Disorders of Human Communication 1

Edited by G.E. Arnold, F. Winckel, B.D. Wyke

E. D. Schubert
Hearing: Its Function and Dysfunction

Springer-Verlag Wien GmbH

Prof. Earl D. Schubert

Stanford Medical Center
Stanford, California, U.S.A.

Originally published by Springer-Verlag/Wien in 1980
Softcover reprint of the hardcover 1st edition 1980

With 86 Figures

Library of Congress Cataloging in Publication Data. Schubert, Earl D. 1916—. Hearing, its function and dysfunction. (Disorders of human communication ; 1.) Bibliography: p. Includes index. 1. Hearing disorders. 2. Hearing. 3. Psychoacoustics. I. Title. II. Series. [DNLM: 1. Ear-Physiology. 2. Hearing disorders. 3. Hearing. W1 DI762 v. 1 / WV270 S384h.] RF290.S4. 617.8'86. 80-23338

ISBN 978-3-7091-3363-7 ISBN 978-3-7091-3361-3 (eBook)
DOI 10.1007/978-3-7091-3361-3

Editors' Foreword

This volume is one in a series of monographs being issued under the general title of "Disorders of Human Communication". Each monograph deals in detail with a particular aspect of vocal communication and its disorders, and is written by internationally distinguished experts. Therefore, the series will provide an authoritative source of up-to-date scientific and clinical information relating to the whole field of normal and abnormal speech communication, and as such will succeed the earlier monumental work "Handbuch der Stimm- und Sprachheilkunde" by R. Luchsinger and G. E. Arnold (last issued in 1970). This series will prove invaluable for clinicians, teachers and research workers in phoniatrics and logopaedics, phonetics and linguistics, speech pathology, otolaryngology, neurology and neurosurgery, psychology and psychiatry, paediatrics and audiology. Several of the monographs will also be useful to voice and singing teachers, and to their pupils.

August 1980

G. E. Arnold, Jackson, Miss.
F. Winckel, Berlin
B. D. Wyke, London

Preface

Despite years of interest and research in the hearing process, much of the exact detail of auditory processing remains in the realm of conjecture. We *do* have some rudimentary understanding of the way the system records changes in frequency and intensity and of the relations between the ear's spectrum analysis and our identification of sound quality. Some of these operations we can duplicate with auditory models of our own, or with laboratory analyzers that can serve as auditory analogs. But the complex, rapidly-changing signals that constitute speech, for example, are processed with a very low error rate by the normally-operating auditory system; and this is accomplished even in the presence of interference or distortion that would render our other sophisticated analyzing systems virtually useless.

This low ceiling on our comprehension of the system is distressing, but fortunately it does not greatly diminish the interest in the auditory process of many experts in fields related to hearing. It is primarily for this group of interested scholars that this book has been written—specifically those with expertise in a related field such as medicine, psychology, physics, engineering, etc. For this reason an effort has been made to keep the treatise brief enough to avoid burdening the interested outsider with more than he wishes or needs to know about hearing. In the same vein, very little time is spent on historical background. For the student who intends to make hearing itself his specialty, this work provides a highly useful overview and many convenient signposts directing the reader to supplementary information.

With this same group of experts in mind, it is not necessary to repeat the basic technical background information required for understanding what we currently can explain of the operation of the auditory system. The beginning audiologist, for example, might find it necessary to fill elsewhere his need for some grounding in elementary principles of sound transmission, basic physiology and neurophysiology, and experimental psychology in order for the material as presented here to be sufficiently comprehensible.

Several topics, among them the role of the auditory system in the perception of music, and the principles of the processing of speech are quite fully covered in other volumes of this same series, but they come in for some attention here because such integrated responses definitely influence our analysis of certain specific auditory dimensions or operations.

For a fairly cohesive overview of the hearing process, reading the chapters in order is the recommended procedure. For a reader whose immediate interest is in a specific aspect, the separate chapters are reasonably independent and contain sufficient references to be of additional guidance.

Not much space is given to auditory theory, since what theories we do have encompass very narrow aspects of auditory operation and fall woefully short of accounting for anything save the most elementary aspects of auditory processing. In contemplating the everyday usefulness of the auditory system as a sense organ we have no theory comprehensive enough to be worth the telling. This is intended not so much as a comment on our shortcomings as scholars in audition but rather as a recognition of the complexity and versatility of the system.

In acknowledging contributions to a treatise of this sort, it's difficult to be appropriately comprehensive. Intellectually, my debt is to a great many of my fellow students of the auditory system—those whose writings and discussions have fashioned our mutual understanding of the total hearing process. Some are cited herein, but of course many are more indirectly represented. Finally, in the technical aspects of turning a manuscript into a book, I am most beholden to my willing and able spouse who took over all concerns about proper organization and form, and made certain I could concentrate on the task of writing.

Stanford, Calif., August 1980 **Earl D. Schubert**

Contents

Introduction

There can be little doubt that a highly diversified auditory system is a primary factor in the development of the species. The complexity of audible communication is perhaps the most discernible way in which humans excel over other animals, spoken language being possibly the most useful accomplishment in the evolution of modern man. Through the auditory channel we also receive a great deal of information about relevant happenings in the environment, but whether the human system is more versatile than other forms in interpreting non-speech sound is not so easily verified.

When we add the sounds of music to our perceptual repertoire, it seems almost self evident that the human auditory system processes a wider variety of signals than any other. Musical sounds are an especially interesting class of auditory signals, since it is difficult to find a close analog in the environment. There are few, if any, naturally occurring sequences of sound that are inherently esthetically pleasing. In vision, the artist finds scenes and patterns in nature that may be almost universally recognized as intrinsically pleasing or beautiful. In audition, pleasure from sound patterns or sequences springs almost entirely from artificially-fabricated sequences. And even though the sequences and the structure of tones may differ widely in different cultures, the existence of some pleasurable auditory ensemble seems to be universal, as does also the existence of a spoken language. So complete is our preoccupation with speech and music that by far the greater involvement with sound, at least in the modern world, centers on perception of sounds which man produces rather than on other useful sounds from the environment. How much this has influenced the evolutionary development of the human auditory system is a fascinating but presently imponderable question.

Interest in the mechanical operation of the ear is nearly as old as recorded history; but as one might expect, it originally had to do with only the visible component of the system. The external ear, according to an Egyptian papyrus dated around 1500 B.C., is the organ of hearing and also has some function related to respiration. One supposes this might be occasioned by noting the sensation of pressure equalization through the Eustachian tube.

The auditory nerve seems to have been located next, long before recognition of the middle ear and inner ear. Such a situation was not conducive to meaningful analysis of mechanical auditory function. Pythagoras, who noted that numerical simplicity of tonal ratios corresponded to heightened blend in the resulting auditory sensation had no knowledge of the anatomy of the cochlea. Nearly two centuries later Aristotle promulgated the idea of the "aer internus", the pocket of internal air behind the eardrum that was supposedly responsible for reproducing the external condition inside the body where it could be read by the internal mechanism responsible for auditory sensations.

Largely because of strictures against anatomical research by the prevailing religions, this doctrine was not challenged until the 16th century. It was still the explanation given in Koyter's book on the ear published near the close of that century. But Vesalius showed two of the small middle-ear bones in his textbook on anatomy, though not in their normal position; and late in the 17th century the form of the inner ear was quite clearly shown in DuVerney's treatise on the ear.

By the time of Helmholtz, great strides had been made and the major anatomy of the inner ear was nearly completely known; the conduction of sound in air, liquid and solids had been established, and the relation of vibrating frequency to perceived pitch had been pointed out by Galileo. Helmholtz put much of this knowledge together in formulating his hypothesis that the auditory system responded differently to different frequencies because the ear itself contained a series of tuned elements (resonators), each of them connected to a different nerve or set of nerves.

This was not the first of the resonance theories; the resonance mechanism had been invoked to explain how sound from the outside could be sensed by the brain as early as 1605 by Bauhin. Later DuVerney employed the principle to account for the separation of high and low frequencies by the ear. These are the simplest forms of the "place" theory of hearing—that the pitch of a tone is dictated by the place of stimulation, or by implication the place of origin of the responding fibers. Some interesting arguments ensued about the specific elements that could resonate suitably, and our later discussion of the structure of the inner ear will make it clear that argument could easily arise. Yet Helmholtz structured for the time a rather elegant theory. It involved an extension of Müller's doctrine of specific energy of nerves. Müller's original exposition stated that the kind of sensation experienced was determined by the particular nerve that was stimulated. Helmholtz' formulation by implication, called for different fibers of the same nerve to elicit different pitches. It also invoked the recently-formulated Ohm's law of acoustics—that the ear analyzes a complex periodic waveform into its constituent sinusoidal components.

Helmholtz' theory was accepted at first, but then became the point of departure for a host of competing theories. As is usual in the absence of direct observation or measurement, explanations proliferated and argument flourished. Békésy's direct observation of the cochlea in action sounded the death knell for many of the mechanical hypotheses, and truly ushered in the modern era of auditory research.

During the period of Helmholtz' contribution, the study of hearing was accelerated and expanded also by rising interest in the study of psychophysics—the relation between the physical stimulus to the sense organs and the resulting sensation or perception. Particularly in Germany during this period, and later in America, experimental psychologists were engaged in systematic study of responses to visual and auditory signals in the environment. Especially in audition, the advent of electronic instruments and the parallel interests of telephone engineers had a highly beneficial effect.

Our current state of understanding of the very complex operation of the auditory system is the result of individual and cooperative effort by physicians, psychologists, physiologists, engineers and audiologists. The complexities of the human visual and auditory systems are such as to tax the explanatory capabilities of the scholars who essay to understand them. So far each new discovery seems to elevate the level of description required rather than bring us closer to complete explanation. The present treatise, therefore, is destined to leave the reader with the impression that we understand the system as a complete sensory system only at a very superficial level. We know disturbingly little of the actual nature of the processing of speech or music by the system. We cannot explain how it comes about that it separates simultaneous signals far better than our own laboratory devices or computer programs, or how it operates so comparatively well in reverberant noisy environments. Perhaps the most heuristic view of this state of affairs is that it is consequently even more imperative that we continue to view what presumably *has* been established with proper skepticism, and where necessary entertain more than one tenable view of those areas that are still poorly verifiable.

This is the only attitude that seems defensible to the writer, and it is urged upon the reader throughout the remainder of this book.

Part I
Anatomy and Physiology of the Auditory System

Outer Ear 1

A highly schematized view of the parts of the peripheral auditory system is shown in Fig. 1. It is drawn for clarity rather than accuracy, and serves, for our present purposes, to highlight the relation between the outer ear and the eardrum. For reasons touched on in the introduction, the external ear has been a subject of interest longer than the rest of the system.

One of the questions seriously discussed about the time of Aristotle was "Why are man's ears stationary?" We may decide to revive this question when we discuss localization of sound. A more easily answered common-sense question about the external ear would be "Why is the eardrum so well hidden from the acoustic environment?" The easiest answer is that it needs protection and it needs to stay in calibration. And as nearly as we can tell, it suffers little or no acoustic handicap from being hidden for these physiological reasons.

The size and shape of the external and middle ear appear to be related to the wavelength of the sounds that are useful to the organism. Regarding the specific size and composition of the outer ear structures, Fig. 2 should be useful. The auricle (pinna) itself is roughly oval in shape with the longer axis about 6.5 cm and the shorter one about 3.5 cm. On the front edge of this oval is a depression known as the concha, crudely of the shape of a truncated hemisphere with a diameter of about 2.5 cm and a radius of about 1.25 cm. The ear canal sits at the front edge of the concha and is itself somewhat oval in shape at the entrance, with a height of about 0.9 cm and a width of about 0.65 cm. The canal is nearly 3.0 cm in length, with the wall of the first one-third of the length being cartilaginous and covered loosely with skin, whereas the innermost two thirds has a bony wall and a more tightly-fitting skin. At the termination of this canal is the eardrum or tympanic membrane. This is the boundary between the outer and the middle ear. It has a rather complicated shape, but loosely resembles a flat cone with an angle of about 135°, not too different from that of many loudspeaker diaphragms. Furthermore, the membrane sits at an angle in the end of the canal, so that it presents a larger

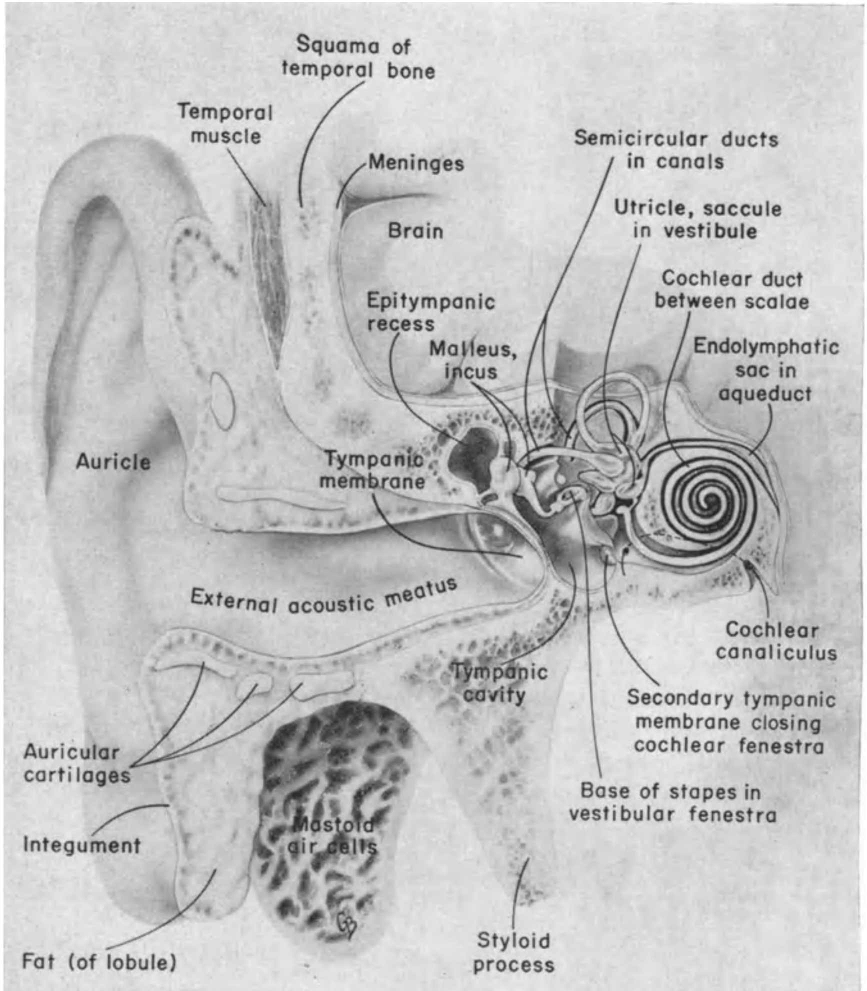

Fig. 1. Cross-section drawing of outer, middle, and inner ear of man. (From Anson and Donaldson, 1967)

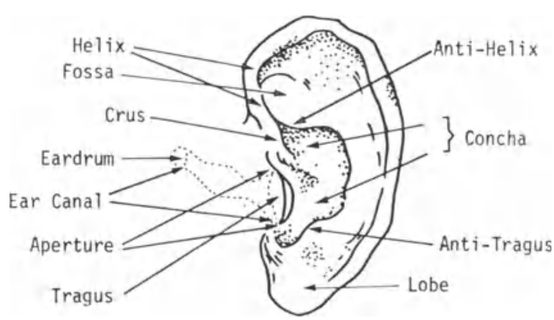

Fig. 2. The shape of the external ear and the names of its principal parts

surface to the air of the canal than it would were it normal to the axis of the canal.

Thus, so far as we have followed it, the outer ear resembles a tapering channel without too many abrupt changes that would cause reflections of the varying pressures that bring about the motions of the eardrum. In the process, the structure of the outer ear also furnishes protection for the eardrum, which, although it is a rather tough, resilient structure, would be much more subject to injury and to spurious loading by foreign material if it were located on the surface of the skull. Further special protection is afforded by the fact the canal contains a few hairs and that it has provision for secreting a wax with an apparently unpleasant effect on curious insects.

As Shaw (1974) has pointed out, these structures make very little difference to the transmission of sounds of low frequency but they do enhance the transmission of frequencies above about 1 kHz. This is shown in some detail in Fig. 3 which gives the ratio of sound pressure measured at a point outside the pinna to sound pressure at the eardrum (left ordinate) for various frequencies. It is apparent that at a 45° azimuth frequencies between 2 kHz and 5 kHz benefit considerably from the size, shape and placement of the outer ear. For sounds from other angles, the picture changes systematically, but for sounds from the front the situation is essentially the same as shown in the figure.

The outer ear, or pinna, in man functions most efficiently in the frequency range important for differentiating the sounds of speech. Whether the specific convolutions of the pinna also perform a special function in the localization of sounds has been a matter of interesting conjecture and will be discussed in

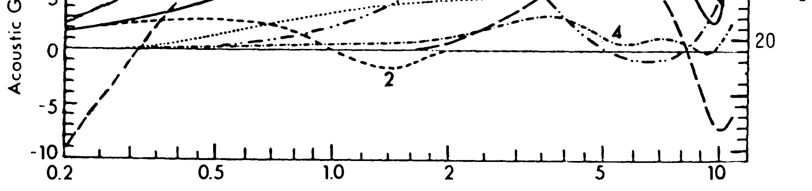

Fig. 3. Acoustic gain contributed by each of these five components: *1* The head, assuming it is a sphere, *2* The torso and neck, *3* The concha, *4* The pinna flange, *5* The canal and eardrum. The solid curve marked T is the total gain in pressure from free field to eardrum for a source at 45° azimuth. The unnumbered dashed line represents the shape of the response of the ear at threshold. This could properly be called the sensitivity curve of the ear. Sensitivity relative to peak is shown on the right-hand ordinate. The uppermost solid curve shows the low-frequency transfer characteristic of the middle ear.

(Modified from Shaw, 1974)

a later chapter. For our present purposes it is only the gross shape that has any significance. Along with the ear canal, the pinna functions in a minor way as a smaller version of the pre-hearing-aid ear trumpet. This is part of the overall gain in sensitivity that accrues from the fact that the closed-tube resonance of the canal and the gain from the baffle effect of the concha lie in the same general frequency region. The advantage afforded by the concha begins to be effective at about the frequency region where the middle ear transfer function shows a drop in gain, namely about 1500 Hz (Møller, 1963). The concha contributes a sound pressure gain of nearly 3 to 1 in the range from 4—5 kHz (Shaw, 1974).

For additional perspective the two higher curves have been included. The solid curve shows the shape of the middle ear transfer function, and one gets a rough idea how the total curve showing the combination of the middle ear, the canal and the outer ear structures adds to the middle ear response to form the total frequency response curve of the ear as portrayed by the dotted upper curve. This is the inverse of the sensitivity or "threshold" curve of the ear, which we will later study in greater detail.

The extent to which the presence of the pinna aids in the location of sound sources has been explored only recently. This will be looked at more closely when we discuss localization of sound.

Middle Ear 2

Although the boundary is an arbitrary one, the tympanic membrane can well be considered to separate the outer from the middle ear as shown back in Fig. 1. For one thing, it is useful to consider that the action changes at that point from acoustical to mechanical, just as at a loudspeaker it changes from mechanical to acoustical. The eardrum does indeed roughly resemble the cone of a loudspeaker in shape as well as in function. Its task is to make efficient use of the sound energy from the air in driving a mechanical system, just as the properly designed mechanical loudspeaker diaphragm will efficiently *radiate* acoustic energy.

The comparison can be carried further. The center of the eardrum is quite rigid for a physiological membrane, and it is loosely mounted at the rim, especially so at the lower edge, where the pars flaccida nearly constitutes a fold in the unstressed drum.

As Davis has pointed out, the application of the term drum is most descriptive for the entire middle ear, with the tympanic membrane as the drum head. In current usage, however, eardrum is routinely taken to mean the tympanic membrane. As seen in Fig. 4, displacements of the drum resulting from changes in pressure are transmitted to the inner ear via a chain of three bones, the malleus, incus and stapes. These are suspended in the middle ear cavity as suggested by Fig. 5, and serve as a rather special transmission chain for carrying the vibrations of the drum to the fluids of the inner ear.

Actually, to understand the mechanical function of the drum and the ossicular chain one needs to consider their close coupling to the fluids of the inner ear and through the fluids to the round window pressure-release mechanism. As we shall see in the next section, it is the movement of the hairs of the hair cells by the inner-ear fluid that initiates the neural activity basic to the hearing sensation. In addition, as is apparent from consideration of Fig. 4, the air cavity of the middle ear has its mechanical effect. Its basic form mechanically is an air-filled cavity of about 1.5 cc volume with a movable diaphragm (the drum) about 0.6 cm^2 in area. Such a piston-driven cavity acts like a mechanical stiffness element (analogous to a spring), and its impedance

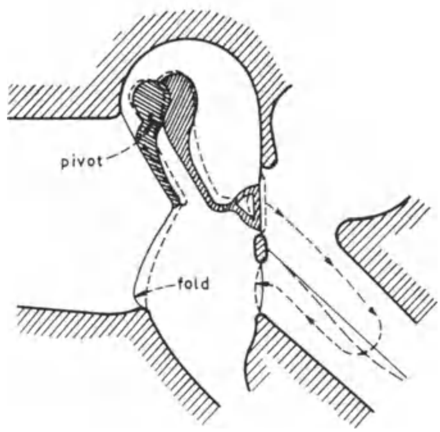

Fig. 4. Two-dimensional scheme showing the action of the middle ear. A moment of condensation (positive pressure) in the air of the ear canal forces the eardrum inward, and the structures move from the solid to the dotted position. The movement is greatly exaggerated, since the drum, which is about 0.1 mm thick moves about 1 micron or 1/100 of its thickness even for a very strong sound. Because of the way it is suspended by muscles and ligaments (not shown) the ossicular chain pivots around a point very close to its center of gravity. Note that since the eardrum and the round window membrane both move simultaneously toward the middle ear cavity the air of the middle ear cavity must be compressed during this phase of the cycle. (From Stevens and Davis, 1938)

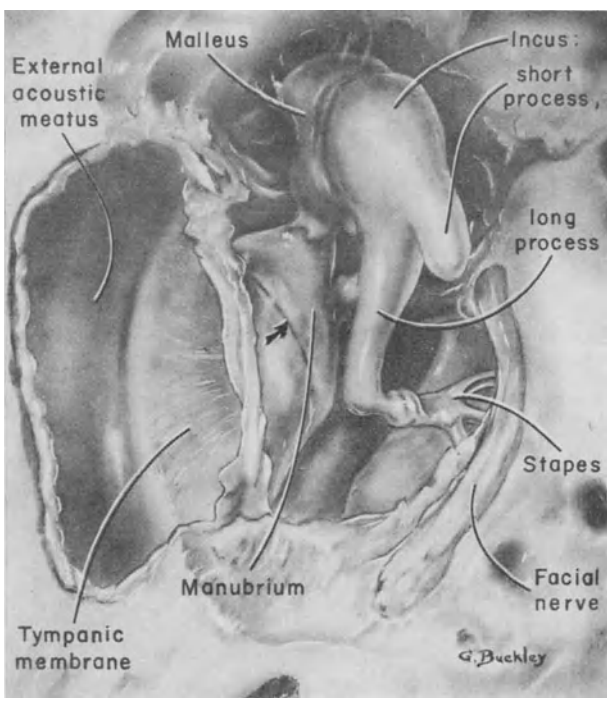

Fig. 5. Photograph of the middle ear. The canal and the middle-ear wall have been cut away to show the position of the drum, ossicles and suspending ligaments. (From Anson and Donaldson, 1967)

to a driving oscillating force doubles for every halving of the driving frequency. The effect of the presence of this middle-ear cavity, then, is to decrease the low-frequency amplitude response of the middle ear.

Over all, then, the task of the middle ear is to transfer the energy represented by the air vibration in the canal to the sensory cells of the inner ear. Converting the motion of lighter air particles into movement of the heavier liquids and tissues of the inner ear calls for the trading of greater displacement for greater force—an impedance-matching transformation. It does this rather well at low frequencies, so that in general, the effect of the drum, the middle ear cavity and the ossicular chain is to transmit frequencies below 1400 Hz with about equal displacement amplitude (this will be a velocity increase of 2 for each octave increase in frequency), but to pass frequencies above that progressively more poorly—decreasing by a factor of 4 for each octave to about 4000 Hz, where the drum ceases to behave as a single rigidly-coupled vibrator and its behavior is more erratic.

Regarding the construction of the ossicular chain, the malleus handle lies along the vertical axis of the oval-shaped drum and is firmly attached to it. The massive portion, or head of the malleus, articulates firmly with the incus and the incus in turn with the projection, or crus, of the stapes. The axis of rotation of this transmitting chain is—very nearly, at least—around its own center of gravity, thus it is readily driven (Kirikae, 1960).

Over the low-frequency range, where it works well, the middle ear may accomplish its task of lessening the impedance mismatch between the air of the canal and the structures of the inner ear by three possible complementary mechanisms. First we need to note that the concept of the rigid cone (the ear drum) driving the lever system of the ossicular chain, as intimated by the analogy to the loudspeaker or microphone, is not quite accurate. From holographic measurements of the vibration pattern of the drum, Tonndorf and Khanna (1972) noted that part of the drum moves with considerably greater amplitude than the attached malleus handle. For a time they were disposed to revive the old Helmholtz hypothesis that the ear drum adduces some mechanical advantage from operating as a curved membrane, as shown in Fig. 6. It would indeed be fascinating if the construction of the drum itself did contribute to the mechanical gain of the system. The relative amplitudes from a cross section of the drum *do* show the appropriate pattern, as in Fig. 6 B. But the drum is best viewed mechanically as an acoustically driven shell, and apparently these areas where the amplitude of the drum is greater than that of the malleus handle simply indicate that because of non-acoustic biological design restrictions it is not an ideally stiff cone. Thus greater vibration of the less-directly-attached parts of the drum probably means a loss of some of the impinging energy. With our present knowledge of the details of drum operation, this first possible mechanism of mechanical gain must be held in abeyance.

The second principle embodied in the efficient energy transfer from air through the middle ear to the inner ear is probably popularly recognized as the analog of the prybar, where the greater displacement of a longer lever arm is traded for the greater force of a shorter one. It is shown in simple form in Fig. 6 C. The more precise description is that if the force on the longer arm is

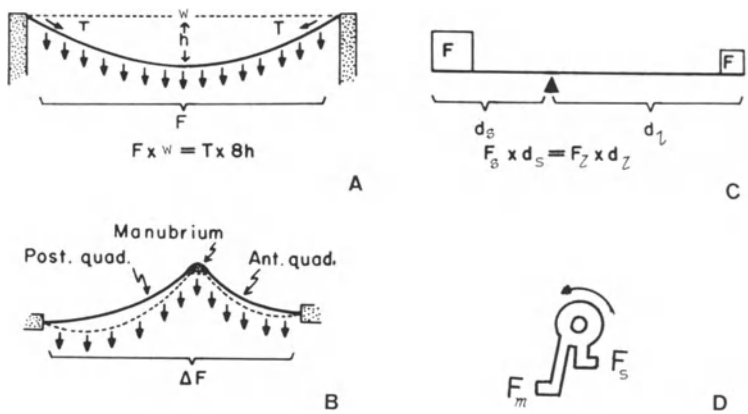

Fig. 6. Principles of the middle-ear mechanical advantage. *A* shows an idealized form of the membrane. See the discussion in the text. Whether the principle actually applies or whether the drum really behaves mechanically like a shell rather than a membrane is still controversial. *B* shows a cross section through the tympanic membrane indicating how the force is transferred to the manubrium (handle) of the malleus at one typical cross section of the drum. *C* shows the general fulcrum form of force gain; and *D* the geometric form embodied in the middle ear. (From Tonndorf and Khanna, 1970)

designated by F_l and that on the shorter by F_s, then using similar designations for the longer and shorter distances

$$F_s = (d_l/d_s)\, F_l$$

and the gain in force for the shorter lever arm is seen to be the ratio of the longer arm to the shorter. The not-quite-so-obvious form of the same principle more closely resembling the configuration in the middle ear is shown in D of Fig. 6. In this instance, the long arm is the manubrium of the malleus and the shorter one the long process of the incus. It is not really visually apparent in Fig. 5, but the pivot point of the ossicular chain is so located that the lever arm on the drum side is slightly longer than that on the stapes side of the pivot; thus some trading of greater drum displacement for greater force on stapes takes place.

Finally, and most important, the area of the tympanic membrane exposed to the vibrations of the air is considerably greater than the area of the footplate of the stapes driving the fluid of the inner ear. This acts in the same direction as the lever-arm advantage because the force on the stapes is the product of the sound pressure in the canal and the area of the drum, whereas without the drum it would be the much smaller stapes area multiplied by the pressure in the canal or the middle ear cavity. Stripped of unnecessary complications, the system looks like the portrayal in Fig. 7. The advantage gained is the ratio of the two areas.

On a superficial look, it appears that sound transmission would suffer very little if the middle ear mechanism were like the system in Fig. 7. The three-bone ossicular chain developed during the evolution of mammals, and probably served other purposes than the enhancement of sensitivity. It may offer some protection by affording a limit on amplitude displacement, but this has never been convincingly demonstrated.