result was a transformation of a long period of stagnation into one of great progress. The same has happened in other fields of science, and thus it is comforting that even failure may sometimes have its benefits.

One of the most important features of scientific research is the detection and rectification of errors. The writer believes that positive results and failures ought to be discussed together. Only by such complete reporting can we get a true conception of a piece of work, of the manner of its development, and of the limitations of its principles.

One way of discovering errors is to repeat the same measurements by different methods. If the same results are obtained by widely differing methods we can feel reasonably confident of their reliability. A way of avoiding errors is to work in a team. The several members can supplement one another's skills and check the procedures. In team research, however, it often happens that the dull, routine work is left to the younger

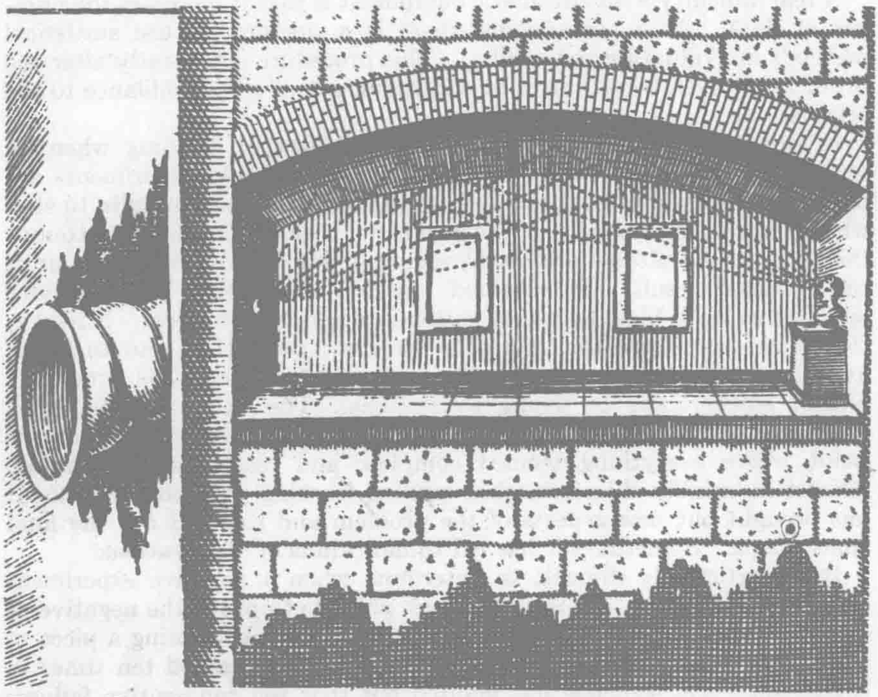

FIG. 1-3. The reflection of sound waves on the ceiling of a room, as represented by Kircher, 1650.

members and not checked by the more experienced. If, for example, the least able individuals are given all the calibrations to do, their mistakes can affect all the results.

Another way of dealing with errors is to have friends who are willing to spend the time necessary to carry out a critical examination of the experimental design beforehand and the results after the experiments have been completed. An even better way is to have an enemy. An enemy is willing to devote a vast amount of time and brain power to ferreting out errors both large and small, and this without any compensation. The trouble is that really capable enemies are scarce; most of them are only ordinary. Another trouble with enemies is that they sometimes develop

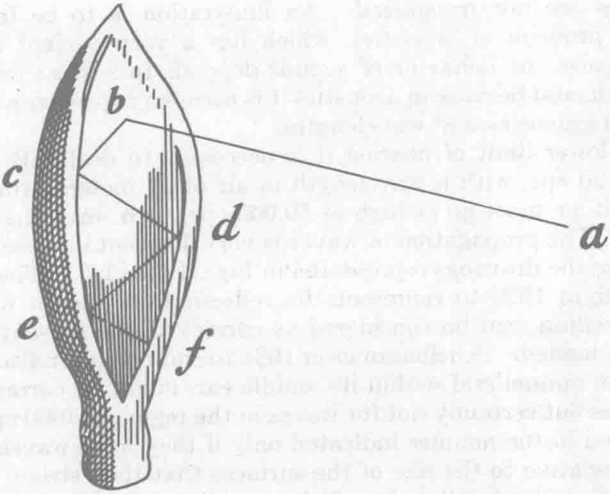

FIG. 1-4. The reflection of sound waves in the pinna of an animal, according to Schelhammer, 1684.

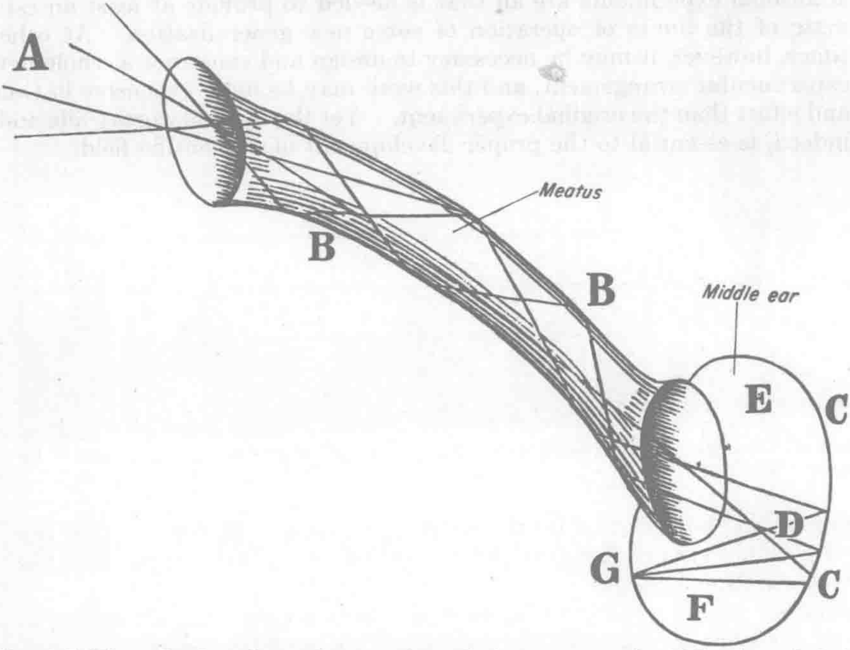

FIG. 1-5. The reflection of sound waves through the meatus and middle ear and their concentration on the cochlear window, according to Schelhammer.

into friends and lose a good deal of their zeal. It was in this way that the writer lost his three best enemies.

A further question concerns the boundaries within which a principle may be considered as valid. Serious errors can be made when such