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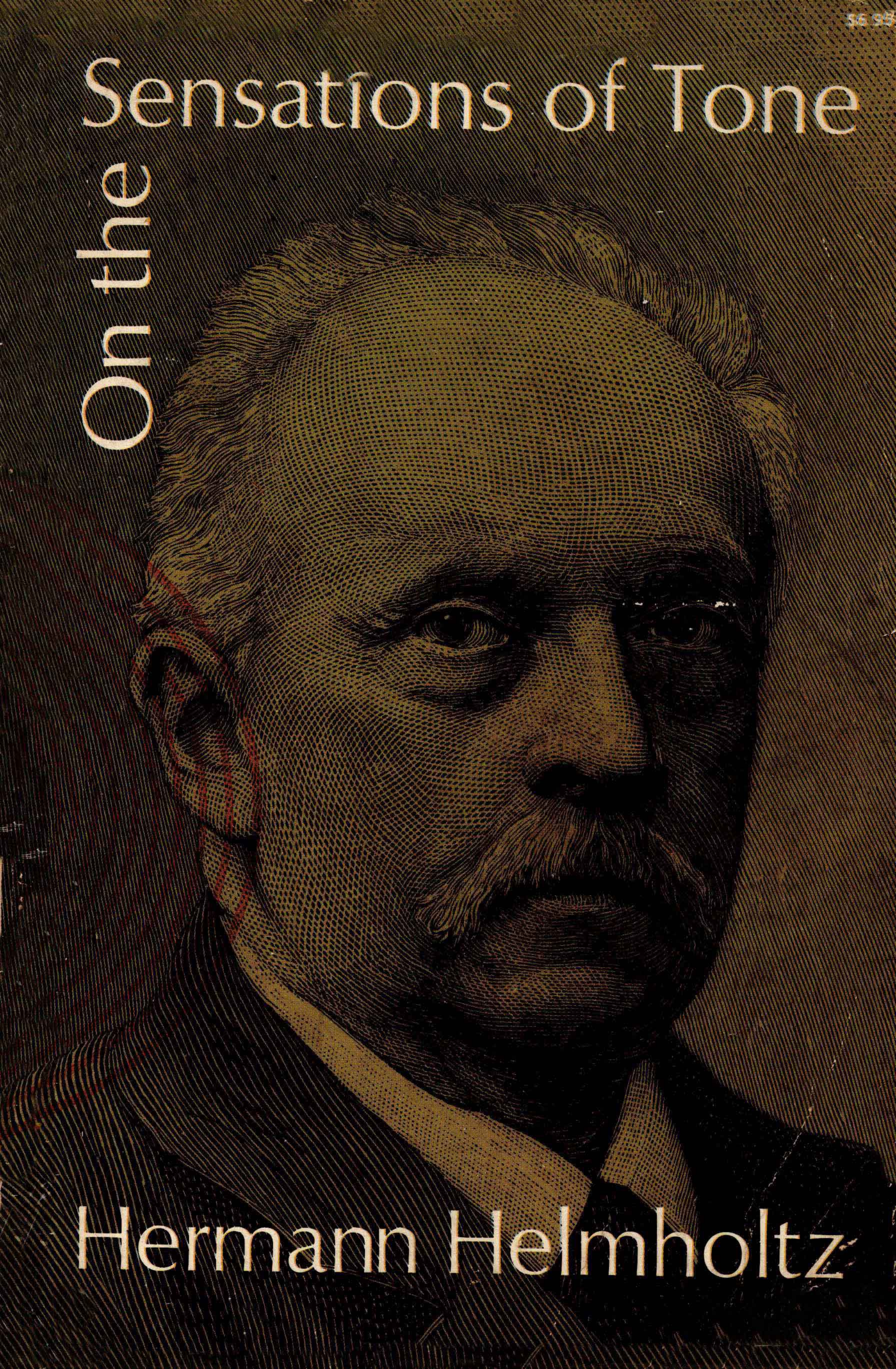
On the Sensations of Tone



Hermann Helmholtz

ON THE

SENSATIONS OF TONE

AS A PHYSIOLOGICAL BASIS FOR THE

THEORY OF MUSIC

HERMANN L. F. HELMHOLTZ

The Second English Edition, Translated, thoroughly Revised and Corrected, rendered conformal to the Fourth (and last) German Edition of 1877, with numerous additional Notes and a New additional Appendix bringing down information to 1885, and especially adapted to the use of Music Students by
ALEXANDER J. ELLIS

With a New Introduction (1954) by
HENRY MARGENAU

DOVER PUBLICATIONS, INC., NEW YORK

This Dover edition, first published in 1954, is an unabridged and unaltered republication of the second (1885) edition of the Ellis translation of *Die Lehre von den Tonempfindungen,* as originally published by Longmans & Co. A new Introduction has been specially written for this Dover edition by Henry Margenau.

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INTRODUCTION

BY HENRY MARGENAU

This book, reprinted more than 90 years after its first publication, is a magnum opus of one of the last great universalists of science. Figures like Helmholtz belong to a dying age in which a full synthetic view of nature was still possible, in which one man could not only unify the practice and teaching of medicine, physiology, anatomy and physics, but also relate these sciences significantly and lastingly to the fine arts. Added to this distinction of the book is yet another, a remarkable circumstance that is unique beyond the historical greatness of the work: its continued usefulness. The *Sensations of Tone* is still required reading for everyone who wishes to prepare himself for work in physiological acoustics, and the musician finds in it unexhausted treasure if he wishes to understand his art.

English readers are particularly fortunate in having available a translation that is excellent almost beyond belief. The clarity of Ellis' prose and his careful choice of technical terms are in no small measure the occasion for the current value of Helmholtz' contributions. This introduction, therefore, wishes to pay more than ordinary tribute to the distinguished translator and annotator whose technical competence in the field of acoustics and whose love of music enhanced the work in a major way. The reader owes Ellis a debt of gratitude for sparing him such literal translations as "clàng tint," proposed by Tyndall for the German "Klangfarbe," and rendering it as "quality." This term has now been generally adopted. The other interesting divergence in terminology which arose from Helmholtz' use of the word "Oberton" has not been settled. Tyndall chose the misleading literal version of "overtone" while Ellis advocates "upper partial." There can hardly be a question concerning the greater fitness of the latter phrase.

Since the book speaks for itself, this introduction can serve the reader best by acquainting him with the life of its author and with his astonishing accomplishments in other fields. To exemplify the account I shall append a chronological list of Helmholtz' publications.

Hermann Ludwig Ferdinand Helmholtz was born on August 31, 1821 in Potsdam, the first child of Ferdinand Helmholtz, a teacher in the Gymnasium of that city. He was a sickly boy and, according to his mother, considered unattractive by all. "However," she says, "I was not worried about it; I admired my child, for whenever he opened his eyes he smiled at me and I saw nothing but spirit and intelligence." Illness interfered with the youngster's early training, but when, at the age of 9, he entered the Potsdam Gymnasium he proceeded rapidly, jumped grades and passed into his maturity at the age of 17. He himself, in reflecting upon this period 50 years later, recalls the difficulties he encountered in memorizing unrelated facts, grammar and vocabulary in particular annoyed him. History was his difficult subject; curiously, too, he says he had trouble in distinguishing left from right.

A pronounced interest in natural science developed early and led to the desire on the part of the boy to study physics. His father, however, had five children to support and saw no possibility of financing so expensive an academic course. He applied, therefore, to the medical institute (Friedrich-Wilhelms Institut) in Berlin for a scholarship which would enable Hermann to combine some work in physics with a regular course in medicine. The scholarship was awarded against the pledge that the candidate, after completing his studies, would spend several years as a military physician.

Thus Helmholtz became an "Élève" at the "Royal Medical and Surgical Friedrich-Wilhelms Institute" in Berlin where he spent the years from 1838 to 1842. The freshman schedule at this school comprised forty-eight hours per week. Here he came under the influence of a great teacher, Johannes Müller, whose advice and example largely determined Helmholtz' career. The desire to combine physiology and physics manifestly stems from this early association with a great scientist. During that period, also, a lifelong friendship with Brücke and Du Bois-Reymond was formed. The work at the Institute led to a doctor's degree, acquired at the age of 21 through a dissertation entitled "De Fabrica Systematis Nervosi Evertebratorum," describing a fundamental anatomical discovery demonstrating that nerve fibers originate in ganglion cells. In 1843 the young military doctor entered service as surgeon in the regiment of the royal guards at Potsdam.

It was during this epoch that his thoughts turned increasingly toward the fundamental problem of the day, the principle of conservation of energy. The equivalence of heat and mechanical energy was known; perpetual motion was generally regarded as impossible. Following Liebig, Helmholtz investigated heat phenomena in muscle action. But his ambition rose beyond the wish to establish the conservation law merely in the realm of empirical fact; he set himself the task of deriving it from more fundamental principles and thus to exhibit it in its full generality.

This he accomplished in his famous lecture before the Physical Society of Berlin, on July 23, 1847. The substance of the lecture had been accumulated painstakingly during long hours of hospital duty; it represents one of the greatest scientific documents of all time. Beginning with two basic assumptions, (1) that all matter consists of mass particles and (2) that these interact by central forces, i.e. forces acting along the lines joining the particles, he was able to give a cogent proof of the conservation law. In his reasoning he introduced the idea of "Spannkraft", the form of energy now generally called potential. The prestige acquired through publication of this paper permitted him to relinquish the duties of a military physician, and in 1848 Helmholtz took his first academic position; he became teacher of anatomy at the Academy for Fine Arts in Berlin. This minor post did not hold him long, for in 1849 he was called to Königsberg as associate (ausserordentlicher) Professor of Physiology.

Having obtained a secure position, he married Olga von Velten, the daughter of a physician, and then turned to his important investigations concerning the speed of nerve impulses. According to the view then current these were so rapid as to escape detection, and astonishment was great when the young professor measured the speed along frog nerves and found it to be about 30m/sec. His discovery of the law of rise of an electric current in an inductive circuit, now named after him, fell into the beginning of the Königsberg period. Indeed it is amusing to find him writing his father in the summer of 1850 that he has become the father of a healthy girl, but that so far as discoveries are concerned he has only a "theorem regarding the rise of electrical currents" to report. Moreover in the same year he invented the ophthalmoscope, that well-known device for illuminating the retina and studying its structure, which brought him fame in the medical world.

Helmholtz' interest in acoustics was aroused for the first time in 1852, apparently by mathematical errors in the publications of Challis, which he corrected. His concern at this time is again with principles, and the subject of acoustics is viewed as a branch of hydrodynamics, the science for which he was later to create the mathematical foundation.

Near the end of his time in Königsberg, he met the man to whom he remained joined in admiration and friendship for the remainder of his life: William Thomson, later Lord Kelvin. The meeting took place in Kreuznach where Thomson had gone seeking a cure for his ailing wife. Helmholtz, 34 at this time, writes this about the occasion. "I expected to find in him, who is one of the foremost mathematical physicists of Europe, a man somewhat older than myself, and I was not a little astonished when a light-blond youth of girlish appearance came toward me. . . . With respect to analytical acumen, clarity of thought and versatility he surpasses every great scientist I have met; indeed I myself feel at times a little stupid in his presence."

In 1855 Helmholtz accepted a call to become full professor of anatomy and physiology in Bonn. His teaching there was a trifle unusual because he mixed fundamental considerations, and indeed a little mathematics, with his anatomy. The minister of education, who received complaints, was ill pleased and felt that "the teaching of anatomy in Bonn was not well cared for." Helmholtz, though never rebuked officially, heard about the complaints and in a letter to Du Bois described their cause: he had once had the temerity of using a cosine in a lecture on physiological optics. Needless to say, such minor infelicities disappeared or were condoned as the magnitude of his scientific achievements was recognized, and the three years at Bonn became a fruitful period.

It was here that his important work on combination tones was done. The occurrence of difference tones arising from two simultaneous simple tones had already been discovered. Helmholtz discovered essentially two experimental facts, the existence of summation tones and the marked dependence of their presence on the strength of the simple tones. His theory, developed in 1856, is well known; it shows how these combination tones originate from the non-linear response of the eardrum or other detector. Two years later there followed the publication of the fundamental work on the physical cause of musical harmony to which a large part of this book is devoted. The author was then thirty-seven years of age.

During this preoccupation with acoustical problems, Helmholtz transferred to a major position as professor of physiology at Heidelberg where he remained from 1858 to 1871. His presence and that of Bunsen and Kirchhoff initiated one of the glorious scientific eras in that beautiful university. Research progressed rapidly; in one year, 1859, he published two remarkable papers, the first dealing with the "timbre" or quality of vowels, the second with air vibrations in open pipes. The paper on vowels develops the relation between quality of sounds and the structure of partial tones; the other presents a mathematical theory of the motion of air near the end of an organ pipe. The solution of this problem had been attempted by well known mathematicians without success. At a later time, Helmholtz described his own method of procedure in a psychologically interesting way. "The pride which I might have experienced over my results in such cases," he said, "was greatly diminished by my realization that success in solving these problems was attained only by way of increasing generalization of favorable instances, by a series of happy conjectures after numerous failures. I was like a mountaineer who, not knowing his path, must climb slowly and laboriously, is forced to turn back frequently because his way is blocked but discovers, sometimes by deliberation and often by accident, new passages which lead him onward for a distance. Finally, when he reaches his goal, he finds to his embarrassment a royal road which would have permitted him easy access by vehicle if he had been clever enough to find the proper start. In my publications, of course, I did not tell the reader of my erratic course but described for him only the wagon road by which he may now reach the summit without labor." It is heartening indeed to have such a confession from a great scientist.

The same productive year, 1859, also dealt two serious personal blows. In June death claimed his father; in December his beloved wife. His own health was impaired to an extent which made scientific work impossible for several months. When he recovered, his attention turned to problems of physiological optics and he conducted investigations which resulted in the publication of his handbook on this subject. For one year he lost himself in his work, producing among other things a careful study of the tempered scale and of certain little-known oriental scales. Then life, and the cares of a father of two small children reasserted themselves, and Helmholtz married in 1861 a young lady of great charm, Anna von Mohl, who remained at his side until his death.

This marriage initiated the period of greatest scientific activity and productivity in the scientist's life. His acoustical researches culminated in the present book, which appeared in 1862; hydrodynamical and electrodynamical problems engaged his attention; indeed the scope of his interest widened to include the theory of knowledge and the axioms of geometry. The impressive range of his genius is recognized in the utterances and writings of his colleagues, Bunsen and Kirchhoff, and in the public esteem he enjoyed. He became "Prorektor" of the University of Heidelberg, invitations to lecture showered down upon him, and tempting offers came from foreign parts. When, in 1870, the professorship of physics in Berlin fell vacant upon the death of Magnus, Helmholtz was free to state his conditions for its acceptance. He required: (1) a salary of 4000 thaler; (2) the promise that a new Institute of Physics would be built; (3) assurance of appointment to the directorship of this institute with authority to permit or refuse its use to others; (4) living quarters in the institute. These conditions were met, and in the spring of 1871 he moved to Berlin.

The period which now begins is one of sustained and general scientific activity, of tremendous successes. It presents a distinguished German professor at the very height of his active career but is in some ways the least interesting from the chronicler's point of view. Helmholtz' main scientific preoccupation was with the problems of the nascent theory of electrodynamics, where his contributions are intertwined with those of Ampère, Maxwell and Hertz. Acoustic researches are mixed with these; indeed in 1878 he published an article entitled "The Telephone and the Quality of Sound." His great work in thermodynamics, too, was done chiefly during this period. One of his papers dealt with the steering of gas-filled balloons, another with thunderstorms. His stature was recognized even by court officials, for it is known that he was once consulted on the arrangement of lightning rods on the Castle of Goslar.

Travels were frequent and extensive and even in those days often paid for by commercial or scientific agencies. He declined two invitations to America because he felt ill at ease at the prospect of writing out popular lectures in English. His letters, to be sure, often contain English phrases, and it is somewhat surprising to find a disposition against visiting the United States in this otherwise adventurous man. Trips to Switzerland, France, Italy, and Spain were undertaken, and diaries indicate the open eye and the critical judgment of the traveler.

In 1877 Helmholtz became Rektor of the University of Berlin, a position which he occupied for one year. His inaugural speech was entitled "On academic freedom in German Universities," and it represents a document of major interest to this day. Ten years later the Physikalisch-Technische Reichsanhalt was founded, and in 1888 Helmholtz became its first president.

His new duties were largely administrative and for a time burdensome. But after one year, when the institute was established and its policies were decided, the eager spirit of its director turned again to research. A congratulatory message from the mathematician Kronecker upon the occasion of Helmholtz' sixty-seventh birthday may have had an influence on the choice of his problem at this time. Kronecker, after playfully commenting on the number 67 as the last of Fermat's three puzzling and critical integers among the first hundred, and predicting smooth sailing for the famous investigator upon passing this numerical hurdle, encourages him to come to the aid of mathematics. "The wealth of your practical experience with sane and interesting problems will give to mathematics a new direction and a new impetus. . . . One-sided and introspective mathematical speculation leads into sterile fields. Therefore, come and join us, esteemed friend, and impress upon pure mathematics the imperishable footprints of your bold and original advances in order that here, too, the paths of the future bear their markings." While Kronecker's sentiment may have outstripped his metaphor, Helmholtz seems nevertheless to have been impressed, and he launched upon a problem, though not of pure mathematics, but exhibiting a goodly measure of mathematical elegance: the motion of air masses.

First he established the existence of discontinuous boundaries between atmospheric layers of different densities. Then he proved the possibility of a transverse wave motion within the boundaries and computed the wave length, arriving at a value of 550m for a certain set of conditions. Later this value was nicely confirmed by observations from balloons. The waves here postulated became of interest in meteorology as they provide a mechanism for the mixing of air masses and the attendant atmospheric circulations. Similar considerations were later applied to water waves. While such researches absorbed the major interest of the aging scientist, he continued an active interest in electrodynamics and took part in controversies regarding the nature of the ether.

At the age of seventy-two, he finally decided to visit America where he was to be sent by the German government as delegate to the Electrical Congress in Chicago (1893). He regarded this journey as a great adventure and viewed it with slight misgivings. Only when he obtained permission to have his wife accompany him, did he willingly accept the assignment. The experiences of the pair are preserved in the letters written by Mrs. Helmholtz to her daughter, many of which throw interesting and amusing side lights upon the cultural life in the United States and also upon the misconceptions of cultured Europeans regarding it. Excerpts from these letters are contained in the three-volume biography (Helmholtz, F. Vieweg and Son, 1903) by Leo Königsberger, to which this brief account is greatly indebted. The return trip was marred by an accident, a fall down the ship's stairs resulting in a considerable loss of blood. He survived this accident, however, though he acquired the scar over his left brow that is in evidence in the beautiful portraits painted by Lenbach during the last year of the scientist's life.

On the 12th of July 1894, Helmholtz suffered what appears to have been a cerebral hemorrhage; he lived in the twilight of delirium and semi-consciousness until he breathed his last, in the midst of a large and devoted family, on September 8, 1894.

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TRANSLATOR'S NOTICE

TO THE

SECOND ENGLISH EDITION.

IN preparing a new edition of this translation of Professor Helmholtz's great work on the Sensations of Tone, which was originally made from the *third German* edition of 1870, and was finished in June 1875, my first care was to make it exactly conform to the *fourth German* edition of 1877 (the last which has appeared). The numerous alterations made in the fourth edition are specified in the Author's preface. In order that no merely verbal changes might escape me, every sentence of my translation was carefully re-read with the German. This has enabled me to correct several misprints and mistranslations which had escaped my previous very careful revision, and I have taken the opportunity of improving the language in many places. Scarcely a page has escaped such changes.

Professor Helmholtz's book having taken its place as a work which all candidates for musical degrees are expected to study, my next care was by supplementary notes or brief insertions, always carefully distinguished from the Author's by being inclosed in [ ], to explain any difficulties which the student might feel, and to shew him how to acquire an insight into the Author's theories, which were quite strange to musicians when they appeared in the *first German* edition of 1863, but in the twenty-two years which have since elapsed have been received as essentially valid by those competent to pass judgment.

For this purpose I have contrived the Harmonical, explained on pp. 466–469, by which, as shewn in numerous footnotes, almost every point of theory can be illustrated; and I have arranged for its being readily procurable at a moderate charge. It need scarcely be said that my interest in this instrument is purely scientific.

My own Appendix has been entirely re-written, much has been rejected and the rest condensed, but, as may be seen in the Contents, I have added a considerable amount of information about points hitherto little known, such as the Determination and History of Musical Pitch, Non-Harmonic scales, Tuning, &c., and in especial I have given an account of the work recently done on Beats and Combinational Tones, and on Vowel Analysis and Synthesis, mostly since the fourth German edition appeared.

Finally, I wish gratefully to acknowledge the assistance, sometimes very great, which I have received from Messrs. D. J. Blaikley, R. H. M. Bosanquet, Colin Brown, A. Cavaillé-Coll, A. J. Hipkins, W. Huggins, F.R.S., Shuji Isawa, H. Ward Poole, R. S. Rockstro, Hermann Smith, Steinway, Augustus Stroh, and James Paul White, as will be seen by referring to their names in the Index.

ALEXANDER J. ELLIS.

25 ARGYLL ROAD, KENSINGTON:
July 1885.

AUTHOR'S PREFACE

TO THE

FIRST GERMAN EDITION.

IN laying before the Public the result of eight years' labour, I must first pay a debt of gratitude. The following investigations could not have been accomplished without the construction of new instruments, which did not enter into the inventory of a Physiological Institute, and which far exceeded in cost the usual resources of a German philosopher. The means for obtaining them have come to me from unusual sources. The apparatus for the artificial construction of vowels, described on pp. 121 to 126, I owe to the munificence of his Majesty King Maximilian of Bavaria, to whom German science is indebted, on so many of its fields, for ever-ready sympathy and assistance. For the construction of my Harmonium in perfectly natural intonation, described on p. 316, I was able to use the Soemmering prize which had been awarded me by the Senckenberg Physical Society (*die Senckenbergische naturforschende Gesellschaft*) at Frankfurt-on-the-Main. While publicly repeating the expression of my gratitude for this assistance in my investigations, I hope that the investigations themselves as set forth in this book will prove far better than mere words how earnestly I have endeavoured to make a worthy use of the means thus placed at my command.

H. HELMHOLTZ.

HEIDELBERG: *October* 1862.

AUTHOR'S PREFACE

TO THE

THIRD GERMAN EDITION.

THE present Third Edition has been much more altered in some parts than the second. Thus in the sixth chapter I have been able to make use of the new physiological and anatomical researches on the ear. This has led to a modification of my view of the action of Corti's arches. Again, it appears that the peculiar articulation between the auditory ossicles called 'hammer' and 'anvil' might easily cause within the ear itself the formation of harmonic upper partial tones for simple tones which are sounded loudly. By this means that peculiar series of upper partial tones, on the existence of which the present theory of music is essentially founded, receives a new subjective value, entirely independent of external alterations in the quality of tone. To illustrate the anatomical descriptions, I have been able to add a series of new woodcuts, principally from Henle's Manual of Anatomy, with the author's permission, for which I here take the opportunity of publicly thanking him.

I have made many changes in re-editing the section on the History of Music, and hope that I have improved its connection. I must, however, request the reader to regard this section as a mere compilation from secondary sources; I have neither time nor preliminary knowledge sufficient for original studies in this extremely difficult field. The older history of music to the commencement of Discant, is scarcely more than a confused heap of secondary subjects, while we can only make hypotheses concerning the principal matters in question. Of course, however, every theory of music must endeavour to bring some order into this chaos, and it cannot be denied that it contains many important facts.

For the representation of pitch in just or natural intonation, I have abandoned the method originally proposed by Hauptmann, which was not sufficiently clear in involved cases, and have adopted the system of Herr A. von Oettingen [p. 276], as had already been done in M. G. Guéroult's French translation of this book.

[A comparison of the Third with the Second editions, shewing the changes and additions individually, is here omitted.]

If I may be allowed in conclusion to add a few words on the reception experienced by the Theory of Music here propounded, I should say that published objections almost exclusively relate to my Theory of Consonance, as if this were the pith of the matter. Those who prefer mechanical explanations express their regret at my having left any room in this field for the action of artistic invention and esthetic inclination, and they have endeavoured to complete my system by new numerical speculations. Other critics with more metaphysical proclivities have rejected my Theory of Consonance, and with it, as they imagine, my whole Theory of Music, as too coarsely mechanical.

I hope my critics will excuse me if I conclude from the opposite nature of their objections, that I have struck out nearly the right path. As to my Theory of Consonance, I must claim it to be a mere systematisation of *observed facts* (with the exception of the functions of the *cochlea* of the ear, which is moreover an hypothesis that may be entirely dispensed with). But I consider it a mistake to make the Theory of Consonance the essential foundation of the Theory of Music, and I had thought that this opinion was clearly enough expressed in my book. The essential basis of Music is *Melody*. Harmony has become to Western Europeans during the last three centuries an essential, and, to our present taste, indispensable means of strengthening melodic relations, but finely developed music existed for thousands of years and still exists in ultra-European nations, without any harmony at all. And to my metaphysico-esthetical opponents I must reply, that I cannot think I have undervalued the artistic emotions of the human mind in the Theory of Melodic Construction, by endeavouring to establish the physiological facts on which esthetic feeling is based. But to those who think I have not gone far enough in my physical explanations, I answer, that in the first place a natural philosopher is never bound to construct systems about everything he knows and does not know; and secondly, that I should consider a theory which claimed to have shewn that all the laws of modern Thorough Bass were natural necessities, to stand condemned as having proved too much.

Musicians have found most fault with the manner in which I have characterised the Minor Mode. I must refer in reply to those very accessible documents, the musical compositions of A.D. 1500 to A.D. 1750, during which the modern Minor was developed. These will shew how slow and fluctuating was its development, and that the last traces of its incomplete state are still visible in the works of Sebastian Bach and Handel.

HEIDELBERG: *May* 1870.