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RUDOLPH KOENIG (1832-1901), HERMANN VON HELMHOLTZ (1821-1894) AND THE BIRTH OF MODERN ACOUSTICS

by

David Alexander Pantalony

A thesis submitted in conformity with the requirements for
the degree of Doctor of Philosophy,
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ABSTRACT

This thesis reconstructs the birth of modern acoustics through its research and teaching instruments. It opens with a biographical sketch of the main constructor of these instruments, Rudolph Koenig. Through Koenig's life we get a detailed case study of how an instrument maker and his instruments can help shape the development of a new science. We also obtain a portrait of one of the key participants in the famed precision instrument trade in nineteenth-century Paris. The second chapter describes the work of Hermann von Helmholtz and the conceptual and experimental development of acoustics between the years 1856 and 1863. Helmholtz revolutionised the study of sound by combining his knowledge of physics, mathematics and physiology into a novel theory of harmony. He also contributed a small number of ingenious instruments for testing these bold claims. The other half of Chapter Two considers the role Rudolph Koenig played in constructing, modifying and spreading Helmholtz's "reform of acoustics." He was more than a mere technician and a study of his instruments reveals that even early in his career he was making original contributions to the new acoustics. The third chapter details how his life as a craftsman of sound, his innovations with graphical instruments, and his exposure to the Parisian scientific scene helped to create his unique approach to acoustics. Later in his career Koenig would combine these influences to become the main critic of Helmholtz's theory. The final chapter examines the disputes that arose involving the nature of vowels, timbre and combination tones. It shows how, through Koenig's influence, these controversies came to centre on instruments, especially the tuning fork, the focus of Koenig's most important innovations. The study of these disputes reveals the tensions that arose between physics and psychology at the end of the nineteenth century.

ACKNOWLEDGMENTS

In the summer of 1997 I was invited by Doug Creelman of the Psychology Department at the University of Toronto to research and catalogue their collection of historic instruments. While searching for the purchase receipt for a set of brass resonators made by Rudolph Koenig, Harold Averill (the university archivist) and I came across a sizeable collection of letters from Koenig to James Loudon the founder of the physics laboratory at Toronto (1878). This discovery led to the present thesis on the birth of modern acoustics from the perspective of Koenig, the main instrument maker in that development. I owe my first acknowledgment to Creelman and Averill for providing the opportunity that led to this project.

I am indebted to my supervisors for their continued support: Trevor Levere, Sungook Hong, Ian Hacking and John Slater. A number of scholars also provided helpful suggestions: David Murray, Kathy Olesko, David Cahan, Erwin and Elfrieda Hiebert, and Tom Greenslade. Friends and colleagues at the IHPST provided much support during this project, especially Muna Salloum, William Zaget, Bert Hall, Janis Langins, Pauline Mazumdar, Conor Burns, Steve Walton, Melanie Martens, and Scott Campbell. Louisa Yick of the Zoology Department took the photographs of Koenig's instruments. Rob Smidrovskis, of the Physics Department, refurbished several instruments so that we could re-enact key experiments. I owe many thanks to the Fellows and the staff of Massey College, where I had the fortune to live and work for the past year and a half.

I am forever grateful to the people at the National Museum of American History, Smithsonian Institution in Washington D.C. for their support for two summers, especially Steve Turner, Debbie Warner, Roger Sherman, and Karen Lee. I would also like to acknowledge the generous help of a number of people at museums in Europe and North America: Paolo Brenni (Paris and Florence); Randall Brooks (Ottawa); Bill Fickinger (Cleveland); Bernie Ziomkiewicz (Queen's);

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Many thanks to Eberhard and Reinhild Neumann-Redlin von Meding of Bückeburg, Germany, for opening their home and family archives. It was through them that I came to learn essential biographical information about "Uncle Rudolph."

This project was generously funded by the following agencies and institutions: Institute for the History and Philosophy of Science and Technology, U of T; Massey College, U of T; School of Graduate Studies, U of T; Smithsonian Institution Pre-Doctoral Fellowship; Ontario Graduate Scholarship; Social Sciences and Humanities Research Council Grant, Government of Canada; Munk Centre for International Studies.

Special thanks to my family for their encouragement, love and support. This thesis is dedicated to my parents, Sheila and Dominic Pantalony.

Toronto, November 19, 2001.

CONTENTS

CHAPTER ONE – BIOGRAPHICAL SKETCH OF RUDOLPH KOENIG

CHAPTER TWO – HELMHOLTZ, KOENIG AND THE INSTRUMENTS OF THE NEW ACOUSTICS

CHAPTER THREE – THE MAKING OF A CRITIC, 1851 - 1866

CHAPTER FOUR – DISPUTES

SOURCES

LIST OF FIGURES

NOTES ON ACOUSTICAL TERMS

Today we use the term **Hertz (Hz)** or **cycles per second (cps)** to refer to the frequency of a vibrating body. One Hz represents a complete sinusoidal vibration, including half of the wave above the "y" axis, and half of the wave below the "y" axis.

In the nineteenth century the French had a tradition of referring to frequency numbers in terms of half a cycle, or **"vibration simple" (v.s.).** Alexander Ellis, the translator of Hermann von Helmholtz's *Sensations of Tone*, added the following explanation of the French system: "French physicists have adopted the inconvenient habit of counting the forward motion of a swinging body as one vibration, and the backward as another, so that the whole vibration is counted as two. This method of counting has been taken from the seconds pendulum, which ticks once in going forward and once again on returning." Helmholtz *Sensations* 16

The French also adopted the term **"vibration double,"** **(v.d.)** which was equivalent to a complete vibration (one Hz) to correspond to American, English and German traditions.

The French notation – **Ut, Re, Mi, Fa, Sol, La, and Si** - derived from a Latin hymn to Saint John, "**Ut** queant laxis **re**sonare fibris **mi**ra gestorum **fa**muli tuorum, **sol**ve polluti **la**bii reatum Sancte Joannes" (Loosen the guilt of the unchaste lip, O Saint John, so that with relaxed throats your servants might seek to resound the wonders of your deeds).

American, German and English systems used the following terms: **c, d, e, f, g, a and b.**

Each octave (the interval between a tone and another tone having twice the number of complete vibrations) had a corresponding number referring to its height on the scale. Ut3 referred, for example, to 256 v.d. (256 Hz), or what was middle "c" on the piano (c' – German notation). For this particular note, Rudolph Koenig's tuning forks would have been marked, "Ut3, 512 v.s." Ut4 was the next octave up in the scale, at 512 v.d. Ut5 referred to the next octave, at 1024 v.d., etc.

Ut3 = c' = 256 Hz = 256 v.d. = 512 v.s.

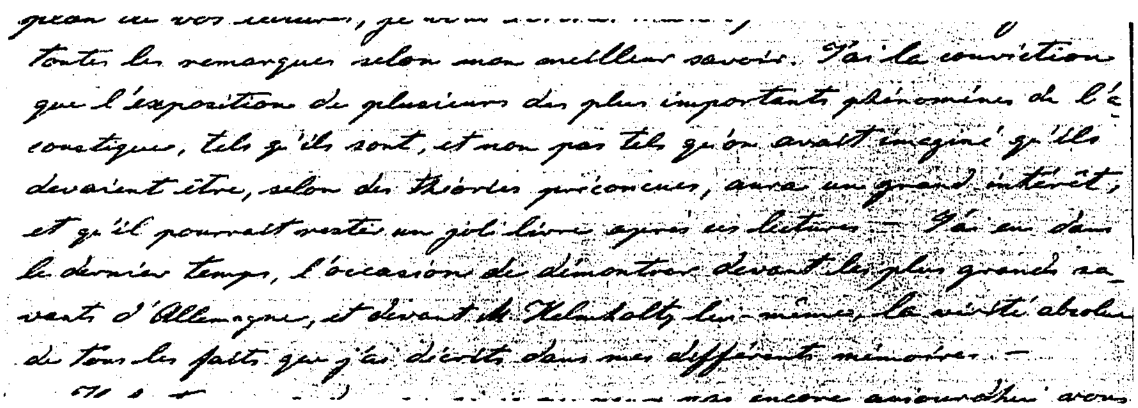
In the current text, I use Hz to refer to frequency unless directly quoting from a text or instrument.

I also use the terms *harmonics*, *upper partial tones* and *overtones* to mean roughly the same thing (see p. 62). Disagreements about these terms did not seriously take root until after the 1890s.

Julia Loudon: **“You surely did not experiment on Sunday?”**

Rudolph Koenig: **“Why not? Le bon Dieu – he loves a good experiment.”**

INTRODUCTION



toutes les remarques selon mon meilleur savoir. J'ai la conviction que l'exposition de plusieurs des plus importants phénomènes de l'acoustique, tels qu'ils sont, et non pas tels qu'on avait imaginé qu'ils devaient être, selon des théories préconçues, aura un grand intérêt; et qu'il pourrait rester un joli livre après ces lectures. — J'ai eu dans le dernier temps, l'occasion de démontrer devant les plus grands savants d'Allemagne, et devant M. Helmholtz lui-même, la vérité absolue de tous les faits que j'ai décrits dans mes différents mémoires. —

Rudolph Koenig to James Loudon, November 25, 1881.[1]

Just as scientific instruments once opened new worlds for scientists, historic scientific instruments now provide historians and the general public with a tangible means of accessing the science of the past. They offer, in the spirit of the quote above, a glimpse of science as it was actually practiced. We read about Galileo's studies of the heavens, but by seeing his original telescopes, we can better imagine how, and in what material context, he made his novel observations. Historians of science are familiar with Antoine Lavoisier's revolutionary chemistry carried out in latter part of the eighteenth century, and yet by examining his laboratory apparatus we gain a new appreciation for his daily practice and experimental creativity.[2] Those interested in Ernest Rutherford's work on radioactivity in the first years of the twentieth century discover, upon visiting the Rutherford museum at McGill University, a series of simple contraptions of

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[1] "I have the conviction that the exposition of several of the more important phenomena of acoustics, such as they are, and not as one imagined them to be according to preconceived theories, will be quite interesting, and could result in a very fine book after these lectures. I recently had the occasion to demonstrate, before the most important German scientists, and before Mr. Helmholtz himself, the absolute truth of all the facts that I described in my different articles." Rudolph Koenig, "Koenig letters, (1878-1901)," *University of Toronto Archives, Loudon Papers, B72 0031//004.*

[2] Galileo's telescopes are on display at the Museum for the History of Science, Florence, Italy. Some of Lavoisier's key instruments are on display at the Musée des Arts et Métiers in Paris. Frederic Homes has written on Lavoisier's creative and skilful use of instruments in his chemical laboratory, see Frederic L. Holmes, "The Evolution of Lavoisier's Chemical Apparatus," in *Instruments and Experimentation in the History of Chemistry*, ed. Frederic L. Holmes and Trevor Levere (Cambridge, Massachusetts: MIT press, 2000).

soldered metal, string and sealing wax that illustrate, better than any written account of his research, the manner in which he investigated his questions, one variable at a time, one instrument at a time.

Even with an abundance of surviving collections around the world, it is still rare that we are able to detail the history of a particular science from the perspective of its instruments. Due to recently discovered archival materials and instruments, this thesis reconstructs the birth of modern acoustics from the perspective of its main instruments and instrument maker, Rudolph Koenig. Historians of music, psychology and physics generally know this story through the bold theoretical and experimental work of the German scientist, Hermann von Helmholtz. By closely examining Koenig's life, research and instruments, and by looking at his intersection with Helmholtz's work, we gain a more complete understanding of these developments.

The French precision instrument makers of the nineteenth century were among the best in creating a material foundation for studies in optics, electricity, magnetism, acoustics, chemistry, medicine and physiology. Paolo Brenni has researched their instruments, catalogues, businesses, and relations with scientists, documenting this critical aspect of nineteenth-century science.[3] He has also singled out Koenig as one of the leaders of this prestigious group of instrument makers.[4] As more is uncovered about the French instrument scene, too long neglected by historians, the more complex and interesting its contributions seem to be. In her studies of electrical instruments, Christine Blondel, for example, has shown how French electrical makers were mediators between diverse groups of scientists and savants, sharing their instruments, practices and values.[5] These sorts of histories bring us into the instrument workshops of science to obtain a feel for the complexities of scientific activity at that time. Chapter One of this thesis adds to this literature by

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[3] Brenni, Paolo. "19th Century French Scientific Instrument Makers." *Bulletin of the Scientific Instrument Society*, nos. 38-51 (1993-1996).

[4] Paolo Brenni, "The Triumph of Experimental Acoustics: Albert Marloye (1795-1874) and Rudolph Koenig (1832-1901)," *Bulletin of the Scientific Instrument Society*, no. 44 (1995).

[5] Blondel, Christine. "Electrical Instruments in 19th Century France, between Makers and Users." *History and Technology* 13 (1997).

providing a biographical account of Koenig based on the letters between him and his main client, James Loudon. These letters (over 250 pages) covered twenty-three years of friendship and a variety of topics, including: science, instruments, business, travel arrangements, condolences, lectures, disputes and health problems. They are a perceptive, sensitive and passionate voice from a pivotal time in the development of science, when laboratories were sprouting up across Europe and North America. They are also a window into the local instrument trade and scientific community in Paris. Furthermore, they provide us with a personal account of the birth of modern acoustics from one of its founders. Through Koenig's studio - a vibrant place of business, creation and experimentation - we are exposed to an aspect of science that did not carry over into the twentieth century. By the turn of the century most instrument makers had adopted factory-like businesses, relinquishing their private laboratories which had served for both their business and science.

The second chapter provides the first thorough account of the key instruments that constituted the "reform" of acoustics in the early 1860s. It opens with an overview of Helmholtz's theoretical and experimental work on acoustics between 1856 and 1863. It then examines the role of instruments and the instrument maker in extending, modifying and spreading these reforms. Historians of science are increasingly using instruments in their studies in order to uncover aspects of science previously taken for granted or ignored.[6] Alan Rocke, for instance, has documented the way in which a simple, but ingenious, piece of glassware developed by the

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[6] For recent collections of essays on the history of instruments, see R.G.W. Anderson, J.A. Bennett, and W.F. Ryan, eds., *Making Instruments Count: Essays on Historical Scientific Instruments* (Aldershot: Variorum, 1993). Robert Bud and Deborah Jean Warner, eds., *Instruments of Science: An Historical Encyclopedia* (London; Washington D.C.: The Science Museum, London and the National Museum of American History in association with Garland Publishing, Inc., 1998). Robert Bud and Susan Cozzens, eds., *Invisible Connections: Instruments, Institutions, and Science* (Bellingham Washington: SPIE Optical Engineering Press, 1992). David Gooding and Trevor Pinch, eds., *The Uses of Experiment: Studies in the Natural Sciences* (Cambridge [England]: Cambridge University Press, 1989). Thomas J. Hankins and Robert J. Silverman, *Instruments and the Imagination* (Princeton, N.J.: Princeton University Press, 1995). Albert Van Helden and Thomas L. Hankins, eds., *Instruments, Orisis* 9 (1994). Frederic L. Holmes and Trevor Levere, eds., *Instruments and Experimentation in the History of Chemistry* (Cambridge, Massachusetts: MIT Press, 2000). M. Norton Wise, ed., *The Values of Precision* (Princeton, N.J.: Princeton University Press, 1995).

chemist, Justus Liebig, in the 1830s completely transformed organic analysis.[7] It reduced several tricky procedures to one easy step, improved accuracy and accelerated research. Students and semi-skilled workers could suddenly perform sophisticated procedures with far more reliability than before. In a similar fashion, in Chapter Two, I focus on the main instruments in the new acoustics and how they transformed practice and pushed the boundaries of early acoustics.

Another theme dealt with in Chapter Two (and partly in Chapter Three) is the relationship between the instrument maker and the scientist. This is an aspect of scientific development often ignored by historians, or simply not covered because of a lack of sources. Trevor Levere's work on Antoine Lavoisier's chemical revolution, for instance, describes the influence the instrument maker Nicolas Fortin had on Lavoisier's work.[8] Levere found that the rapid development of the precision balance under Fortin's skilful work conditioned Lavoisier's approach to chemistry and helped to define his conception of error. The dynamic between the researcher and the maker and between theory and instruments had a profound impact on the chemical revolution.

In the present case study, I find noteworthy variations on Levere's model of interaction. Koenig was the main instrument maker of the acoustical revolution, but he was not located down the street from Helmholtz (who was in Germany), nor was he called upon as a collaborator in the way that Fortin and Lavoisier worked together. He worked in Paris with its very different traditions in science and acoustics becoming a mediator between the German world of Helmholtz and the French experimental culture. He introduced the theories and instruments of Helmholtz to Paris, modified and perfected some of Helmholtz's instruments, and later, after developing a

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[7] Alan J. Rocke, "Organic Analysis in Comparative Perspective: Liebig, Dumas, and Berzelius, 1811-1837," in *Instruments and Experimentation*, eds. Holmes and Levere (2000).

[8] Trevor Levere, "Balance and Gasometer in Lavoisier's Chemical Revolution," in *Chemists and Chemistry in Nature and Society, 1770-1878*, ed. Trevor Levere (Aldershot: Variorum, 1994). For an example of this kind of dynamic in early electrical studies, see Sherman, Roger. "Charles Page, Daniel Davis, and Their Electromagnetic Apparatus," (1988): 34-47. The famous Dutch physician, Boerhaave, and the instrument maker, Fahrenheit, collaborated on the making of thermometers, see Golinski's chapter in, Holmes and Levere, eds., *Instruments and Experimentation*. Sergey Kapitza described a more recent form of this dynamic (between engineers and scientists) in his history of particle accelerators. "The Story and Lessons

distinctive approach to acoustics, emerged as Helmholtz's main critic. On the other hand, Helmholtz more or less removed himself from original acoustical research after publishing his treatise on sound in 1863. Except for brief interactions, revised editions and his instruments, he remained relatively quiet regarding the controversies, and maintained his position without significant changes. This unusual dynamic between the main theoretician and principal instrument maker shaped the new acoustics in unexpected ways.

There are many kinds of scientific instruments – models of nature, passive measurers of phenomena, active producers of phenomena, demonstration instruments and imitation instruments.[9] In Chapter Two I focus on the broader distinction between research apparatus and teaching apparatus. These two groups best reflect the activities of Koenig and his clients. Some of the instruments in this story inhabited both domains, and as W.D. Hackman has found in other histories of instruments, some started as research instruments but later degenerated into demonstration instruments.[10] In Chapters Three and Four, the story demands a further distinction between analytic and graphical instruments, two groups of instruments that represented the vastly different approaches of Helmholtz and Koenig.

Chapter Three describes Koenig's training as a craftsmen, his early graphical innovations and his involvement in the Parisian scientific community. These three aspects of his career in Paris contributed to his eventual break with Helmholtz. As a model I draw on Myles Jackson's recently published history of Joseph Fraunhofer (1787-1826), the celebrated optical instrument maker of the early nineteenth century. Jackson's account is one of the first histories to look directly at the development of a science from the perspective of an artisan, his commitments and his context.[11]

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of Particle Accelerators," Lecture Delivered at the XIX Scientific Instrument Symposium at Oxford, Sept 4-8, 2000.

[9] W.D. Hackman, "Scientific Instruments: Models of Brass and Aids to Discovery," in *The Uses of Experiment: Studies in the Natural Sciences*, ed. David Gooding and Trevor Pinch (Cambridge [England]: Cambridge University Press, 1989).

[10] Ibid. 43.

[11] Myles W. Jackson, *Spectrum of Belief: Joseph von Fraunhofer and the Craft of Precision Optics* (Cambridge Massachusetts: MIT press, 2000).

Fraunhofer's techniques, developed independently of the standard theories of the day, reveal that science does not develop on one unitary path, but often in many directions at once, emerging from a complex fabric of craftsmanship, experiment, instruments, social context and theory. Jackson's work shows that experiments and instruments can often develop their own pathways and influences independent of theory.[12]

An important influence on Koenig's early career was his involvement in the Parisian scientific scene. Drawing on the work of Alan Rocke, Robert Fox, and Mattias Dörres, I situate Koenig in the experimental culture of Paris.[13] In his study of the chemist Adolphe Wurtz, Rocke has woven a story that includes instruments, education reform, philosophical commitments, theoretical development, political developments, and daily life in the Paris of the Second Empire. The present study is more limited in scope (I reconstruct only the scientific developments in acoustics related to Koenig's contributions), but it adds to the growing literature on French science at this time.

In the fourth chapter I examine the disputes that arose during Koenig's career. These disputes touched on some of the fundamental notions of Helmholtz's acoustics, and growing tensions between physiology, physics and psychology. Robert Silverman offers one of the more insightful accounts of one of Koenig's key disputes. He contends that the dispute over timbre (§4.7) derived from Koenig's pictorial view of sound, which was opposed to the analytic view of Helmholtz. Silverman's dissertation on nineteenth-century scientific instruments, later turned into a book with Thomas Hankins, argues that "a scientific instrument embodies an approach to the study of

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[12] Peter Galison, "History, Philosophy, and the Central Metaphor," *Science in Context* 2, no. 1 (1988). Ian Hacking, *Representing and Intervening* (Cambridge [England]: Cambridge University Press, 1983).

[13] Matthias Dörries, "Easy Transit: Crossing Boundaries between Physics and Chemistry in Mid-Nineteenth-Century France," in *Making Space for Science. Territorial Themes in the Shaping of Knowledge.*, ed. Crosbie Smith and John Agar (Basingstoke: MacMillan, 1998). Robert Fox, *The Caloric Theory of Gases from Lavoisier to Regnault* (Oxford: Oxford Press, 1971). Robert Fox, *The Culture of Science in France, 1700-1900* (Aldershot, U.K.: Variorum, 1992). Robert Fox, "The Savant Confronts His Peers: Scientific Societies in France, 1815-1914," in *The Organization of Science and Technology in France, 1808-1914*, ed. Robert Fox and George Weisz (Cambridge: Cambridge University Press, 1980). Robert Fox, "Scientific Enterprise and the Patronage of Research in France, 1800-70," *Minerva* 11 (1973).

nature."[14] They may embody, for instance, the idea that instruments are extensions of the senses (the telescope), the desire to visually represent nature, or the desire to imitate nature. In the present case, Koenig's graphical and visual instruments embodied a pictorial approach to sound that strongly influenced the way he conceived of, and experimented with, sound. In Chapters Two and Four I look at the two groups of instruments – analytic and visual – around which these disputes centred, and I describe how they came into being and the impact they had on practice and theory. In Chapters Three and Four I make use of what is known of Koenig's training and career to provide the reader with a fuller examination of the different aspects of his approach aside from the pictorial, in order to show how these aspects influenced his practice.

The main disputes treated in Chapter Four were situated in the murky boundaries between physics and psychology, involving inflamed tensions between theory and experiment, and due to Koenig's influence, these battles were fought mostly through instruments. By reconstructing these stories we gain a better appreciation of the scientific context of early acoustics, and the choices scientists make when facing troublesome phenomena.

This thesis uses instruments as a historical source. By actually examining instruments, one gathers information about technical developments that was not always recorded in print. Sometimes I examined the materials used, the quality of the craftsmanship, and the design changes for clues about Koenig's struggles and efforts in his studio. Comparisons are made between models from different time periods. Comparisons are made between Koenig's models and competitors. I studied the instruments for evidence of how they were made, thus revealing a more complex story of the creativity involved in construction. I also re-enacted some important experiments in order to understand what it was like to use these instruments. Above all, I used Koenig's instruments for the same purpose for which many of them were used over a hundred

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Alan J. Rocke, *Nationalizing Science: Adolphe Wurtz and the Battle for French Chemistry* (Cambridge, Massachusetts: The MIT Press, 2001).

[14] Hankins and Silverman, *Instruments and the Imagination.*

years ago – to illustrate and understand complex and abstract acoustical concepts. Some of the acoustics in this story, especially related to the disputed concepts (see Chapter Four), is not easy to grasp. To make matters even more difficult, present experts on acoustics cannot apply their knowledge, based on different language and laboratory traditions, to penetrate the acoustics of long ago. The instruments themselves serve as a means for taking the historian back to the original intentions of people like Koenig and Helmholtz, and help to make difficult ideas intelligible.

Ultimately the instruments are the best way to access an easily overlooked part of this history – experimenting with these well-crafted acoustical instruments was (and is) fun. Scientists like James Loudon anxiously waited for months for a shipment of instruments to arrive from Europe. The arrival of the instruments would be followed by days of testing and demonstrating the latest marvels on the science of musical sounds. Koenig lived and worked surrounded by his instruments. They were his escape from the pressures of a tough business climate. He was an entertaining demonstrator, and for this reason his apartment was well frequented by scientists and even tourists on their visits to Paris. Perhaps through a study of his instruments, and his love of experiment, we can recapture this important aspect of nineteenth-century science.

Robert J. Silverman, "Instrumentation, Representation, and Perception in Modern Science: Imitating Function in the Nineteenth Century" (University of Washington, 1992) 9.

CHAPTER ONE – A BIOGRAPHICAL SKETCH OF RUDOLPH KOENIG

After the fire there was a tiny whispering the sound. 1 Kings 19.12

1.1 HIS CHILDHOOD IN KÖNIGSBERG AND EARLY CAREER IN PARIS, 1832-1870

Rudolph Koenig was born November 26, 1832 in Königsberg, East Prussia (now Kaliningrad, Russia). His father, Johann Friedrich Koenig (1798-1865) was professor of mathematics and physics at the Kneiphöfischen Gymnasium. He had been a pupil of Friedrich Wilhelm Bessel (1784-1846), the well-known astronomer, and enjoyed wide connections in Prussian scientific circles. Rudolph's mother, Mathilde Koenig (c.1806-1893), born Preuss, descended from a Königsberger family. Her father, Martin Preuss (b.1774) was a clockmaker and two of her ancestors were organ builders, Jakob and Johann Preuss, one of whom graduated from the "Albertina," the Albertus-University of Königsberg, as an instructor of organ music. In the latter part of the eighteenth century they restored the organ at the Königsberger Dome Cathedral, which at the time was the largest organ in East and West Prussia.[1] The Preuss family also made concert pianos when these instruments became popular after the turn of the eighteenth century.[2]

Königsberg was a thriving port town on the Baltic Sea adorned with the architecture of the Hanseatic league, a castle where Prussian kings had been crowned, and the Kneiphöf island in the

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[1] Information about Koenig's early life in Königsberg comes from the personal archives of the Neumann family at Bückeburg. One of the better sources on Koenig's personal life is a tribute by his niece, Helene Neumann, "Rudolph Koenig zu seinen hundertsten Geburtstag," in *Neumann Family Archives* (1932a). Eberhard Neumann-Redlin von Meding, the keeper of the family archives, has published an article on Koenig's background and life. Eberhard Neumann-Redlin von Meding, "Feinmechaniker und Wissenschaftler für akustische Präzisionsinstrumente und Grundlagen der Tonlehre," *Königsberger Bürgerbrief* No. 57 (2001). Neumann-Redlin von Meding's article derives from a talk he gave on Koenig on May 15, 2001 at the German-Russian House in Kaliningrad, Russia. Other biographical information comes from the Loudon Papers (B72-0031/004) at the University of Toronto and a number of obituaries. Jacques Boyer, "Rudolph Koenig," *Revue Universelle*, (1901). W. Le Conte Stevens, "Rudolph Koenig," *Scientific American Supplement* 1353 (1901). W. Le Conte Stevens, "Sketch of Rudolph Koenig," *The Popular Scientific Monthly* 37 (1890). James Loudon, "Rudolph Koenig," in *University of Toronto Archives, Loudon Papers, B72 0031//016(05)* (1901). "Nécrologie Mort De M. R. Koenig," *Moniteur Scientifique* 15 (1901). Silvanus P. Thompson, "Rudolph Koenig," *Nature* 64, no. 1669 (1901). For secondary sources on Koenig see Paolo Brenni, "The Triumph of Experimental Acoustics: Albert Marloye (1795-1874) and Rudolph Koenig (1832-1901)," *Bulletin of the Scientific Instrument Society*, no. 44 (1995). Dayton Clarence Miller, *Anecdotal History of the Science of Sound* (New York: MacMillan Company, 1935). Robert S. Shankland, "Karl Rudolph Koenig," in *Dictionary of Scientific Biography* (New York: Scribner, 1970).

[2] Fritz Gause, *Die Geschichte der Stadt Königsberg in Preussen*, vol. 2 (Köln: Böhlau, 1965) 218.

centre of town where the philosopher Immanuel Kant, Königsberg's most famous citizen, was buried in the Dome Church. Koenig, who had three sisters, grew up in a stimulating, cultured environment. In later years he fondly recalled musical and literary evenings with friends such as the Dulks, a prominent Königsberger family. Friedrich Phillipp Dulk (1788-1852) had founded the chemistry institute at Königsberg. His son Albert Dulk (1819-1884) was an actor who became a radical journalist during the turmoil of the 1848 revolution. During the first half of the nineteenth century, Königsberg was a renowned location for studying physics, and through his father, Koenig met several figures in German physics and mathematics. One acquaintance of the father was Franz Neumann (1798-1895), the head of one of Prussia's leading seminars in mathematics and physics. Neumann's seminar, one of the first of its kind to focus almost entirely on precision measurement, emerged in the wake of the Prussian education reforms after Napoleon's defeat.[3] Rudolph Radau (1835-1911), one of Neumann's students, would later become a supporter of Koenig's efforts in Paris. Of course, the most famous physicist to work in Königsberg who also was a friend of the elder Koenig, was Hermann von Helmholtz (1821-1894).[4] Helmholtz, who would revolutionise the science of acoustics was the professor of physiology at Königsberg from 1849 to 1855. Ironically, at that time Königsberg lacked the skilled mechanics and machinists that Helmholtz needed so badly for his novel experiments.[5]

Koenig showed an early aptitude for art, literature and music. In fact, he developed a lifelong passion for music, encouraged by the traditions in music in Königsberg. He also demonstrated abundant mechanical skills and was encouraged by his grandfather Preuss, who had travelled in France and England and had been impressed by the precision instrument trade in both countries.

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[3] Kathryn M. Olesko, *Physics as a Calling: Discipline and Practice in the Königsberger Seminar for Physics* (Ithaca, N.Y.; London: Cornell University Press, 1991). R. Steven Turner, "The Growth of Professional Research in Prussia, 1815 to 1848 - Causes and Context," *HSPS* 3 (1971). For more on Königsberg culture during this period see Kathryn M. Olesko, "Civic Culture and Calling in the Königsberg Period," in *Universalgenie Helmholtz: Rückblick nach 100 Jahren*, ed. von Lorenz Krüger (Berlin: Akademie Verlag, 1994).

[4] Neumann-Redlin von Meding, "Feinmechaniker und Wissenschaftler."

[5] Olesko, "Civic Culture," 23.

Unfortunately, he could not channel these abilities toward a formal education. He had great difficulty with the classical languages, a main requirement for passing the humanist orientated Kneiphöpf Gymnasium. The end of the year report for 1849, when he would have been approaching his senior year, showed that there was a large emphasis on Greek, Latin and Hebrew.[6] Aside from the formal language courses, there were three courses devoted solely to Ovid, Homer and Virgil. In English, the students read, among several items, the *Christmas Carol* by Dickens and the *Prisoner of Chillon* by Byron. In French they read *l'Avare* by Moliére and a history of Napoleon by Dumas. There were also courses in history, geography, singing, penmanship, natural history and German. Koenig's father, Friedrich, taught French, mathematics and physics – three courses that would be crucial for his later career in Paris. The report did not specify Prof. Koenig's course outline for physics, but we do know that he had a modest physical cabinet at his disposal for demonstrations. In 1849 he added to this cabinet a magnetic needle with a stand, a large brass concave mirror on a tripod, an achromatic optical demonstration device, and a magnifying glass. He not only had a doctorate, but had obtained his habilitation (post-doctoral lecturing qualification) in 1839. He was the only full professor at the Gymnasium and he frequently published articles on mathematics in such leading journals of the day as *Crelle's Journal für die reine und angewandte Mathematik* and *Grunert's Archiv der Mathematik.*

Koenig subsequently failed the Abitur (the state regulated examinations for leaving secondary school), which was a great disappointment to his father. Prof. Koenig had put much pressure on his only son to succeed. The Koenig family did not have enormous resources, however, and Rudolph decided to take up a trade he could easily master. Inspired by his grandfather's stories of England and France, and the family traditions in musical instrument making, he moved to Paris in 1851 at the age of 19 and joined the workshop of the celebrated violinmaker Jean Baptiste Vuillaume (1798-1875). In this endeavour he combined his unusually good ear for musical sounds

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[6] Rudolph F. L Skrzeczka, *Zur öffentlichen Prüfung im Kneiphöfischen Stadt-Gymnasium* (Königsberg: E.J. Dalkowski, 1849).

with his skilled hands. His subsequent training in the violin workshop had a profound influence on his career (see Chapter Three).

The bohemian Paris of the post-revolution years (following the uprisings of 1848) was the ideal setting for the romantic young Königsberger who wanted to reinvent himself. Since the thirties, Koenig's literary hero, the poet Heinrich Heine, had been sending dispatches from Paris to German readers, and now Koenig wanted to be an active part of one of Europe's most sophisticated cities. In fact, he arrived in Paris at a remarkable time. His new employer, Vuillaume, had just won the grand medal for stringed instruments at the London Exposition of 1851. Also in that year, Vuillaume had invented the famous Octobass, an eleven-foot giant double bass, and played it at St. Eustache church in Paris. In the world of French musical instruments, this was the era of Vuillaume's violins, Adolphe Sax's innovations with brass instruments and Erard's stronger and more powerful pianoforte. In late 1851, Napoleon III declared himself emperor in a coup, thus beginning the Second Empire that would last until the Franco-Prussian War in 1870. The 1850s would witness massive economic and industrial expansion, and a reversion to more conservative politics. Baron Haussman's sweeping renovation of Paris began in 1852 shortly after Koenig's arrival, as we will see later, would provide an opportunity for one of his more memorable series of experiments in the sewers of Paris.

After seven years of working with Vuillaume, and becoming a master violinmaker, Koenig started his own business in 1858 as an acoustical instrument maker for scientists. He had been attending public lectures and studying mechanics in his leisure time, and with the recent retirement of Albert Marloye (1795-1874), the acoustical instrument maker of Félix Savart (1791-1841), Koenig saw an opportunity for his own career in the science of music. He opened his shop at Place Lycée Louis le Grand, which was on the grounds of the famous Lycée in the heart of the school district. One of his first commissions came from the local scientist and inventor, Édouard-Leon Scott, to help build the phonautograph, the first instrument to graphically record sound on a revolving drum. This ingenious apparatus and other graphical instruments provided the young maker with instant notoriety (§3.4). They added a totally new dimension to the study of sound.

In 1859 Koenig issued his first catalogue, which strongly resembled that of the earlier acoustical maker, Marloye. There was a long history of acoustical research in Paris, rooted in the mathematical treatises of Leonhard Euler (1707-1783), Jean d'Alembert (1717-1783) and Joseph-Louis Lagrange (1736-1813), and then later in the experimental work of Savart. Koenig was closely involved in Parisian scientific circles in his early years of business. He was attracted to their straightforward experimental approach and their emphasis on methodology. He even participated in the regular Monday séances at the Academy of Sciences (l'Institut) (§3.6).

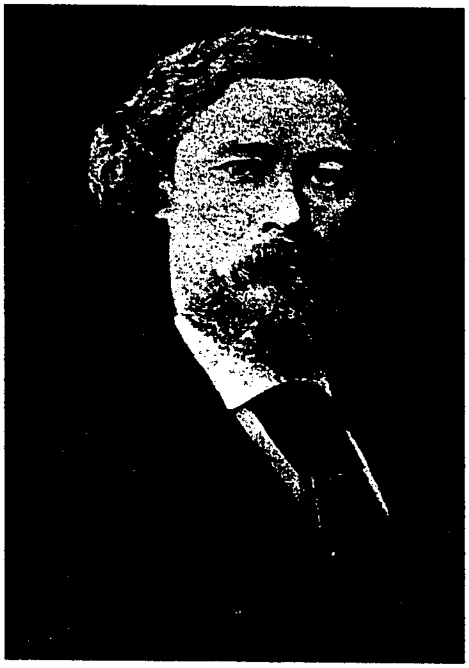

Figure 1.1 Rudolph Koenig (circa 1876). Miller (1935)

During this period he began active research on his own. His first experiments in 1858 were psychological. With a series of high pitched tuning forks he mapped out the threshold for distinguishing musical intervals (such as the third, fourth or fifth) and discovered that even in the higher octaves of the piano, the best musicians failed to "judge exactly" the basic intervals.[7] Surveying the range of the activities in his new workshop at this time, we find him performing novel research on the laws governing vibrating plates, inventing instruments to measure the velocity of sound, developing a new stethoscope, creating instruments for graphically representing sound, constructing precision tuning forks, and inventing an instrument for testing the quality of violin strings. He quickly became part of the famed precision instrument industry of Paris, winning a medal of distinction at his first world fair in 1862 in London. During this period Koenig's atelier became a meeting space for diverse activities and people (§3.6).

In Paris it was not unusual for instrument makers to be active in shaping their respective fields. One of the leading scientific figures in Paris of this time was the instrument maker Gustave Froment (1815-1865).[8] Froment had constructed the pendulum apparatus for Léon Foucault (1819-1868) in 1851, and a year later a gyroscope that demonstrated the rotation of the earth. In September 1862, Foucault, Froment, the astronomer Le Verrier, and the organ builder and scientist Aristide Cavaillé-Coll (1831-1899) collaborated on their celebrated experiment to measure the speed of light. Cavaillé-Coll, who had just completed his masterpiece organ of over 7000 pipes at Saint Sulpice, joined these sessions in order to help operate a wind-driven siren that was to calibrate the rotation of a small mirror.[9] Another notable figure in Parisian scientific circles was a young German instrument maker, who, like Koenig, had permanently relocated to Paris in the late 1830s. Heinrich Daniel Ruhmkorf (1803-1877), from Hanover, developed an extremely powerful and efficient electrical coil in the mid-1850s, the "Ruhmkorf coil," which would thrust electrical studies into a new era.[10] Ruhmkorf's successor, Jules Carpentier (1851-1921), who be-

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[7] Rudolph Koenig, "Quelques notes," in *University of Toronto Archives, Loudon Papers B72-0031/017(05)* (1901).

[8] Paolo Brenni, "Paul Gustave Froment (1815-1865)," *Bulletin of the Scientific Instrument Society* 45 (1995).

[9] Gerard L'E. Turner, *The Practice of Science in the Nineteenth Century: Teaching and Research Apparatus at the Teyler Museum* (Haarlem: Teyler Museum, 1996) 184.

[10] Paolo Brenni, "Heinrich Daniel Ruhmkorff (1803-1877)," *Bulletin of the Scientific Instrument Society*, no. 41 (1994).

came known for his excellent precision workmanship, worked closely with Marcel Deprez (1843-1918) and Arsène d'Arsonval (1851-1940) in their pioneering electrical work.[11]

In the world of acoustics, one preoccupation of the late 1850s that steadily grew in urgency was the need to standardise pitch. Throughout Europe pitch standards had varied considerably causing much confusion and making some music almost impossible to play. In 1858 the French government established a commission to create a standard French pitch. In response to this challenge, Jules Lissajous (1822-1880) of the Lycée Saint-Louis developed a new visual method for making precision tuning forks and created a standard tuning fork, La3 = 870 v.s (a' = 435 Hz). Lissajous collaborated with the instrument maker Marc François Louis Secretan (1804-1867) and the resultant fork came to rest in the Conservatoire National de la Musique.[12] Lissajous's method of making forks, to be discussed more fully later, became the technical catalyst for a revolution in precision tuning under Koenig (§2.19).

While the concert halls of France were coming in tune with each other, taste in the musical world was changing dramatically. This was the age of the soloist represented by the piano virtuoso Franz Liszt, and violinist Paganini. On March 13, 1861 Richard Wagner's (1813-1883) controversial opera *Tannhäuser* was performed in Paris. Some protested the new sounds of Wagner and a scandalous riot ensued. These kinds of fundamental questions about harmony fuelled the desire to understand the laws that governed the most ephemeral of humankind's artforms.

In 1863 Helmholtz, who had moved from Königsberg to Bonn and then to Heidelberg to take up prestigious physiology chairs in the growing German university system, published his groundbreaking work, *Die Lehre von den Tonempfindungen als Physiologische Grundlage für die Theorie der Musik (Sensations of Tone as a Physiological Basis for a Theory of Music).* This work completely changed how scientists and musicians conceived of, and experimented with, sound. For the first time science had provided a comprehensive explanation of timbre (the character,

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[11] Paolo Brenni, "Jules Carpentier (1851-1921)," *Bulletin of the Scientific Instrument Society* no. 43 (1994).
[12] Paolo Brenni, "Lerebours and Secretan," *Bulletin of the Scientific Instrument Society* no. 40 (1994).

"tone colour," or quality of a musical sound) as a unique combination of elemental tones. The "g" note on a trumpet sounded different from a "g" on a French horn because of the presence of the *fundamental* tone "g" with a series of different kinds and intensities of *harmonics* or *upper partials* in the compound musical sound. At the same time Helmholtz provided precise mathematical laws to explain the resonating properties of aerial chambers, musical or natural. Harmony (the subjective notion that some sounds "agreed" with others in pleasing ways) was given a foundation in physiology. He placed emphasis on the variations of a musical phenomena known as beats (the periodic fluctuations in tone caused by the interference and amplification of converging sound waves) to explain why some combinations of sounds created agreeable sensations in the inner ear, whereas others did not. He elaborated this theory by refining and clarifying a related musical phenomenon called a *combination tone* (a tone that resulted when two notes were played at the same time), and made such tones, like beats, a key part of the fabric of harmony. Each of the above areas depended heavily on the newly defined phenomena called *simple tones*, or the elements of sound. Helmholtz clarified the mathematical and physiological basis for these elements and made them into a laboratory reality with a handful of new scientific instruments. Beats, combination tones, fundamentals, upper partials, and simple tones served as the foundation for the new acoustics.

A year or two after the 1862 London exhibition, Koenig moved into a new instrument shop near the faculty of medicine at 30 rue Hautefeuille. The early years of his business had been very difficult as he had little financial resources, but he gradually developed the means to expand in business and perform his own research. This move also marked a phase in his career when he began to focus increasingly on making instruments for the reforms of Helmholtz. In 1865 he published his second catalogue with several woodcut illustrations of new instruments. This catalogue was a definitive break with past acoustics, including several innovations from the theories and instruments of Helmholtz and other instruments from his own research.

One of Koenig's more sensational instruments related to the idea of visualising sound vibrations by use of a vibrating flame. In 1862 he invented the manometric flame capsule that made sound vibrations visible through a vibrating membrane connected to a gas flame burner. A sound stimulated the membrane and the flame flickered creating a wave pattern when viewed in a strobe-like mirror. It was used extensively for the next fifty years to investigate and demonstrate sound vibrations of all kinds. By 1865, the year his father died, Koenig had earned an enviable reputation as a young instrument maker. In fact, for his early accomplishments he won the prestigious Médaille d'Or from the Société d'Encouragement, a society devoted to promoting progress in science and industry.

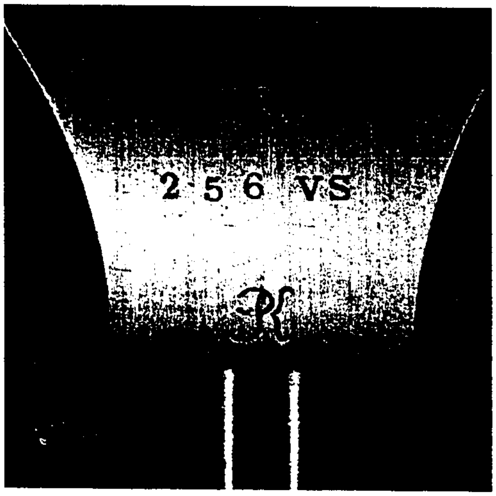

Figure 1.2 Koenig's monogram with frequency number and notation on a tuning fork from the tonometer, c. 1876. University of Toronto Museum of Scientific Instruments (UTMuSI).

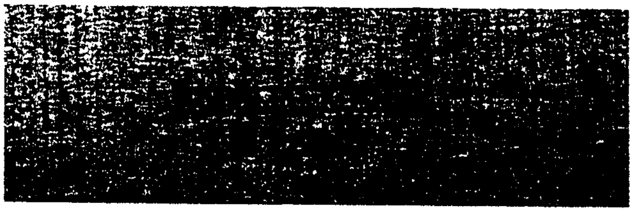

Figure 1.3 Koenig's stamp on a pine resonator box for the 65-fork tonometer, c. 1876. UTMuSI.

His rise in the scientific world continued after the publication of the catalogue of 1865. In the midst of Haussman's extensive renovations of Paris, he collaborated in 1866 with the great Parisian experimentalist Victor Regnault (1810-1878) in the sewers of Paris on an exhaustive series of experiments to measure the speed of sound. The city's engineers allowed them to use over 5 km of freshly laid gas and water pipes. As a result of these experiments he produced his premium precision graphical timing apparatus, the Regnault chronograph (§3.9).

In 1867 Koenig won the gold medal at the Paris exposition for his new graphical instruments, manometric instruments, tuning forks and instruments derived from Helmholtz's studies. In April of the next year, at the age of thirty-five, he received an honorary doctorate from the University of Königsberg. At this time he had just begun a lengthy series of experiments on vowels, another central area of study in the new acoustics, which would be presented to the Academy of Sciences by Regnault in the spring of 1870. This study was his first correction to Helmholtz's work (§4.2).

In the autumn of 1870 war broke out between France and Prussia. Forced into exile, Koenig moved to Switzerland and then to Prussia. For a while he was in Königsberg, Berlin and Magdeburg with his family. In the spring of 1871, following Prussia's victory, France endured further chaos through the disastrous Commune that was finally brought to a close by the government of the Third Republic. Remarkably, he kept his business going (albeit at a very slow pace) from a distance, and was pleased to find upon his return in June 1871 that loyal workers had kept his studio intact, and nothing had been looted.

In contrast to the loyalty of his workers, Koenig returned to an inhospitable environment in Paris. He was accused of fighting for the Prussians during the war and was deserted by almost all of his friends in the scientific community. Regnault, who had lost his son Victor (the painter) in the last days of the war, was a broken man and withdrew from the Parisian scientific scene altogether. One person who remained a staunch supporter was the Abbé François Napoléon Marie Moigno (1804-1884), editor of the local weekly scientific journal *Cosmos* and later *Les Mondes*. After Koenig's return in 1871, Moigno passionately defended him against the "odious slander" that he had served in the Prussian artillery. Moigno claimed that Koenig could just as easily have moved permanently to Berlin where he was needed, but instead he had returned to Paris where he became a prisoner in his own workshop. He mentioned as well that the German instrument makers Ruhmkorf and Hofmann had followed Koenig's example in choosing to continue to work in the "inventive atmosphere of France" and "we appreciate and thank them."[13] Another Frenchman who remained a loyal friend and colleague was the physiologist, Etienne-Jules Marey (1830-1904). Marey, as we will see later, was also a pioneer in graphical studies in Paris in the late 1860s (§3.5).

Koenig was fortunate in having good friends abroad during this period. They promoted his interests outside of Paris, and provided needed encouragement during a very difficult period. A good friend in Austria was Franz Joseph Pisko, a professor of physics and mathematics at Vienna. In 1865 Pisko published a book on the new acoustics in which all of Koenig's instruments figured prominently. Pisko would remain one of his key supporters in the German world. In the United States, Alfred Marshall Mayer (1836-1897), who left the civil war in America in 1863 to study in Paris under Regnault, remained until his death in 1897 one of his closest collaborators and supporters. Mayer, who would become one of the premier acoustical researchers of the later nineteenth century, founded the Stevens Institute of Technology in Hoboken, New Jersey. Like Koenig he was a follower of Regnault and therefore had a love of experiment and a deep appreciation for honing methods and instruments. Before his death Mayer spent two summers living at 27 Quai d'Anjou performing a series of experiments on Koenig's masterpiece series of tuning forks, the grand tonometer.

England was especially good to Koenig. Following his isolation from the Parisian scientific scene, William Spottiswoode a physicist from England became a close promoter and collaborator. Spottiswoode, a wealthy eccentric with a love of acoustics, was the president of the Royal Society in the late 1870s and one of the founders of the British Musical Association, a group of scientists and musicians devoted to "the investigation of subjects connected with the art and science of music." Spottiswoode spread Koenig's name throughout the English scientific community. Upon his

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[13] François Napoléon Marie Moigno, "Calomnie," *Les Mondes* 26 (1871) 602.

death in 1883, Koenig wrote that "during the long years after the war, he was the only scientist who would show a true interest in my work, and I can say that I possibly never received his visits, without having felt after his departure more courage to continue the path of my labours."[14]

1.2 EXPERIMENTS, FAIRS AND CLIENTS, 1871-1882

France and Germany went through profound changes following the Franco-Prussian war. In Germany Otto von Bismark was able to complete the long sought goal of creating a united Germany, thus providing even more momentum to German economic expansion. The explosion of German industrialisation between 1850 and 1880 was giving way to a culture of progress and a strong belief in the power of science and technology. German science, for example, began to enjoy world renown through its competitive and well-funded universities, practical teaching methods and strong research traditions. France, on the other hand, went through a period of intense soul-searching. Politicians argued that France owed its defeat in the war to the demise of French science and technology. Scientists complained that the lack of reform in science education had placed France at a distinct disadvantage compared to Germany. Under the new republican government, education reform became a top priority.[15] This would lead to the creation of more laboratories for research and teaching, and therefore more business for instrument makers. Unfortunately, the fall-out from the war also led to strong anti-German sentiments that made life very difficult for immigrants like Koenig.[16]

We also see in this period the emergence of laboratory science and teaching in American universities and institutions. Although a depression in the early 1870s thwarted some of their spending, by the mid-1870s many universities began building research institutions modelled on the

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[14] Undated letter circa 1883 Rudolph Koenig, "Koenig Letters (1878-1901)," in *University of Toronto Archives, Loudon Papers, B72-0031/004.*

[15] Alan Rocke details the movement to reform French science in, Rocke, *Nationalizing Science: Adolphe Wurtz and the Battle for French Chemistry.* Also see Harry W. Paul, *From Knowledge to Power: The Rise of the Science Empire in France, 1860-1939* (Cambridge; New York: Cambridge University Press, 1985).

[16] The police archives in Paris have countless surveillance files on Germans from the period 1870 to 1900. A cursory search through these records, however, did not turn up Koenig's name.

German system. French instrument makers, still the leaders in the precision instrument trade, now looked across the ocean to a new, growing market.[17]

The field of acoustics blossomed into a thriving research discipline rivalling other areas of study – optics, chemistry, electricity and magnetism – that had developed experimental traditions in the earlier part of the century. Part of this surge in interest came from the work of Helmholtz, and part came from the new instruments made and sold by Koenig. In England, William Strutt (Lord Rayliegh) (1842-1919) expanded upon Helmholtz's work by developing a refined theory of resonance. John Tyndall (1820-1893) did some groundbreaking acoustical research on sound transmission in the atmosphere and he popularised the new experimental acoustics with his treatise *On Sound* (1867).[18] Alexander Ellis (1814-1890) translated Helmholtz's masterpiece, *Sensations*, and performed numerous experiments on the standard-pitch question. William Thomson (later Lord Kelvin) (1824-1907) had a keen interest in experimental acoustics. In the 1840s he had worked with Regnault for a short time "learning patience and precision" and he also purchased acoustical instruments from Marloye.[19] The physicist Silvanus P. Thompson (1851-1916) took an active role by supporting Koenig's research and instruments.

The German world as well saw the emergence of a small group of specialised acoustical researchers; in physical research there was August Kundt (1839-1899), Karl Friedrich Sondhaus (1815-1886), Ernst Mach (1836-1916), Gustave Kirchoff (1824-1887) and August Toepler (1836-1912); in physiological acoustics there was W. Preyer (1841-1897), Ludimar Hermann (1838-1914) and Adam Politzer (1835-1920).

America was equally enthusiastic about acoustics. Joseph Henry (1797-1878) of Princeton and later the Smithsonian Institution led the way with his pioneering research on foghorns and architectural acoustics. Alfred Mayer performed foundational acoustical experiments on timbre

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[17] Deborah Jean Warner, "French Instruments in the United States," *Rittenhouse* 8, no. 1 (1993).

[18] For more on Rayleigh and Tyndall see Robert T. Beyer, *Sounds of Our Times: Two Hundred Years of Acoustics* (New York: Springer-Verlag, 1998).

and beats, two areas of focus for Helmholtz and Koenig. He also did pioneering studies on the duration of sound sensations. The real thirst for acoustics in America, however, came from the two great inventions of the 1870s, the telephone of Alexander Graham Bell (1847-1922) and the phonograph of Thomas Edison (1847-1931).

Aside from his troubles as a German in Paris, the period just after the war was one of the most productive of Koenig's career. Remarkably, he was able to build on the success and momentum – in business and research – that he had obtained before the war. In 1872 he published a detailed account of his manometric flame studies which appeared in English a year later.[20] This proved to be a classic paper that introduced a whole family of visual methods for studying sound. Many scientists quickly adopted his visual methods for their investigations, making them standard for research and teaching. He also began a monumental series of studies on two key areas of the new acoustical fabric, combination tones and beats. Doubts surrounding Helmholtz's experimental work fuelled his activities, as he attempted to refine and clarify the empirical foundation of these elusive phenomena. Armed with his new findings, he published in December 1875 a major experimental critique of Helmholtz's theory of beats and combination tones.[21] It was an experimental tour de force and when communicated to the English scientists through Spottiswoode, became his most controversial paper (§4.4).[22] Capping off this work, he constructed a giant tuning fork tonometer, consisting of 670 forks covering four octaves, from middle "c" on the piano to the upper note. This instrument was a monument to the new acoustics, providing almost every shade of tone for tuning and basic research.

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[19] Crosbie Smith and M. Norton Wise, *Energy and Empire: A Bibliographical Study of Lord Kelvin* (Cambridge: Cambridge University Press, 1989) 28, 107-08.

[20] Rudolph Koenig, "Die manometrischen Flammen," *Annalen der Physik und Chemie* 146 (1872). Rudolph Koenig, "On Manometric Flames," *Philosophical Magazine* 45, no. 297 (1873c).

[21] Rudolph Koenig, "Ueber den Zusammenklang zweier Töne," *Annalen der Physik und Chemie* 157 (1876a).

[22] Rudolph Koenig, "On the Simultaneous Sounding of Two Notes," *Philosophical Magazine* 1, no. 6 (1876c).

Business was also improving, although it proved a rather rocky road. One of his better clients in the 1870s was Joseph Henry of the Smithsonian Institution in Washington D.C. In 1865 Henry had his agent in Paris inquire into the cost of a complete set of acoustical apparatus from Koenig. From 1865 to 1878 the Smithsonian became one of his first major institutional clients. Henry was America's foremost physicist and a pioneer in electromagnetism. He was also keenly interested in acoustics. As mentioned above, he had done landmark studies of architectural acoustics and a long series of tests on the foghorns of lighthouses.[23] After working at Princeton for a number of years and gaining great international repute for his powerful electromagnets, he was named the Smithsonian's first secretary in 1848. He survived nine presidents as secretary and became a powerful influence on science policy in the United States.[24] The instruments of the great Parisian ateliers figured prominently in Henry's plan for science in America.[25] He envisioned a research-based institution where scientists and teachers could visit to see and use the latest apparatus of natural philosophy. At the "Castle," the main Smithsonian building, there was an apparatus room, or museum of physical instruments, which, in Henry's words, "may be used for experimental illustration and original research, and may serve as models to workmen as well as to illustrate the general progress of inventions in this line."[26] Henry spelled out the role of new instruments, and the role they would play in the future development of American science, in a letter of 1847 to Alexander Dallas Bache, one of the regents of the new Smithsonian.

> ... since we are to form a large collection of articles of Foreign and curious research which may serve to excite the love of learning, a collection of Physical instruments should form an essential part of this and be of such a character as to induce a pilgrimage

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[23] Joseph Henry, "Research in Acoustics," in *Annual Report, Smithsonian Institution* (Washington D.C.: 1856).

[24] Albert E. Moyer, *Joseph Henry: The Rise of an American Scientist* (Washington D.C.: Smithsonian Institution Press, 1997).

[25] For more on French instruments in the United States, see Warner, "French Instruments."

[26] Joseph Henry, *Fourth Annual Report of the Board of Regents of the Smithsonian Institution to the Senate and House of Representatives* (Washington D.C.: United States Senate, 1850) 18.

> to Washington of all the *quid nunc* professors in our country to enlighten themselves as to the progress of science and to witness the new phenomena.[27]

In the 1870s, Koenig and other French makers would directly benefit from Henry's mission for science in America.

In 1873 Koenig published his second catalogue in order to increase some of his prices since his last catalogue of 1865. In a brief forward to the catalogue he stated that there had been a considerable increase in the cost of materials and labour. He also added some new instruments because "the progress of acoustics since 1865 has been considerable enough to demand a new catalogue."[28] Unfortunately, the release of a new catalogue would be drowned out by larger forces in the market place. A depression hit Britain in 1873 that had a large impact on the world economy. On September 23, 1873, Henry wrote of a banking failure in the United States, stating that he would have to countermand one of his large orders for instruments. Koenig responded on October 11 that he would give the Smithsonian a credit of an entire year "if you should think it of any advantage for the institution to have the instruments." Henry, who was beginning to see the fruits of his vision take shape, was undeterred by this set back. He waited a year and ordered a portion of the key instruments again for 3000 francs. A year later he ordered fifty more instruments for a total of 3070 francs.[29] He purchased several more important apparatus before he died in 1878.[30]

Aside from the problems that Henry had in recouping his funds, the North American market for instruments grew steadily during this period. New student laboratories significantly increased

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[27] Joseph Henry, "Letter to Alexander Dallas Bache, March 31, 1847," in *The Papers of Joseph Henry*, ed. Marc Rothenberg (Washington and London: Smithsonian Institution Press, 1847) 70.

[28] Rudolph Koenig, *Catalogue des Appareils d'Acoustique* (Paris: 1873a) 2.

[29] In the order of August 8, 1874 he asked in particular for the grand bellows for experiments and demonstrations with organ pipes. The next order (January 1875) included a Seebeck siren, the standard series of nineteen spherical resonators, the sonometers of Barbareau and Marloye, the double siren of Helmholtz and several demonstration apparatus of plates, membranes, organ pipes, rods and reed pipes. "Letters to Rudolph Koenig, 1865-1878," *Smithsonian Institution Archives, Office of the Secretary, 1863-1879 Outgoing Correspondence, Record Unit 33, vol. 35, reel 55, 635; vol. 40, reel 61, 352; vol. 41, reel 64, 733; vol. 44, reel 69, 416.*

[30] "Letters to Joseph Henry, 1865-1878a," in *Smithsonian Institution Archives, Office of the Secretary, 1863-1879, Incoming Correspondence, Record Unit 26, vol. 166, 269-275.* The instruments that Henry purchased in 1877 included Koenig's premier graphical instruments: the Regnault Chronograph and the tuning forks for graphically demonstrating Lissajous figures.

the demand for teaching and demonstration instruments. In 1876, eager to fully capitalise on this potential market, Koenig went to the Philadelphia Centennial Exposition. This fair would be both a great triumph and a great tragedy for the forty-three year old instrument maker. He came to Philadelphia with high expectations, bringing his entire collection, especially his masterpiece tuning fork tonometer. His display did not go unnoticed and won a medal of distinction. The judges included William Thomson of Glasgow, F.A.P Barnard of Columbia College and Joseph Henry. A summary of his exhibit by Barnard, who was also his customer for the new physical and physiological laboratories at Columbia, read:

> In the department of acoustics, as represented in the Exhibition, the field was occupied almost wholly by a single exhibitor, Dr. Rudolph Koenig, of Paris. As a constructor, indeed, Dr. Koenig may be said to have monopolized this field before the world almost as exclusively as in the Exhibition, for its to his skill that most eminent investigators have been accustomed continually to resort for the means of realizing their many ingenious conceptions.[31]

The official report of the judges described his tonometer as "giving as many different shades of pitch extending over four complete octaves, and making equal intervals of eight simple vibrations each for the first octave, and of twelve each for the succeeding octaves; the whole forming an absolutely perfect means of testing, by counting beats, the number of vibrations producing any given musical sound, and of accurately tuning any musical instrument."[32] They also mentioned the manometric flame invention and his new instruments for challenging Helmholtz's theories. "Of the exhibit of Dr. Koenig as a whole, it may be said that there is no other in the present International Exhibition which surpasses it in scientific interest."[33] One visitor noted that "before the

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[31] Francis A. Walker, ed., *United States Centennial Commission. International Exhibition 1876. Reports and Awards. Groups XXI-XXVII*, vol. 7 (Washington D.C.: Government Printing House, 1880) 12-13.
[32] Ibid., ed., 167.
[33] Ibid., ed.

fair closes, [Koenig] proposes to give still further exhibits of the control he has in detecting the most delicate tones."[34]

The praise was high but the pockets were shallow. Koenig's instruments, which were of the highest quality and craftsmanship, were simply too expensive for most colleges and universities trying to build laboratories. Nevertheless, Henry and Barnard wanted to keep his instruments in the United States where they would "be made serviceable to the progress of American science." They asked Koenig if the instruments could stay for a short while as they put out a subscription to buy the collection. Together with J.C. Watson of Ann Arbor, Michigan, and J.E. Hilgard of Washington, D.C., they wrote a letter of appeal to American scientists to keep the instruments in the United States. They spoke of the great value and scientific interest these instruments would provide for scientific associations and educational institutions. Some of the instruments they argued were built on a scale "without previous example" and with acoustical effects of great power "which must make them invaluable to the instructor or investigator." The tonometer, for example, was said to produce "any given sound for investigation." "These instruments are the perfected result of years of laborious study and great mechanical skill, and they are entirely unique of their kind. The undersigned cannot but feel that it would be a misfortune to the cause of scientific progress in the United States if they should be permitted to leave the country." They underscored that "their costliness puts them beyond the reach of any of our institutions of learning except a few of the most wealthy," but they hoped that "friends of science in the United States...may purchase this valuable collection and generously present them to an institution in which they may be made useful in promoting the advancement of science."[35]

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[34] Samuel J. Burr, *Memorial of the International Exhibition* (Hartford: 1877).

[35] F.A.P. Barnard et al., "An Appeal to the Friends of American Science," in *UTA, Loudon Papers, B72-0031/004* (1876).

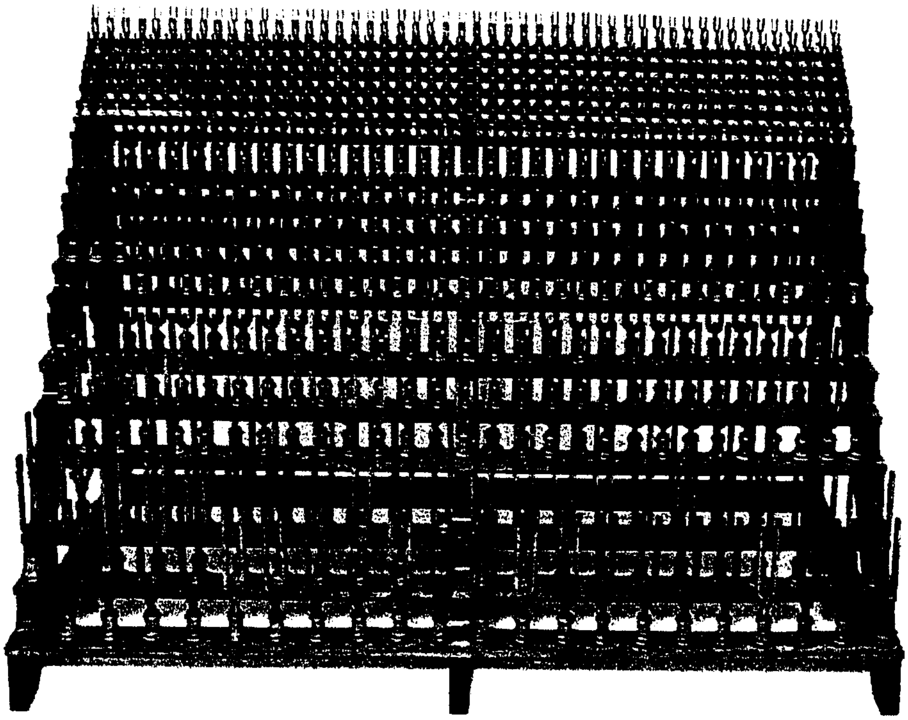

Figure 1.4 Grand tuning-fork tonometer, with 670 tuning forks, as displayed at the Philadelphia Exhibition in 1876. National Museum of American History, Smithsonian Institution, Washington D.C. (cat. no. 315,716).

The appeal failed. After a year Henry himself purchased some of Koenig's premier graphical instruments for the Smithsonian.[36] The remaining instruments were sent to the University of Pennsylvania for better storage and put under the care of Professor Barker, who wrote to Koenig asking to keep the instruments longer, ensuring that they would soon be sold. Five years later, many instruments had still not been sold.[37] This was an enormous source of stress for Koenig. Barker had frequently written to him predicting that they would soon sell, and, what was more distressing, it appeared that Barker was using the instruments during this whole period.[38] Eventu-

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[36] See letter of June 22, 1877. Koenig, "Letters to Joseph Henry, 1865-1878a." Henry bought nos. 205a, 208a and 209a for 2936 francs .

[37] Contrary to what Miller (1935) claimed, many of the instruments bought for Toronto in 1878 came from Koenig's studio in Europe, and not from Philadelphia. Perhaps as of 1878 Koenig still expected the Philadelphia collection to sell in the United States and therefore did not ship them to Toronto.

[38] Barker apparently demonstrated some of the instruments for Henry. See, June 22, 1877. Koenig, "Letters to Joseph Henry, 1865-1878a."

ally Koenig was forced to return to America to take them home. He was particularly worried that his reputation had been damaged by the ensuing battles with Barker and the University of Pennsylvania, so he published a pamphlet quoting all of Barker's letters to clear up "erroneous rumours." "While some said they [the instruments] had been bought by the University, but never paid, others thought I had abandoned these instruments to the mercy of the University. So I think it will be well both for the good of the University and for me that the truth should be known."[39] He claimed that he was induced to permit the instruments to go to the University and remain there year after year. When he returned in 1882, he spent almost an entire month scrambling from university to university trying to sell the collection. He managed to sell a number of instruments to Mayer at the Stevens Institute, to Barnard at Columbia and to a few other professors on the East Coast. Before his return, the University of Toronto had purchased portions of the collection.[40] Professor Peter S. Mitchie, professor of natural philosophy at the United States Military Academy at West Point, purchased the great tonometer of 670 tuning forks for over 8,000 francs. But even with this minor success, Koenig had to pack and send eleven crates home at considerable expense. He was devastated by the ordeal and would thereafter refer to Philadelphia as "cette ville de malheur."[41]

In 1876, just following the exhibition in Philadelphia, he travelled to Buffalo for the meeting of the American Association for the Advancement of Sciences where he met James Loudon (1841-1916) of Toronto. Loudon had recently been named professor of physics at the University of Toronto and he was eager to set up an undergraduate teaching laboratory based on the successful German model of laboratory-based teaching. Several colleges, both large and small, in North America were in the process of establishing "object based" practical teaching of science and they

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[39] Pamphlet of 1882 in Koenig, "Koenig Letters (1878-1901)."

[40] These consisted of large tuning forks and resonators for demonstrations and experiments on beats. See Oct 17, 1882 Ibid.

[41] At times Koenig wrote daily descriptions of these events in October 1882 to James Loudon in Toronto Ibid.

were looking to Europeans for guidance.[42] Loudon, who had an interest in acoustics, was immediately attracted to Koenig's work. "As it was the year of the centennial Exhibition a large number of foreigners were present [in Buffalo] and amongst them Koenig, who addressed Section A in German, speaking with great animation, and receiving a most enthusiastic reception." Thus began a friendship that would last until Koenig's death in 1901.

After two years of administrative struggles for his new vision of science, Loudon secured in 1878 the large sum of $12,000 from the university to establish the first physical laboratory in Canada. Refusing to use agents (the norm of the time) Loudon went directly to Europe for a buying spree. He first stopped by the Cavendish laboratory at Cambridge. "There I met W. Glazebrook, assistant to Professor Clerk-Maxwell who was absent. On mentioning my intention of proceeding to Paris, and consulting with Dr. Rudolph Koenig, the acoustician whom I had met two years before...Glazebrook said I could do no better."[43]

Paris was the centre of the precision instrument trade at the time, and therefore could be a rather complex, intimidating market to navigate for a thirty-seven year old professor from Toronto. Upon arriving in Paris, Loudon was greeted by a business commissioner (agent) who, somehow learning of his mission, offered help in introducing Loudon to all the reputable instrument makers. Loudon coyly replied that he had merely come to get an idea of the scientific instrument scene in Paris and would not as yet need help. "On arriving at Dr. Koenig's place, his first expression was one of delight that I had come unaccompanied by a commissioner (who it appeared generally accompanied purchasers from America) adding that I should get better in-

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[42] For more on the history of physics at Toronto, see Elizabeth J. Allin, *Physics at the University of Toronto: 1843-1980* (Toronto: University of Toronto Department of Physics, 1981). For more on the development of the German teaching model in Canada, see Yves Gingras, *Physics and the Rise of Scientific Research in Canada*, trans. Peter Keating (Montreal & Kingston: McGill-Queen's University Press, 1991). For more on the social and cultural context of these developments in the United States, see Deborah Jean Warner, "Physics as a Moral Discipline: Undergraduate Laboratories in the Late Nineteenth Century," *Rittenhouse* 6, no. 24 (1992).

[43] James Loudon, "Memoirs," in *University of Toronto Archives, Loudon Papers* (1916), 40.

struments and full value for my money."[44] Koenig told him of the high percentage that agents often exacted from clients and he coached him on the best way to go about his mission. Over the next 20 years he became Loudon's agent helping him buy instruments from the leading makers in Paris – Golaz in heat, Lutz and Laurent in Optics, Carpentier in electricity, and Froment in mechanics.[45] But the largest number of instruments came from Koenig himself. Through his connections and guidance Koenig had a large impact on the eventual shape of Canada's first physics laboratory.

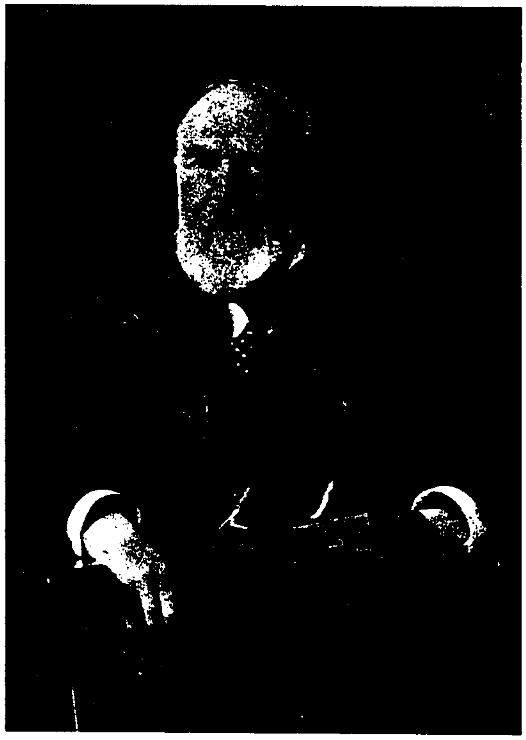

Figure 1.5 James Loudon (circa 1900). Alexander (1906).

Loudon's choice of Koenig was no accident. He saw in him an ideal model for his vision of science education at Toronto. "Dr. Koenig was not only a most celebrated maker of acoustical instruments but an eminent scientific man who had received an honorary degree from the University of Königsberg for his discoveries in acoustics." Koenig was also a very good promoter of

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[44] Ibid.

[45] Paolo Brenni, "19th Century French Scientific Instrument Makers."

Loudon's mission for bringing practical hands-on science to the University of Toronto, a struggle he had waged against the Toronto establishment for six years before being given the money. The first $12,000 had been hard to get, but in the following twenty years there seemed no limit to Toronto's eagerness to spend on laboratories. Loudon attributed part of his later successes in building the laboratories at Toronto to his initial trip to Paris.

> On learning that our Chancellor (William Blake) [the second premier of Ontario] and Vice Chancellor C.T. Thomas Moss [Loudon's neighbour in Toronto] were in Paris at the same time, Dr. Koenig invited us all to a scientific séance at his place where we witnessed many of his most beautiful acoustical experiments, such as Lissajous figures, sympathetic vibrations, interference of sound, sounds of beats etc. The success of this séance was not without its influence in interesting the Chanceller and Vice Chanceller in the development of experimental science in their own university.[46]

During his Paris trip Loudon purchased an almost complete collection from Koenig at a whopping sum of 21,000 francs. Even Joseph Henry at the Smithsonian had balked at spending that much in one area of physics. It would be one of the largest orders Koenig had ever filled. Loudon was at that time, and for the next twenty years Koenig's best client. In addition to Loudon, Ramsey Wright (1852-1933) of physiology, another proponent of research-based education, befriended Koenig and purchased instruments for his new laboratory. In the 1890s James Mark Baldwin (1861-1934) and August Kirschmann (1860-1932) (a student of Wilhelm Wundt's), the founders of the psychology laboratory at Toronto, also made purchases. Even the "Toronto Technical School" (a specialised high school) enquired about his instruments.[47]

The Toronto money gave Koenig the security to renew serious research and invent several new instruments. In effect, he continued where he had left off before Philadelphia. This mode of business formed a pattern throughout his life – he sold instruments primarily to fund his research. A colleague in Britain remarked upon Koenig's death:

> If by some stroke of luck he sold instruments that brought in a few hundred francs above the regular income of his business he would hail it as the means of constructing some new piece of experimental apparatus that might never find a sale, but would help his in-

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[46] Loudon, "Memoirs," 40.

[47] See March 10, 1895. Koenig, "Koenig Letters (1878-1901)."

> vestigations. And so with a slender business and a few faithful workmen at his back he maintained a proud independence, sufficient to enable him to continue research.[48]

In the late 1870s, following several responses to his initial experiments challenging Helmholtz's theories of beats and combination tones, Koenig invented several new instruments (based on tuning forks) for studies of beats and combination tones. They formed the basis for his next round of attacks on Helmholtz, and significantly modified and improved the instruments for tone production. In the area of precision tuning, he established the standard French tuning fork (adopted by the Conservatoire National) which used a newly invented instrument called the clockfork. This instrument, most likely partly inspired by his earlier involvement with his grandfather Preuss, made use of a clock mechanism to verify with remarkable accuracy the pitch number of a selected tuning fork (§4.6). During this time he also published the first of his attacks on a specific aspect of Helmholtz's theory of timbre, the difference of phase (where a combination of simple waves are at different stages in their periodic cycle) in determining the quality of sound. He did this with one of his more exotic inventions called the wave siren. It consisted of rotating belts of brass or copper cut in the shape of various waveforms. A jet of air blown against the spinning belt produced a distinctive sound for each waveform. The waveforms were created to mimic different phase conditions. He found that such differences caused differences in timbre, contrary to Helmholtz's view. All of the above researches, described in Chapter Four, occupied Koenig for nearly four years and resulted in a flurry of articles before 1882.[49]

In April of 1877 due to the demolition of his premises (for the new medical faculty being erected in Paris), Koenig was forced to move from 30 rue Hautefeuille to nearby 26 rue Pontoise. A typical advertisement in *Nature* from this time read: "Rudolph Koenig (Dr. Phil.) Manufacturer

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[48] Thompson, "Rudolph Koenig," 630.

[49] Rudolph Koenig, "Bemerkungen über die Klangfarbe," *Annalen der Physik* 14 (1881f). "Beschreibung eines Stosstöneapparates für Vorlesungsversuche," *Annalen der Physik* 12 (1881d). "Uber den Ursprung der Stösse und Stosstöne bei harmonischen Intervallen," *Annalen der Physik* 12 (1881c). "Ueber die Beobachtung der Luftschwingungen in Orgelpfeifen," *Annalen der Physik* 13 (1881e). "Ueber die Erregung harmonischer Töne durch Schwingungen eines Grundtones," *Annalen der Physik* 11 (1880b). "Untersuchungen über die Schwingungen einer Normalstimmgabel," *Annalen der Physik* 9 (1880a).

of Acoustical Instruments to illustrate the laws and produce the phenomena of sound. Paris, 26 rue de Pontoise, price list free." He gave catalogues away for free, such as one sent to Joseph Henry that was inscribed: "A Smithsonian Institution à Washington D.C. hommage de l'auteur, Rudolph Koenig." He also sold them to agents for three francs. As he was preparing his third catalogue in 1880 he wrote to Loudon, "These publications have become all the more necessary for me, that during these last years, despite the good order from your university, business has been far from good enough to erase ever so little the consequences of my disastrous undertaking at the Philadelphia Exposition."[50] He published this catalogue in 1882 with significant price increases for most of the instruments.[51] The increases reflected the fact that the European and North American economies were going through a period of high inflation in the early 1880s. He also included several new instruments for studying timbre and beats which derived from his research of the last ten years.

As if he was not busy enough – preparing for his return to Philadelphia, preparing his catalogue, preparing a lecture series at Toronto, publishing his research, carrying out orders for clients - in 1882 Koenig published a book, which was a collection of all of his writings since 1858. He translated his earlier articles from German to French.[52]

The early eighties were certainly one of Koenig's busiest periods and his apartment, aside from being the location of his business, also served as a meeting place for scientists. During the electrical congress in Paris in 1881, for example, several notable physicists, Helmholtz among them (§4.8), came one evening to witness his latest experiments. As time moved on, and he became more isolated from fairs and conferences, his atelier became the main place for witnessing his experiments and purchasing his instruments.

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[50] See June 24, 1880. Koenig, "Koenig Letters (1878-1901)."

[51] The tonometer, for example, went from 2000 francs in 1873 to 3000 francs in 1882. The synthesiser cost 1000 francs in 1873, and cost 1500 francs in 1882.

[52] Rudolph Koenig, *Quelques Expériences d'Acoustique* (Paris: A. Lahure, 1882b).

In January 1882 Koenig was again forced to move to another address, 27 Quai d'Anjou on the Île St. Louis. This move, which would be his last, was more difficult as he had to wait until April to move his entire workshop. Eventually he set up the atelier on the ground floor and lived in an apartment above. Quai d'Anjou was centrally located and, being on an island, offered one of the last relatively quiet places in the city. He came to love this apartment and in later years referred to it as his "cher Quai d'Anjou."[53]

Koenig never married, but he remained close to his mother and younger sister, Anna, and her family. In 1870 Anna (1839-1903) married Ernst Christian Neumann (1834-1918), the famed pathologist and son of the already-mentioned Königsberger physicist, Franz Neumann. "Uncle Rudolph" was a favourite of Anna's children, especially Helene, who became an artist, and Ernst Richard, a mathematician. The family had a place on the Baltic "where the baths and walks were very good for my health," he wrote to Loudon.[54] When business was good, however, he had no time for vacations. In the midst of one of his busiest periods, he wrote: "I think this year I will scarcely only visit the lakes of Bois de Boulogne, and yet it is not even certain that I will be able to part at all with Quai d'Anjou."[55] Helene claimed that the insecurity of life as a businessman and the difficulties of being a foreigner in Paris made it difficult to form a family of his own. She romanticised her uncle as a starving scientist who escaped to his research "without any regard for monetary reward."[56] Koenig seemed to cultivate this image, as it was repeated in all his obituaries. It was quite a shock, therefore, when Helene found over 20,000 francs hidden in his apartment after his death.[57]

Koenig produced hundreds of instruments over a forty-year period. When he died, his firm was almost closed but, according to Helene, he still had six workers finishing off a large order to

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[53] See October 3, 1890. Koenig, "Koenig Letters (1878-1901)."
[54] See October 3, 1890. Ibid.
[55] See July 3, 1884. Ibid.
[56] Helene Neumann, "Rudolph Koenig zu seinen hundertsten Geburtstag," in *Neumann Family Archives* (Bückeburg: 1932a).

Moscow.[58] This was most likely the minimum needed to keep the firm operating. The number of workers would have varied considerably with the fluctuations of the market. During the spring of 1889 business was so slow that Koenig was forced to reduce his staff, but he did not say by how much.[59] A conservative estimate, based on information from other instrument makers in Paris circa 1880 would put the number of workmen at six to twelve.[60] L. Landry was his main collaborator for thirty years; he took over the business when Koenig died in 1901.[61] Koenig contracted much of the basic work, such as stands and frames, etc., to tradesman. In addition, it was common in Paris for instruments makers to employ men who worked from their homes, "travailleurs à domicile."[62] All of the fine-tuning, however, he did himself. "Not one tuning fork, during these more than thirty years, left the place without being personally adjusted and verified by him," S.P. Thompson wrote.[63] In a letter to Loudon of the 1890s, while finishing another tuning fork tonometer, Koenig claimed to "only supervise" the "pure mechanical work" doing the more refined tuning himself.[64] The great difficulties involved in tuning resonators and forks will be described in Chapter Four.

In 1882 he travelled to North America to bring an end to the Philadelphia fiasco and to give a series of six public lectures in Toronto. He saw these lectures as a kind of advertisement. "I would be naturally delighted if [the collection] would inspire in some professors the desire to stock their physical cabinets in acoustics." He also planned the trip to coincide with the American

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[57] Helene Neumann, "Letter to Ernst Christian Neumann from Paris, Oct. 22, 1901," in *Neumann Family Archives* (Bückeburg: 1901).
[58] Ibid.
[59] See March 28, 1889. Koenig, "Koenig Letters (1878-1901)."
[60] Conversation with Paolo Brenni (2001), who is currently writing a history of the nineteenth-century French scientific instrument makers. For more on these makers see Brenni's series of articles at Brenni, "19th Century French Scientific Instrument Makers."
[61] Abbé Rousselot and E.B. Titchener both list Landry as Koenig's successor. P.J. Rousselot, *Principes De Phonétique Expérimentale*, vol. 2 (Paris, Leipzig: Welter, 1908) 760. E.B. Titchener, *Experimental Psychology: A Manual of Laboratory Practice*, vol. 2 (London: MacMillan, 1915) 13. Landry's tuning forks were almost identical to Koenig's, except they were marked "LL." Copies of them can be found in the Rousselot phonetics collection at the Biblioteque Nationale (Mitterrand Branch) in Paris.
[62] Paolo Brenni, "The Chevalier Dynasty," *Bulletin of the Scientific Instrument Society*, no. 39 (1993): 14.
[63] Thompson, "Rudolph Koenig," 630.
[64] See October 4, 1891. Koenig, "Koenig Letters (1878-1901)."

Association for the Advancement of Science meeting in Montreal in August where it "would be important for me to see as many American scientists as possible." Most importantly, he saw these lectures as a chance to demonstrate the significance of his new research. "I think the delay of a few months [September instead of June] would only serve to increase the interest of these lectures, by permitting you to take into consideration my latest research on timbre that you find in my book, and by giving me the time to prepare more drawings and photographs."[65] For six months before the lectures, Loudon and Koenig corresponded regularly regarding the appropriate outline and content of the lectures. Koenig suggested that he bring some of his new instruments. Loudon agreed and paid for the shipping and ended up buying a few of these items (§4.8).

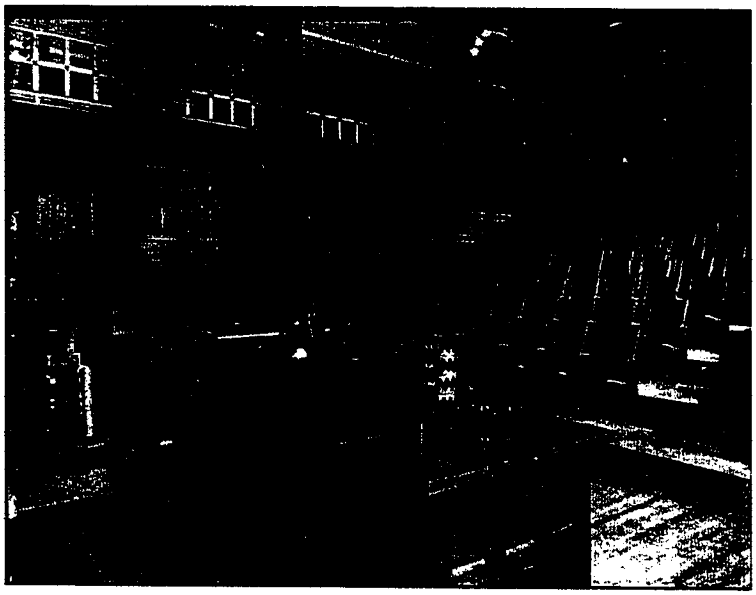

Figure 1.6 McGill Lecture Hall, c. 1890, with Koenig apparatus (double siren, analyser, and wave siren) Physics Department at McGill University.

The six lectures, sponsored by the Canadian Institute, were advertised in Toronto's *Globe*: "Canadian Institute Science Lectures. A Course of Lectures on Sound will be delivered by Dr. Rudolph Koenig, Paris, France, inventor of many of the most important instruments used in the

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[65] See November 25, 1881. Ibid.

study of acoustics, and Prof. Loudon, in the library of the Canadian Institute, Richmond Street."[66] The lectures, delivered twice a week during the month of September, were "illustrated by a series of new and beautiful experiments, commencing at 8 sharp." Tickets were three dollars for the entire course of lectures. The *Globe* published articles summarising each of the lectures and praised Koenig as "the most profound experimenter in acoustics in the world" while "his invaluable instruments have a world-wide reputation." In the crowded library of the Institute Koenig "performed experiments" while Loudon lectured. The audience was "distinctly one of 'culture rare'...drawing heavily from the ranks of the *savants* of the city."

1.3 LIFE AT QUAI D'ANJOU - 1883-1901

By the 1880s educational reform in many countries was taking place, and French instrument makers were barely able to keep up with the demand for new instruments. Long delays were the norm as eager professors waited to stock their new laboratories. The University of Toronto was typical in that it was ordering instruments to build new research and teaching laboratories; it was not typical in that it seemed to have a little more money than the average college or university in North America. Following confederation in 1867, the Ontario Government had gained almost total control over education and one of its goals was to build a centre in English Canada for training in science and technology. Provincial administrators became interested in any form of technical or scientific education that could contribute to the new economic and industrial expansion. With this in mind, James Loudon created the School of Practical Science (school of engineering) at the University of Toronto.[67] Loudon was therefore in charge of ordering instruments for two faculties in the 1880s.

Koenig was essential to Loudon's undertaking, in effect, as we have seen, acting as Loudon's agent. The letters from Koenig to Loudon provide a rare picture of the ups and downs of the in-

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[66] See *The Globe*, Aug. 30 p. 8, Sept. 13 p. 8, Sept. 16 p. 14, Sept. 19 p. 6, Sept. 21 p. 8, Sept. 21 p. 8, Sept. 23 p. 14, Sept. 26 p. 6, Sept. 28 p. 8 (Toronto: 1882).

strument trade in Paris, and the challenges of building a laboratory in North America, far from the centre of action in Europe. Due to the sheer number of instruments being ordered by Toronto and other schools, much of Koenig's time was spent waiting and prodding for orders. The famous Brunner brothers who made precision instruments for astronomy, geodesy and meteorology were, according to Koenig, "maniacs," and he was anxious to terminate his business dealings with them. Jules Carpentier, the precision electrical instrument maker, was "very rich and a constructor by preference rather than to make money." [68] Koenig seemed to value instrument makers like himself who strove for quality and worked from pure motives. One maker whom Koenig did not name and who was constructing a precision lathe for Loudon, was referred to as the "mechanician who works a little more like an artist than as a tradesman."[69] Alvergniat, who made glass apparatus for laboratories (e.g. precision thermometers, hydrometers and mercury vacuum pumps), was totally disorganised. Koenig had to go through his books methodically to save Loudon from being cheated; he finally gave up with "this totally detestable atelier." Laurent, the famous optician, does "great work," wrote Koenig, but he is very busy and ordering from him "will be like playing roulette."[70] The Seguy brothers, according to Koenig, made Geisler tubes "with love."[71]

Koenig was not the average agent. He provided critical guidance on the purchase of instruments and made suggestions for effective lectures and demonstrations. In 1882 when Loudon sought advice for buying a complete collection of cutting-edge electrical equipment, he responded that there was no one who could possibly make all the desired instruments: "In seeing the enormous quantity of electrical instruments that already exist, and that will always be grow-

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[67] For a history of the Engineering at Toronto see Richard White, *The Skule Story: The University of Toronto Faculty of Applied Science and Engineering, 1873-2000.* (Toronto: University of Toronto Press, 2000).

[68] See June 22, 1883. Koenig, "Koenig Letters (1878-1901)."

[69] See June 29, 1883. Ibid.

[70] See November 7, 1884. Ibid.

[71] See February 20, 1885. Ibid.

ing, one can no longer know where true science ends and simple industry begins."[72] He suggested going to a handful of makers for a selection of instruments.

Koenig provided reading lists and ideas for lectures as well. He forwarded to Loudon several pages of notes for a public lecture on the standardisation of pitch.[73] In the 1890s he developed a series of projection instruments for Loudon's lectures on sound. On one such improvement he wrote: "I thought one would increase interest in acoustics courses, if one made it easy to hear the sounds that produce the projection phenomena, Lissajous figures, inscriptions, or others."[74]

More than most instrument makers, Koenig kept impeccable records and knew the contents of his client's laboratories. When D.C. Miller (1866-1941) of Case School in Cleveland visited his studio in 1896 and ordered a number of instruments, he was surprised that Koenig remembered each instrument that A.A. Michelson had ordered for the school a number of years earlier.[75] In fact, he often refused to sell instruments if they overlapped with the client's collection.[76] His relationship with his clients did not stop at the sale of his instruments; he constantly made tiny improvements to his instruments and informed them of the changes. He sent Loudon advice on how to keep the instruments in good working condition, how to prevent rust on the tuning forks, and how to replace membranes in certain instruments. He provided long hand-written instructions for the use of the more complex instruments.

Aside from waiting for instrument makers to complete orders, scientists had to endure shipping delays as well. This sometimes meant that a whole course would be cancelled, or important research put on hold while instruments made their way to remote destinations. Much of Koenig's time, as an instrument maker and agent, included packaging orders into crates and organising shipping to his clients. For Toronto Koenig used a company called Sherbette, Kane, & Co. He

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[72] See June 22, 1882. Ibid.
[73] See November 7, 1888. Ibid.
[74] See August 31, 1888. Ibid.
[75] Miller, *Anecdotal History of the Science of Sound.* 90-91.
[76] In the first years of his business relationship with James Loudon of Toronto Koenig took pains to cut items from an order that were duplicated in other instruments. See "Koenig Letters (1878-1901)."

sent the crates by train to Le Havre, by steamer - "the Labrador" - to New York, and then by train - "Merchants Dispatch Transportation Company" - to Toronto. There were often problems with the delivery and he threatened to take his business elsewhere. But in the end he remained with Sherbette and Kane for over twenty years. Part of the shipping routine involved follow-up letters where the client listed parts that were broken in transit. Koenig would then replace the broken parts, which entailed more visits to instrument makers, and more waiting, followed by another shipment. To save money he would wait to send these replacement parts with another big shipment months later.

Promotion was another constant concern for a small instrument maker. Koenig spent an enormous amount of time and energy on his catalogues. He started working on his last catalogue in 1887 and it took almost a year and a half to complete. All of the descriptions were in French, but the titles of the instruments were also given in English and German, (Loudon helped with the English translations). He was clearly interested in catering to the English world, where his best supporters and customers were found, but he could not afford the costs of printing a second catalogue. With the arrangement of having the titles in three languages, "someone without French can easily go through the catalogue and if an instrument interests him, he can take the pain to read the description in the less familiar language."[77] In addition, the new catalogue had engravings on almost every page. He had first intended to take the instruments to a photography studio, but soon realised that was too difficult. He took the photographs himself, fretting over the right angles, and submitted them to a reputable photoengraver for the final images. "In order to have good figures it is most difficult to find the best arrangement of the apparatus and the most convenient size for each engraving, these trial and error sessions take a long time."[78] By early 1889 the catalogue was not yet complete and there were new problems with the photoengraver. Koenig wanted the "maleureux catalogue" done before the summer expositions and upcoming conferences, so he

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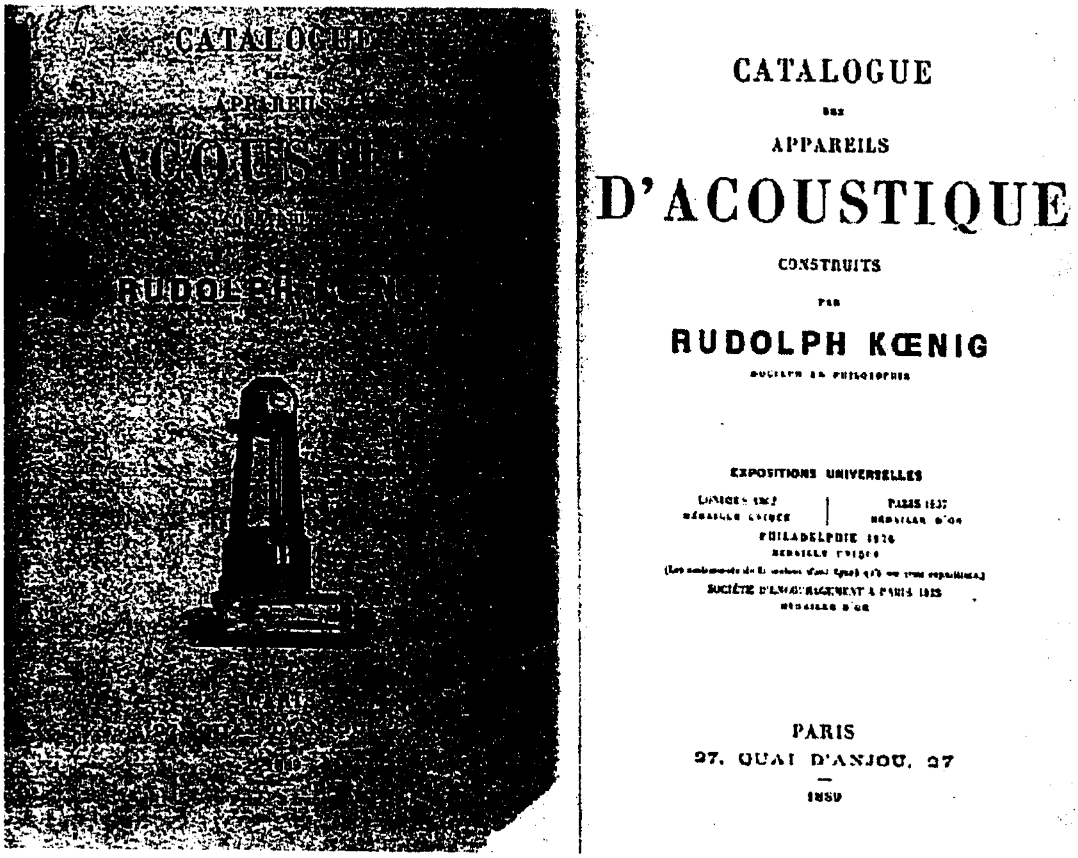
[77] See August 31, 1888. Ibid.
[78] See August 31, 1888. Ibid.

was forced to go to a wood engraver to redo all the images. In February he was still arranging apparatus and taking pictures for the engraver and was finished by early summer 1889. "When this catalogue will be finished, no one will be able to imagine all the troubles and all the sacrifices that it cost me."[79]



CATALOGUE
DES
APPAREILS
D'ACOUSTIQUE
CONSTRUITS
PAR
RUDOLPH KŒNIG

EXPOSITIONS UNIVERSELLES

PARIS
27, QUAI D'ANJOU, 27
—
1889

Figure 1.7 Koenig *Catalogue* (1889) with picture of the clockfork.

He produced the above catalogue at the start of a new, less stable phase in his career. A world economic slump hit the instrument market quite suddenly and forced him to contract his business.[80] By the end of the 1880s the Parisian instrument scene, which had dominated the instrument market for over fifty years, was suddenly entering a period of decline. Many scientific and technical innovations were now coming from German laboratories, and Germany was emerging

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[79] See May 23, 1889. Ibid.
[80] See March 28, 1889. Ibid.

as the world leader in precision instruments. Universities in North America and Europe, that had traditionally looked to Paris for guidance, were now looking further east. In addition, most French workshops did not adopt factory techniques for manufacturing instruments more efficiently. Firms that did change their manufacturing techniques, such as Carpentier, thrived in the more competitive market.[81] Firms like Koenig's, that worked with a craftsman ethic, had a harder time keeping up with orders, and keeping prices down.[82] To make matters worse, by the end of the 1880s there was less interest in acoustics. Electrical studies were getting all the attention, and more traditional areas of study were not a priority for professors outfitting a laboratory.

The first clear indication that times were changing for Koenig and his Parisian colleagues came with the Paris Exposition held in the summer of 1889. Koenig had been working hard on his catalogue, partly in the hope of meeting with potential buyers and scientists at this international fair. Unfortunately, the fair turned out to be poorly organised and he ended up not participating in it at all.[83] In fact, he reported to Loudon that the precision instrument section was empty for almost two weeks at the start of the fair. Such a state of affairs reflected the beginning of what would be a precipitous decline of the once powerful French instrument market.

Amid his work as an agent and the fluctuations of his own business, Koenig's happiest hours were spent researching. This was his escape. In 1888 after five years of straight business, and a few good orders providing "tranquility" for a while, he was able to get back to his studies of beats and timbre. He wrote to Loudon during this period of how his recent experiments "will greatly complicate the theory of 'timbre'."[84] He was still determined to modify some of the fundamental aspects of Helmholtz's theory. In 1881, as mentioned earlier, he had had the opportunity of dem-

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[81] See, for example, Brenni's description of how Jules Carpentier modernised his firm in the early 1880's to keep up with competition. Brenni, "Jules Carpentier (1851-1921)."

[82] In his forthcoming book on nineteenth century French Instrument makers, Paolo Brenni argues that French makers continued to make instruments with an aesthetic appeal, even though the market was demanding more functional, less pleasing objects. This stubborn refusal to adapt to the changing needs of the market would be a key reason for the demise of the great French makers.

[83] See May 23, 1889. Koenig, "Koenig Letters (1878-1901)."

[84] Undated letter from c. 1889. Ibid.

onstrating these experiments in the presence of Helmholtz himself, but he had failed to convince the great German physicist of his controversial claims. In the mean time, he had gathered more evidence and, in the case of his work on timbre, invented new instruments that he believed imitated better what was actually going on in nature. He was convinced that Helmholtz's view of sound was too abstract and idealised. The battle was between theory and experiment and Koenig's staunchest supporter at this time, S.P. Thompson, sided with his experienced ear:

> No living soul has had a tithe of the experience of Dr. Koenig in handling tuning forks. Tens of thousands of them have passed through his hands. He is accustomed to tune them himself, making use of the phenomena of beats to test their accuracy. He has traced out the phenomena of beats through every possible degree of pitch, even beyond the ordinary limits of audibility, with a thoroughness utterly impossible to surpass or equal. Hence, when he states the results of his experience, it is idle to contest the facts gathered on such a unique basis.[85]

Koenig's decisive moment soon arrived in the form of a conference. In the autumn of 1889 he presented his recent studies on timbre and beats at a meeting of the Society of Naturalists in Heidelberg. Besides the opportunity to prove his case in the presence of Helmholtz and many German scientists interested in acoustics, he hoped that his talk would spark interest in the coming generation of scientists in Germany, as he had not attended a German meeting in twenty-one years. As it turned out, Helmholtz himself chaired the session at which Koenig spoke, and he provided a short commentary on each of Koenig's chief claims. To Koenig's great disappointment, Helmholtz repeated his old arguments and was not in the least swayed by the new evidence. What was worse, he claimed not to hear the effects that Koenig produced with his new wave siren (§4.8).

Although Helmholtz did not accept Koenig's findings, the physiologists at the meeting were quite interested and asked him to make the same presentation again before their own section. As another encouragement, Professor Wiedemann, the editor of *Annalen der Physik*, the journal in which Koenig had always published his articles, asked him to publish these recent studies, and they came out earlier the next year.[86] But these gestures could not fully console Koenig, who too often took the rejection of his experiments personally. By the end of the conference, he was thoroughly deflated and worn out by all the packing and installing of instruments. "I had to work for almost the whole trip to Heidelberg as a real unskilled workman by unpacking, mounting, and transporting from one auditorium to the other and back again, to repack and resend my 700 kilograms of instruments."[87] He had spent his whole career trying to be recognised as a scientist on an even footing with the likes of Helmholtz and other university professors, and was now forced to leave Heidelberg feeling like a common worker. In the early part of his career he had almost been viewed as an equal in scientific circles, but he now had to face the growing authority of academic science.[88] There seemed no longer to be a place for independents and creative instrument makers.

It was Heinrich Hertz, Helmholtz's student, who stole the show at Heidelberg with his groundbreaking announcements on electromagnetism. It was to him that Helmholtz's favour fell. Helmholtz wrote to his wife: "Today we had the address from Professor Hertz: it really was extraordinarily good, very finished in style, tactful and tasteful, and called out a storm of applause."[89] Ironically, Koenig met Hertz at this meeting and was grateful for the kindness and respect the young star paid to him.[90]

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[85] Silvanus P. Thompson, "The Researches of Dr. R. Koenig on the Physical Basis of Musical Sounds," *Nature* 43 (1891): 201.

[86] Rudolph Koenig, "Ueber Klänge mit ungleichförmigen Wellen," *Annalen der Physik* 39 (1890b). "Ueber Stösse und Stosstöne zweier in demselben Körper erregten Schwingungsbewegungen," *Annalen der Physik* 39 (1890a).

[87] See October 11, 1889. Koenig, "Koenig Letters (1878-1901)."

[88] Robert Fox described the tensions between amateurs and professional academics in his study of science in nineteenth century France. Robert Fox, "The Savant Confronts His Peers: Scientific Societies in France, 1815-1914," in *The Organization of Science and Technology in France, 1808-1914*, ed. Robert Fox and George Weisz (Cambridge: Cambridge University Press, 1980). On a related theme, see J.A. Bennett, "Instrument Makers and the 'Decline of Science in England': The Effect of Institutional Change on the Elite Makers of the Early Nineteenth Century," in *Nineteenth-Century Scientific Instruments and Their Makers*, ed. P. R. de Clercq (Amsterdam: Rodopi, 1985).

[89] Leo Koenigsberger, *Hermann von Helmholtz*, trans. Frances A. Welby (New York: Dover Publications, 1965) 389.

[90] When Hertz died in 1894, Koenig wrote to Loudon: "The year has begun very sadly through the death of Hertz at Bonn, who had not even reached his thirty-seventh year. I am profoundly sad at this, because al-

The disappointments of the Paris Exposition and the meeting at Heidelberg marked a turning point for Koenig's career. One of his friends, Le Conte Stevens, a professor of Physics at Washington and Lee University, wrote to him in 1894 that acoustics should be abandoned because it had nothing new to offer. "Under these circumstances," Stevens wrote, "not only do I feel no stimulus to scientific research, but I feel that research which does not relate to questions of industrial importance tends rather to injure me in my relations with those who are my colleagues."[91] This letter upset Koenig greatly and drove him into further isolation. The next year he wrote to Loudon: "Business is as good as it can be at this time where the electrical rage fills most scientists with contempt for acoustics, that produces neither lighting apparatus nor electric motors, but one lives all the same and make ends meet."[92]

Even though Koenig still dominated the acoustical instrument trade in the 1890s (he never had any real competitors) the ascendance of German science and the German precision instrument trade meant that there were fewer pilgrimages by scientists to Paris, and therefore less business. When one of Loudon's students, J.C. McLennan (1867-1935), visited Quai d'Anjou in 1898, Koenig informed him that Carpentier was the only good maker left in Paris, the rest were in Germany.[93] In fact, McLennan was at the Cavendish laboratory in England at this time and was on his way to Germany to learn German, tour the laboratories and buy instruments for Toronto. Koenig refused to leave Paris, even though his family and others suggested that he move back to Germany. He told Loudon that he "would rather live in Paris amongst his enemies than in any other city in the world among his friends."[94] In reality, Germany may not have been friendlier to him. Through his attempts to dethrone Helmholtz, he had become unpopular in Berlin. During a

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though I only had the fortune to be in relation with him during my trip to Heidelberg in 1889, he had left me with the impression of being the most amiable and benevolent man that I had met in my long life." See January 4, 1894. Koenig, "Koenig Letters (1878-1901)."

[91] See March 30, 1894. Ibid.

[92] See April 4, 1895. Ibid.

[93] J.C. McLennan, "Letter to James Loudon, Sept. 4, 1898," in *University of Toronto Archives, Loudon Papers, B72-0031/004* (Toronto: 1898).

[94] Loudon, "Rudolph Koenig."

visit there in 1892, Le Conte Stevens reported that a laboratory assistant warned him not to mention Koenig's experiments in front of Kundt or Helmholtz.[95]

Koenig's best customers and supporters remained in the English world. He was somewhat of an experimental folk hero in Britain, sometimes compared to Faraday.[96] This situation revealed the values that were prevalent in the different scientific communities at the turn of the century. British scientists celebrated the independents and experimentalists who had worked their way to the top using their hands.[97] They admired Koenig for his courageous stand against Helmholtz. Following his lecture at Heidelberg in 1889, Koenig shied away from any big commitments to other lectures or fairs. So in the spring of 1890, when S. P. Thompson invited him to present his case against Helmholtz before the Physical Society of London, he refused at first, saying that he did not want to go through the same ordeal as in Heidelberg. Thompson convinced him to come and make the demonstrations, while he (Thompson) would read the paper. He ended up going and it was a big success. Lord Rayleigh invited him to make the same presentation before the Royal Institution a month later.[98]

In the 1890s S.P. Thompson continued to visit Koenig's studio from London to see the latest experiments. Lord Kelvin wrote to Koenig congratulating him on his latest papers on timbre.[99] Loudon, C.A. Chant, McLennan and even some administrators from Toronto visited Koenig in Paris. McLennan, who became a leader of the next generation of Canadian researchers, often visited him in Paris.

In 1891 Koenig returned to a job he had been working at since 1877, the completion of an even larger tuning-fork tonometer. He had announced in his catalogue 1889 that he had nearly finished the job, but realised that he first had to overcome some serious technical difficulties. He

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[95] See December 16, 1892. Koenig, "Koenig Letters (1878-1901)."
[96] Thompson, "The Researches of Dr. R. Koenig " 200.
[97] For more on the English approach to science, see John Theodore Merz, *A History of European Thought in the Nineteenth Century*, vol. 1 (Gloucester, Mass: Peter Smith, 1976) 227-301.
[98] See June 26, 1890. Koenig, "Koenig Letters (1878-1901)."
[99] See June 11, 1896. Koenig, "Koenig Letters (1878-1901)."

completed it in 1894 and believed it to be his masterpiece. It ranged from 32 v.s. to 43,690 v.s. (16 Hz to 21,845 Hz), which was just beyond the threshold of human hearing. There were 158 forks with resonators, stands and sliding weights to adjust the frequency. In total the tonometer produced 1618 tones. He had finally succeeded in his lifetime goal - to produce the ultimate instrument for precision tuning that offered a full range of sounds in the smallest possible gradations of pitch. He had also intended to create an instrument that could confirm in all ranges of sound (even beyond normal hearing) his own findings of beats and combination tones as a powerful empirical argument against Helmholtz.

During this period, Koenig also invented a new wave siren as part of his continuing efforts to challenge Helmholtz's theory of timbre. The latest wave siren was intended to better imitate more accurately the role of phase in the production of vowel sounds. At this time, physiologists such as Hermann of Königsberg were paying more attention to his work. By 1895 Koenig had prepared two articles describing his new "grand wave siren" and his latest series of studies.[100]

Some visitors stayed at Koenig's apartment to conduct experiments on his prized instruments. Mayer spent two summers in the 1890s at Quai d'Anjou performing experiments with the grand tonometer. Le Conte Stevens, as well, was a regular visitor. At one point in July of 1892, both Mayer and Stevens were staying at his studio performing experiments. A.A. Michelson (1852-1931), the American physicists famous for his experiments on the speed of light, also visited his studio at that time.[101] When McLennan visited in 1898, after spending a week of afternoons at the studio, he wrote to Loudon in Toronto that Koenig had "impressed on me that I had heard things with him that nobody else had heard."[102]

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[100] Rudolph Koenig, "Die Wellensirene," *Annalen der Physik* 57 (1896a). "Zur Frage über den Einfluss der Phasendifferenz der harmonischen Töne auf die Klangfarbe," *Annalen der Physik* 57 (1896b).

[101] See July 24, 1892. Ibid. Mayer also returned for the summer of 1894, when the tonometer had been completed, see July 26, 1894. Ibid. Mayer published portions of this research in Alfred Mayer, "Researches in Acoustics," *American Journal of Science* 1 (1896).

[102] McLennan, "Letter to James Loudon, Sept. 4."

Figure 1.8 Koenig's apartment, 27 Quai d'Anjou. Photograph by the author, 2001.

Aside from the focus on science, Koenig was a gracious and entertaining host. Evenings at his apartment included humorous stories, music and literature. His guests were often treated to special wine from his cellar, and a simple meal from his kitchen. [103] He kept a garden in the courtyard of his apartment.[104] His apartment was a home, a business and a laboratory.

An instrument studio could also be a very lonely place. Koenig no longer went to fairs and did not have the luxury of reporting to an academic laboratory everyday with its built in social life. He often waited for scholars who wrote in advance of a pending visit to Paris, even passing up vacations to his beloved Baltic in the hope of experimenting or making a sale. In 1897, for example, he decided not to attend the British Association meeting in Toronto because he felt it

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[103] Neumann, "Rudolph Koenig zu seinen hundertsten Geburtstag."

[104] Loudon's children loved the "little greens peas" from Koenig's garden so much that Koenig forwarded some of his seeds to Toronto with instructions for planting. See May 1, 1888. Koenig, "Koenig Letters (1878-1901)."

would be “ridiculous” to take his grand wave siren across the Atlantic for a group of scholars who could see the same experiments in his studio. Unfortunately, the guests did not always come as he planned. In December 1897 he wrote to Loudon with New Year’s greetings saying that the “year was less lively, because I did not leave my Quai in order to wait here for the visits of foreign scientists who, besides, did not come.”[105] Throughout this period, he was continually disappointed when scientists promised big orders and then backed out.[106] Saddened by this state of affairs, he wrote to Loudon that the big donations to American universities were usually not for acoustics, a science that in his words had been “almost entirely abandoned.”[107]

In the midst of these ups and downs, Koenig won a major order from Moscow in 1895.[108] This order was so large that it kept his studio working beyond his death in 1901. In the summer of 1897 he also sold his new wave siren for 10,000 francs, a large sum for the day. These successes provided the financial security to carry out more research. With some new techniques for constructing high-frequency tuning forks and measuring the vibrations of high frequencies, he created a whole line of inaudible frequencies up to 90,000 Hz (§4.10). Through this work he added considerable range to his masterpiece tonometer. His last publication in 1899 on the production of these high frequencies was the first comprehensive study in ultrasonics, destined to become a major part of twentieth-century acoustics.

In late 1897 one of his last close friends, Alfred Mayer, died, which saddened him “profoundly.” At this time Koenig’s own health was starting to slip. He developed Bright’s disease, a degeneration of the kidney. For the next four years his stomach was often swollen and sore, he lived off milk alone, and he had to have surgical procedures to relieve the symptoms. In the midst of this he continued his novel research on ultrasonic frequencies. He also continued to fill new orders and the large order for Moscow.

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[105] See December 17, 1897. Ibid.
[106] See September 13, 1893. Ibid.
[107] See October 10, 1895. Ibid.
[108] See April 4, 1895. Ibid.

As the end neared, and he was more and more bed-ridden, Koenig received a number of new orders "as if people know that my end is near and they want to profit."[109] Nevertheless, he was forced to start slowing his business and he asked Loudon for advice on how to sell the remaining instruments in his shop. He was particularly worried about his grand tonometer that now included his new inaudible tuning forks. He was asking 50,000 francs for the instrument, an unheard of sum in those days. He was also trying to sell one of his grand wave sirens for 6000 francs. By the spring of 1901, knowing that he was dying, he wrote to Loudon that he would be willing to sell his remaining collection for half price, including the tonometer and the grand siren for half price. Loudon came that summer to try and sort out these sales. He ended up buying Koenig's prized collection of projection instruments that, in Koenig's earlier description to Loudon, would "render very good service to a professor who would like an acoustical course before a large public."[110] But the potential buyers for the tonometer, which included the South Kensington Museum in London and Stanford University in California, hesitated at such large sum, even at the reduced price.

The difficulties Koenig was going through were somewhat relieved by a letter from S.P. Thompson in London informing him that he had been named an honorary fellow of the Physical Society in London. He wrote to Loudon: "I was quite surprised by this whole affair, because I had thought that the new generation of scientists in England no longer knew me at all."[111] The English remained his faithful supporters to the end.

Loudon remained Koenig's most important customer. In the spring of 1901 he asked Koenig to help him draft some notes for a lecture he wanted to give on "progress in acoustics." Even though bedridden, Koenig responded by writing a short, but complete, history of acoustics from his own perspective, with several references to himself in the third person. Following his death, Loudon translated this history, gave it as a presidential address to the American Association for

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[109] See January 3, 1901. Ibid.

[110] See March 10 and July 31, 1901. Ibid.

the Advancement of Science, and published it in *Scientific American* under his name, with no mention of Koenig.[112] Loudon visited Paris in August of 1901, to help Koenig sort out his business affairs and to seek buyers for his prized instruments. Perhaps during his visit they agreed to publish it under Loudon's name, or perhaps Loudon simply stole it from a dead friend. We do not know the truth about this, but we do know that Koenig was the author of the document and it therefore provides a unique perspective on the history of acoustics. It will be referred to throughout this thesis.

Koenig died on October 2, 1901 with his niece Helene, his sister Anna and his brother-in-law, Ernst Neumann at his side. He was cremated and buried at the Parisian cemetery, Père Lachaise. Anna and Helene stayed for a month afterward sorting out his possessions and arranging to sell some of his prized instruments. There were still six workers at the shop and the family decided to keep the firm going until the Russian order was completed. They also wanted to create the impression that the firm was not closing so as to keep bargain hunters from taking advantage of the situation (they kept the apartment until 1903). Abbé Rousselot, a phonetics researcher at the Collège de France, came by later in the month and offered to buy the tonometer for 25,000 francs. The family initially held out for more money, but eventually sold it to him for the above sum.[113] Part of this instrument has been recovered and now rests in the Mitterrand branch of the Biblioteque Nationale in Paris. In 1901 the family also sold and donated Koenig's large collection of books and journals. He still had over 800 copies of his own book from 1882. Among the personal items left by Koenig which were divided into six parts for his nieces and nephews – over 60,000 francs and a beautiful set of furniture - was his prized violin and a handmade clock.

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[111] See March 10, 1901. Ibid.

[112] Koenig, "Quelques notes." James Loudon, *A Century of Physics in Acoustics: Presidential Address to Section* (Toronto: Copp-Clark, 1901). "A Century of Progress in Acoustics," *Scientific American Supplement*, no. 1362 (1902).

[113] Neumann, "Letter to Ernst Christian Neumann, Oct. 22, 1901."

Figure 1.9 Sketch of Koenig in 1901 by Helene Neumann. Neumann (1932b).

Koenig was not forgotten by the new generation of acousticians. The large number of his instruments ensured that he would not fade quickly from memory even amidst the dramatic changes in early twentieth-century physics. Max Kohl, who would emerge after the turn of the century as one of he leading precision instrument makers in Germany, offered a whole line of instruments copied from Koenig's designs. These instruments are almost as numerous as Koenig's in surviving physics and psychology collections. Koenig and Kohl's acoustical instruments remained a key component of teaching acoustics well into the twentieth century and many schools still use these instruments for demonstrations.

During his lifetime and for a few years afterward, many scientists, particularly in the English world, identified with Koenig's devotion to experiment. They admired the skilled and independent instrument maker who challenged the theories of Helmholtz. One of the leading acoustical researchers at the turn of the century, D.C. Miller of Case University in Cleveland, continued to praise his research and instruments well into the second quarter of the twentieth century. Miller, who was one of the founders of the Acoustical Society of America in 1928, wrote the first detailed history of acoustics in 1935 in which he described Koenig as one of the founders of modern acoustics. The American physicist, Henry Crew of Northwestern University, wrote to Miller agreeing with the prominence given to Koenig in his history. Like many scientists of his generation, Crew recalled a time when the instrument maker was a key participant in science, and when the maker's workshop was a necessary meeting place for savants of all stripes: "There are other things which I have never seen in print; such as the story of Koenig's mode of work, and his combination of reception room, salesroom, and study all in one, at his atelier up by Notre Dame. A visit of an hour or two there, in company with A.G. Webster in 1900, only a few months before the old gentleman's death, is one of the high spots in my recollections of the last fifty years."[114] In 1905 Miller oversaw the building of a new physics laboratory at Case School. The top of each wall of the J.D. Rockefeller building, which still stands today, has a row of cement plaques with the names of renowned physicists. The South wall reads: Regnault, Verdet, Gilbert, Pascal, Ampere, Wheatstone, Henry, Koenig, Kepler, Kelvin, Arago, Fraunhofer, and Joule. The greatest monument to Koenig, however, is the sheer number of his instruments that survive in collections around the world.

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[114] D.C. Miller's personal papers are housed in the physics department at Case Western Reserve University.

CHAPTER TWO - HELMHOLTZ, KOENIG AND THE INSTRUMENTS OF THE NEW ACOUSTICS

> I have gradually accumulated a considerable amount of material for the reform of physiological acoustics, and am waiting for instruments to carry it out.
>
> Letter from Helmholtz to du Bois-Reymond, May 18, 1857.[1]

2.1 INTRODUCTION

This chapter sets the stage for a broadened interpretation of the "reform" of acoustics. There is no doubt that in the late 1850s and early 1860s, the science of sound went through a radical transformation. Hermann von Helmholtz has been generally credited with this development.[2] But upon closer inspection, we will see that the reform did not simply end with Helmholtz's first experiments, nor with the publication of his treatise on sound in 1863. Part of the reform entailed the creation, refinement and acceptance of a whole class of instruments reflecting the analytic conception of sound, and part of the reform entailed bringing these instruments into laboratories and classrooms in Europe and North America.

The tools of this reform – the tuning forks, resonators, sirens, analytic and synthesising instruments – came from the workshop of Rudolph Koenig. These instruments of precision quickly overwhelmed the traditional instruments for research used in the early part of the nineteenth century and just as quickly established themselves in the demonstrations and teaching laboratories. By including Koenig in this story, we see how the new instruments became the main vehicles for

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[1] Leo Koenigsberger, *Hermann von Helmholtz*, trans. Frances A. Welby (New York: Dover Publications, Inc., 1965; reprint, 1906) 157.

[2] For general histories of acoustics see Robert T. Beyer, *Sounds of Our Times: Two Hundred Years of Acoustics* (New York: Springer-Verlag, 1998). Sigalia Dostrovsky, James F. Bell, and C. Truesdell, "Physics of Music," in *The New Groves Dictionary of Music and Musicians*, ed. Stanley Sadie (London: MacMillan, 1980). Dayton Clarence Miller, *Anecdotal History of the Science of Sound.* (New York: MacMillan, 1935). For more detailed accounts of Helmholtz's role in the reform of acoustics see V. Carlton Maley Jr., *The Theory of Beats and Combination Tones*, ed. Owen Gingerich, *Harvard Dissertations in the History of Science* (New York; London: Garland, 1990). R. Steven Turner, "The Ohm-Seebeck Dispute, Hermann von Helmholtz, and the Origins of Physiological Acoustics," *The British Journal for the History of Science* 10, no. 34 (1977). Stephen Vogel, "Sensation of Tone, Perception of Sound, and Empiricism," in *Hermann von Helmholtz and the Foundations of Nineteenth Century Science*, ed. David Cahan (Berkley: University of California Press, 1993).

the spread of Helmholtz's ideas. Without them Helmholtz's work would have had less impact on the practice and teaching of acoustics.

Koenig played a complex role in the reform of acoustics. He copied and transmitted Helmholtz's core instruments; he significantly improved and refined whole classes of instruments that were crucial for testing and communicating the fundamental concepts of Helmholtz; he created entirely new instruments to communicate and test Helmholtz's theories. He also performed his own research and eventually became the main critic of Helmholtz. All of these factors worked to shape the birth of modern acoustics.

The idea of simple tones, or the elements of sound, is central to this story. The birth of our modern notion of simple tones is largely due to Helmholtz; the successful diffusion of this concept into the world of practice came through Koenig's instruments. Simple tones and their carriers reflected the new analytic conception of sound instigated by Helmholtz. Just as with the chemical revolution of Antoine Lavoisier roughly seventy years earlier, in which the concept of an irreducible chemical element as the fundamental building block of chemical substances had been established, the Helmholtzian simple tones became the central figures in the overhaul of acoustics. Much of the initial theory, instrument refinement, teaching and experiments focussed on the development of this class of phenomena. Even the language of acoustics had to change to meet this new reality. The phrase *simple tone* itself came from the translator of Helmholtz's work, Alexander Ellis:

> It has been my object to employ terms which should be thoroughly English, and should not in any way recall the German words. The word *tone* in English is extremely ambiguous. Prof. Tyndall (*Lectures on Sound*, 2nd ed. 1869, p. 117) has ventured to define a *tone* as a *simple tone*, in agreement with Prof. Helmholtz, who in the present passage limits the German word *Ton* in the same way. But I felt the English reader could not be trusted to keep this very peculiar and important class of musical tones, which he has very rarely or never heard separately, invariably distinct from those musical tones with which he is familiar, unless the word *tone* were uniformly qualified by the epithet *simple*. The only exception I could make was in the case of a *partial tone*, which is received at once as a new conception.[3]

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[3] For a full explanation of Ellis's choices for English words see Hermann Helmholtz, *On the Sensations of Tone as a Physiological Basis for a Theory of Music*, trans. Alexander J. Ellis (New York: Dover Publications, Inc., 1885) footnote on page 23. In the present thesis I use the terms

The proliferation of analytic instruments was so successful that these instruments became a source of stability for the Helmholtzian reforms. When Koenig later challenged some of the fundamentals of Helmholtz's theory with a resurrection of a waveform notion of sound, it was his own analytic instruments that formed the strongest resistance to any major reconception of sound (see Chapter Four). The great proliferation of simple tone producers and detectors between the years 1860 and 1890 cemented the reforms of Helmholtz.

The following sections describe the initial stages of this reform. The first section provides a basic chronological description of the theoretical and experimental origins of Helmholtz's groundbreaking studies in acoustics. In particular I focus on the novel instruments he developed. The second section offers an introduction to Koenig's role in extending the work of Helmholtz. In some areas Koenig played a relatively minor role in forwarding Helmholtz's reforms. In other cases, even early in the developments, Koenig pushed the technical boundaries of Helmholtz's reform.

2.2 HERMANN VON HELMHOLTZ

The birth of modern acoustics owes much to the importance of music in German culture in the nineteenth century. In 1838 when Helmholtz left Potsdam, his birthplace, to attend medical school at the Friedrich Wilhelm Institute in Berlin, he wrote immediately to his father to report about his new home:

> I got here safely on Friday. My things arrived shortly after. The servant and the porter made difficulties at first on account of the piano, as there was no place for it in my quarters. The room next this is intended for two, and has ample space. Accordingly, I depos-

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harmonics, *overtone* and *upper partials* to mean the kinds of simple tones that relate mathematically, through Fourier Analysis, to a *fundamental tone*. As we will see in later sections, the term *harmonics* had been used for centuries but took on new meaning under Helmholtz. Overtone and *upper partial tones* derived from Helmholtz's word, *oberton*. I also use the phrase "quality of tone" coined by Ellis to describe a distinctive compound of *simple tones*. In French the word is *timbre*, and in German, *Klangfarbe*. All three words were used interchangeably. Ellis, however, did not use *timbre*. "*Timbre* properly a kettledrum, then a helmet, then the coat of arms surmounted with a helmet, then the official stamp bearing that coat of arms (now used in France for a postage label), and then the mark which declared a thing what it pretends to be, Burn's 'guinea's stamp,' is a foreign word, often odiously mispronounced, and not worth preserving."

> ited it there...My room-fellow is the son of a Silesian engineer...He has extraordinary execution on the piano, but only cares for the florid pieces and for modern Italian music.[4]

The elder Helmholtz responded: "Above all, don't let your taste for the solid inspiration of German and classical music be vitiated by the sparkle and dash of the new Italian extravagances – these are only a distraction, the other is an education."[5] As we will see, the piano itself, and not just the music, would provide inspiration for Helmholtz's coming reforms.

"Florid pieces" and "Italian extravagances" were just a taste of the changes that Helmholtz would be exposed to in his early student years. There was growing social and political uneasiness that culminated in the failed revolution of 1848. There was the triumph of steam power, the beginnings of train travel, the introduction of the telegraph and new forms of prosperity brought on by industrial change. Even Helmholtz's favourite pastime, music, went through dramatic changes in this period. We see the emergence of the modern, far more powerful, pianoforte that would change the making of pianos and the playing of the piano.[6] There were major alterations in the fundamental relations of harmony with the growing acceptance of the well-tempered scale.[7] There were also the problems, recognised throughout Europe, related to the standardisation of pitch.[8]

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[4] Leo Koenigsberger, *Hermann von Helmholtz*, trans. Frances A. Welby (New York: Dover Publications, Inc., 1965) 13-14.

[5] Ibid.

[6] Erwin Hiebert and Elfrieda Hiebert, "Musical Thought and Practice: Links to Helmholtz's Tonempfindungen," in *Universalgenie Helmholtz: Rückblick nach 100 Jahren*, ed. von Lorenz Krüger, 295-311. (Berlin: Akademie Verlag, 1994).

[7] Johann Sebastion Bach promoted the scale of equal temperament, or well-tempered scale, so as to make piano playing more convenient. If one were to use the pure intervals, every time one switched keys the piano would have to be retuned. Equal temperament offered a series of slightly compromised intervals. Each octave included thirteen semitones where the pitch of each successive note was obtained by multiplying the next lower note by the twelfth root of two. "Just temperament" divided the scale using unequal, pure intervals or the ratios, i.e. the octave = 1:2, the third = 4:5, the fifth = 2:3. For more on the development of the scale, see James Jeans, *Science and Music* (London: Cambridge University Press, 1937) 160-86.

[8] In the nineteenth century cities throughout Europe had different standards of pitch. Some orchestras used a standard "a" as low as 400 Hz, others as high as 500 Hz. See, Alexander J. Ellis, "On the History of Musical Pitch: A Paper Read before the Society of Arts, 3 March 1880," in *Studies in the History of Musical Pitch: Monographs by Alexander J. Ellis and Arthur Mendel*, ed. Arthur Mendel (Amsterdam: Frits Knuf, 1968).

The Prussian education system went through a dramatic upheaval during the post-Napoleonic period becoming the first system to replace classical teaching methods with a strong emphasis on research and laboratory-based teaching. In turn, the decentralised German states established a dynamic network of competing research institutes.[9] Justus Liebig's chemical institute, founded in the 1830s, was probably the most famous place of research. It attracted students from Europe and North America and became a veritable factory for research in organic chemistry. Several schools in Germany and later around the world would imitate Liebig's model for success.[10]

We see the impact of this new teaching and research emphasis in Helmholtz's medical training. In his thesis year, 1841, Helmholtz joined the laboratory of the well-known physiologist, Johannes Müller (1801-1858), and became acquainted with Ernst Brücke, Emil du Bois-Reymond and Carl Ludwig. This circle of young researchers formed the "1847" group becoming leading advocates for a new school of physiology based on physical and chemical principles. Helmholtz's first paper showed his early dedication to mechanistic notions, with detailed studies on animal heat and muscle contraction. To complement his schooling in the new physiology, Helmholtz read the masters of eighteenth century mechanics and mathematics -- Euler, Bernouilli, D'Alembert and Lagrange. In 1847 he combined this mathematical background with his knowledge of physiology to write a groundbreaking memoir on the conservation of energy.[11]

Helmholtz taught physiology from 1849 to 1855 at Königsberg, where he started focussing his research on sensory physiology. This early research became a template for his views on the sensations and perception of musical sounds. In particular, he began studies on optics and colour research. Synthesising the material of previous investigators, as far back as Newton, Helmholtz

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[9] R. Steven Turner, "The Growth of Professional Research in Prussia, 1815 to 1848 - Causes and Context," *HSPS* 3 (1971).

[10] William H. Brock, *Justus von Liebig: The Chemical Gatekeeper* (Cambridge: Cambridge University Press, 1997). Alan J. Rocke, *Nationalizing Science: Adolphe Wurtz and the Battle for French Chemistry* (Cambridge, Massachusetts: The MIT Press, 2001).

[11] For detailed information on Helmholtz's career, see David Cahan, ed., *Hermann von Helmholtz and the Foundations of Nineteenth Century Science* (Berkley: University of California Press, 1993). Koenigsberger,

clarified the fundamental principles of colour sensation and perception. As he would do in acoustics, he went to great lengths to understand the relations between the basic elements of light (the frequencies of the spectrum) and their counterparts in physiology, the receptors and nervous tissues. He relied on Müller's doctrine of specific nerve energies whereby specific nerves performed specific sensory jobs.[12] Since Descartes there had been a notion of the mechanics of sensation (e.g. based on a reflex system), but no one had ever suggested that the nervous system had a built-in, differentiated structure that divided processing jobs automatically. Müller's doctrine enunciated the first clear architectural blueprint for the sensory system and allowed for further appreciation of the interplay of physical stimulus, sensation and mental functioning (perception).

Early in his research career, Helmholtz showed an aptitude for inventing instruments. In one of his first major series of studies at Königsberg, he determined the velocity of a nerve impulse with some delicate electrical apparatus of his own invention. Before that time, nerve transmission was thought to be far too fast, even instantaneous, for study in the laboratory. He used a precise electrical timing apparatus that was connected to a 50 to 60 mm long nerve of a frog's leg to produce a fairly reliable figure of 25 m/s. He then checked his results using a graphical apparatus, invented by his friend Ludwig, to map the sequence of the nervous impulse over time.[13] In addition to these researches, in 1851 Helmholtz became a celebrity in medical circles for his invention of the ophthalmoscope that allowed physicians a novel means of studying the inner structure of the eye for the first time. The ophthalmoscope became an indispensable instrument for his studies in optics. These studies produced Helmholtz's first clear statement of his empiricist outlook that emphasised the primacy of sensory systems in forming a picture of the outside world.

Hermann von Helmholtz. Steven R. Turner, "Hermann Von Helmholtz," in *Dictionary of Scientific Biography* (New York: Scribner, 1973).

[12] For a good account of Helmholtz's work in optics, see Richard L. Kremer, "Innovation through Synthesis: Helmholtz and Colour Research," in *Hermann von Helmholtz and the Foundations of Nineteenth Century Science*, ed. David Cahan (Berkley: University of California Press, 1993).

[13] Frederic L. Holmes and Kathryn M. Olesko, "The Images of Precision: Helmholtz and the Graphical Method in Physiology," in *The Values of Precision*, ed. M. Norton Wise (Princeton, N.J.: Princeton University Press, 1995).

Taking advantage of his growing fame, and his ability to harness more research time and facilities, Helmholtz took up two new positions in 1855 and 1858 at Bonn and Heidelberg, respectively. In 1855, as he neared the completion of his first volume on physiological optics, he began seriously researching acoustics. For the next eight years, this research would overlap with equally groundbreaking work on fluid dynamics and optics, culminating in his grand treatise *Die Lehre von den Tonempfindungen als physiolgische Grundlage für die Theorie der Musik* (*On the Sensations of Tone as a Physiological Basis for a Theory of Music*), hereafter referred to as *Sensations*.

Amazingly, Helmholtz published little work in acoustics after 1863. Following the publication of *Sensations* he moved away from physiological problems to thermodynamics, electrodynamics and hydrodynamics. He published three more editions of *Sensations*, but each with relatively minor changes. In 1871, after some very productive years in Heidelberg, he went to Berlin to start a new institute devoted to physical research. This move signalled his decisive break with physiology. The scope of physiology, he believed, had become too great for one individual to master. He was leaving the field of acoustics just as his theories were becoming the mainstream of teaching and research in the physics.

2.3 COMBINATION TONE AND BEATS

In the spring of 1856 Helmholtz wrote to a colleague at Königsberg that he had already formulated the basis for the reform of acoustics: "I hope to derive the whole theory of harmony from the fundamental fact that the ear perceives movements that are *regularly* repeated at given intervals as a continuous sensation of tone, and that a continuous sensation of tone is felt to be a consonance, a discontinuous sensation to be a dissonance."[14] Earlier theories of music had stated that harmony derived from the human mind's abstract appreciation for the simple mathematical ratios found in western music. According to the enlightenment mathematician, Leonhard Euler, the mind sought simplicity and order, and therefore the chords with the simplest relations (e.g. the

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[14] Koenigsberger, *Hermann von Helmholtz* 150-51.

fifth with 2:3) would create the most appealing harmonies.[15] Helmholtz, on the other hand, said that harmony and dissonance had a physiological basis in the inner ear.

Specifically, Helmholtz viewed the phenomena of beats as the key mechanism of harmony. He conceived of beats, (the periodic augmentations of tone that result from the interference effects of two combined sound waves), on physiological terms. The more rapid beats became (i.e. in the range of thirty pulses a second), the more they tended to produce an irritating or grating effect on the inner ear. Such a grating effect could be perceived as discord among combined musical notes.

Beats were one of a group of physical phenomena that Helmholtz sought to clarify before understanding the physiological substrate for hearing. In the winter of 1856, one of the first experimental problems he attacked related to combination tones, musical notes that resulted from the combination of two notes played together. In 1748 and 1754 respectively, the organist, Georg Sorge (1703-1778), and the violinist, Giuseppe Tartini (1692-1770), both observed that when two tones were played a third tone resulted. These notes, in different periods of history, came to be called resultant tones, third tones, difference tones, combination tones and Tartini tones. For over a century scientists and musicians failed to provide a predictive framework or explanation for studying combination tones. The accepted view in Helmholtz's time was that they were simply very rapid beats that blended into a tone. This assumption derived from the fact that most combination tones were seen to be the mathematical difference between the two generating tones, just as beats were the resultant difference between two simultaneously played tones.[16] If one played two tones of 100 and 103 Hz, one heard three beats; if one played two tones of 100 and 250 Hz,

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[15] Dostrovsky, Bell, and Truesdell, "Physics of Music" 666-669.

[16] For a detailed history of these debates, see Maley Jr., *The Theory of Beats*. Patrick McDonald of Notre Dame has recently written a thesis on Helmholtz's experimental philosophy (2001) that includes a thorough discussion of Helmholtz's work on combination tones.

one heard a resultant tone of 150 Hz. Helmholtz, however, thought that combination tones and beats were not related.[17]

The first indication that combination tones were a problematic anomaly in the world of musical sounds came from a new mathematical conception of sound put forward by Georg Ohm (1789-1854) in 1843. In the context of a more general debate on the physical nature of sound,[18] Ohm had used Fourier analysis[19] to describe complex (compound) sounds as being made of a mathematically-related series of simple sinusoidal waves (henceforth referred to as upper partials, harmonics, or overtones).[20] In addition, he claimed that the ear functioned as a Fourier analyser enabling humans to sense these partials. Critics, such as August Seebeck, claimed that one could not always detect the higher harmonics predicted by a Fourier series – these tones appeared to be mere mathematical abstractions with no basis in reality. Furthermore, there was no room for combination tones in this strict mathematical definition. If, for example, two or more simple (elemental) sound sources combined to make a complex sound, a Fourier analysis would only reveal the constituent simple sounds. Other sounds, no matter how well established by musicians and natural philosophers, were unexplained anomalies.

Even with these potential problems, Helmholtz saw the enormous potential of Ohm's views, particularly as it related to timbre (the distinctive quality of sound) and the physiology of hearing. He was attracted by the way it seemed to fit his emerging conception of the ear as a Fourier analyser. But before adopting this theory as a basis for his research he needed to develop a way to explain combination tones.

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[17] A brief summary of these views is found in Helmholtz, *Sensations* 167.

[18] For a review of these debates, see Turner, "The Ohm-Seebeck Dispute." Vogel, "Sensation of Tone."

[19] In 1822 Baron Jean Baptiste Joseph Fourier (1768-1830) published the mathematical treatise, *Théorie Analytique de la Chaleur (Analytic Theory of Heat)* where he demonstrated that any finite and continuous periodic motion can be decomposed into a series of simple, pure sinusoidal motions.

[20] In his French papers Koenig used the old-fashioned term "harmonique." In his German papers he used Helmholtz's new term "Oberton" which better reflected the new Ohmian conception of sound. This term was (and still is) commonly mistranslated as "overtone." Alexander Ellis preferred to call it "upper partial tone" after Helmholtz's original term, "Oberpartialtöne." See "translator's footnote" *Sensations* 24-25. Even with Ellis's attempts to tighten the language, these terms were often used interchangeably until the 1890s when new developments (§4.9) demanded more precision in the terms used.

Late in 1856 Helmholtz published his initial experiments on combination tones. With some ingenious instruments he carried out a series of careful observations and measurements and was able to produce a powerful new framework for predicting their occurrences with great accuracy. From these results he proposed a new physical and physiological mechanism underlying combination tones (see below). In addition, he used Ohm's theory to locate with great precision previously unobservable higher Fourier harmonics. He did this by making higher-order combination tones (combination tones generated from other combination tones that were predicted from his new theory) beat with higher, unobservable harmonics of a fundamental tone, predicted by Ohm's theory. This latter demonstration was remarkable because the higher harmonics could not be heard, and, in essence, Helmholtz used the beats to verify the existence of both the predicted harmonics *and* combination tones. With one stroke he provided evidence for his new explanation of combination tones, and confirmed Ohm's controversial theory.

The two apparatus he devised for these experiments show the first conscious production and manipulation of Ohmian simple tones in the laboratory. As Carlton Maley has noted, "the newly revealed importance of overtones cast doubt on all acoustical experiments done with sources of unknown overtone structure."[21] Helmholtz, therefore, set out to make sure his instruments produced pure, simple tones, a goal that would not have been necessary in the old framework. Ohm's theories had changed the expectations for a good acoustical instrument. Tuning forks, for instance, seemed to offer the best source of simple tones free of harmonics. They were not used by scientists at that time, however, and in fact were not deemed pure enough by Helmholtz. In order to prevent this source of error, he stimulated the forks lightly so as not to activate other harmonics and then put the fork in front of a cylindrical resonator of pasteboard to reinforce and amplify the single tone that he wanted. If the resonator was a specified shape, any other unwanted harmonics would not be reinforced leaving a pure, powerful, simple tone. These apparatus, in effect, became

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[21] Maley Jr., *The Theory of Beats* 121.

the first sound sources specifically designed to produce single frequency sound waves free of harmonics.

The other apparatus was a variation on an instrument called the siren. In 1819 the French scientist, Charles Cagniard de la Tour (1777-1859), invented an acoustical instrument called the siren, in which pressured air from a wind bellows forced a perforated disk to rotate producing a series of pulses that blended into a tone.[22] Late in 1855 Helmholtz wrote to Emil du Bois-Reymond in Berlin and asked him to find a mechanic to build his newest invention, the polyphonic "multi-voiced" double siren.[23] This siren could produce several simple tones simultaneously, in musical chords, and under greater pressure. It was a combination of two polyphonic sirens, modelled after the sirens that had been invented by the German physicist and former teacher of Helmholtz, Heinrich Wilhelm Dove (1803-1879).[24] It consisted of two siren disks facing each other, placed in a wooden frame. The upper disk had four separate rings of holes, 9, 12, 15 and 16; the lower disk had the holes, 8, 10, 12 and 18. Each connected to a powerful air bellows and had four pins to activate (open) a particular row of holes. Counting dials were placed in the middle of the two sirens for recording the number of turns per second and, with the aid of a clock for timing the revolutions, determining the frequency of a particular row of holes. An ivory handle at the top allowed one to rotate the upper siren by degrees in order to create a shift in the phase of the upper sound source compared to the lower sources (for studying interference effects). Helmholtz also created a feature to ensure that the sounds were pure and without harmonics.

> In order to damp the upper partial tones in the siren by means of a resonance chamber, I caused cylindrical boxes of brass to be made...These boxes are each made in two sections, so that they can be removed, and be again attached to the windchest by means of screws. When the tone of the siren approaches the prime tone of these boxes, its quality becomes full, strong and soft, like a fine tone on the French horn.[25]

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[22] The introduction of the siren inspired Ohm's definition of tone. As Stephen Vogel has observed, "The essential feature of this new definition was the reduction of tone to mere periodicity and the elimination of the former assumptions about the form of the vibration." Vogel, "Sensation of Tone," 263.

[23] Vogel, "Sensation of Tone," 267.

[24] Anna Giatti and Mara Miniati, eds., *Acoustics and its Instruments: The Collection of the Istituto Tecnico Toscano* (Firenze: 2001) 88.

[25] Helmholtz, *Sensations* 163.

The polyphonic double siren, therefore, produced a means for investigating complex (compound) musical sounds from a generator of known purity and elemental construction. F. Sauerwald of Berlin constructed this new invention for Helmholtz.[26]

With these new instruments, Helmholtz discovered a large number of combination tones, and concluded (as his predecessors had done) that the first-order combination tones were the difference between the two prime generators ("difference tones"); the second-order combination tones resulted from the first combination tone interacting with one of the prime generators; the third-order combination tones derived from the difference with any of the previous tones, etc. Each order of tones became successively weaker. He detected the tones by listening, or by tuned membranes to visualise the tones that were difficult to hear. In these experiments he not only confirmed observations made by earlier investigators, but added several more inaudible combination tones that he had detected using beats. He was thus was able to map the appearance of combination tones with great precision and certainty. Furthermore, he claimed to have discovered a new class of combination tones called *summation tones* (the sum of the two generating tones). But the summation tones, Helmholtz stated, were much weaker than the difference tones.[27]

Even with these remarkable empirical results, Helmholtz still had to explain combination tones in light of Ohm's theory of compound sounds. For this step, he had to grapple with the nature or mechanism of the combination tone. Were they beats or were they unexplained subjective phenomena (products of the mind or ear)? In the course of his experiments he made two important observations that provided crucial clues for a new explanation. First, combination tones came about when the generators were very loud. The siren, for instance, produced more clear combination tones due to the powerful prime tones it generated. Second, he noticed that there was a nonlinear relationship between the intensities and numbers of the resultant combination tones and the intensity of the generating tones. He speculated that the source of combination tones may lie in a

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[26] Ibid., 161.

[27] Summaries of these experiments are found in Koenigsberger, *Hermann von Helmholtz* 151-55.

non-linear disturbance in the production and reception of the sound wave. In short, the generally accepted law of superposition, that oscillatory motions of any vibrating bodies when combined with each other will be the exact sum of the individual motions, did not apply under all conditions.[28]

The combination tones, in Helmholtz's opinion, were not beats, nor were they subjective phenomena, nor were they tones that threatened Ohm's mathematical analysis of sound, but were objective "accessory phenomena" deriving from non-linear conditions that could be explained by mechanics and proven by experiment. He discovered, for example, that he could detect some combination tones with resonators or with vibrating membranes.[29] He proposed that these tones had a real existence through the mechanics of the ear or at the sound source. In the ear, the asymmetrical form of the drumskin, with a certain structure of fibres, created a situation where even relatively small amplitudes caused deviations in the superposition of two simultaneous vibrations.[30] He further claimed that the siren was an ideal instrument for producing non-linear disturbances at source. The pressure conditions in the windchest created powerful combination tones, even as strong as the generator tones themselves. In the case of these kinds of combination tones, Helmholtz claimed that their "objective existence in the mass of air can be proved by vibrating membranes tuned to be in unison with the combination tones."[31]

The first part of Helmholtz's reform of acoustics, therefore, entailed clarifying the physical nature of combination tones as a way of verifying Ohm's theory of sound. A crucial part of this reform derived from instruments that could produce simple pure tones. These developments would frame the pursuit of laboratory acoustics for the next forty years. Koenig's workshop, as

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Maley Jr., *The Theory of Beats and Combination Tones* 120-136. Vogel, "Sensation of Tone, " 270-272.

[28] Helmholtz. *Sensations* 152.

[29] Ibid., 157.

[30] Even better candidates for these kinds of combination tones, Helmholtz argued, were the disturbances caused by the asymmetries of the hammer and anvil (the two small bones in the middle ear). He claimed to notice a peculiar tingling in the ear under certain conditions. Ibid., 158.

[31] Ibid., 157.

we will see, became a factory and business for making and spreading precision, simple-tone producers throughout the world.

2.4 THE PHYSIOLOGICAL BASIS OF TIMBRE

Helmholtz next sought to clarify the physiological substrate for the sensation of simple tones, which led to his theory of timbre. He had verified the physical existence of the higher harmonics and now needed to investigate the physiological aspect of Ohm's theory. In November 1857, in the midst of intensive investigations on the nature of vowel sounds, he wrote to the Dutch physiologist, Franz Donders (1818-1889):

> In the next place I must attack the problems relating to the origin of timbre (Klangfarbe), since these will solve the fundamental problem of physiological acoustics discussed by Ohm and Seebeck: what kind of vibration corresponds with a single audible tone? I believe Ohm to be right in his view that the ear analyses and hears the motions of the air in exact correspondence with Fourier's theorem.[32]

Helmholtz had done some preliminary experiments with his piano and discovered that specific vowel sounds were related to the number and strength of upper partials.[33] He found, for example, that the piano strings, tuned to specific notes, responded in sympathy to the partials of a sung vowel, thus providing physical evidence of the existence and strength of a partial in a vowel sound. In effect, the piano was the first sound analyser, and as we will see below it served as a powerful model for his emerging physiological conception of sound.

These experiments and Helmholtz's belief in Ohm's theories were supported by recent discoveries of the anatomy of the ear. In 1851 Marchese Corti (1822-1876) published an intricate anatomical study of the inner ear, or the cochlea. He devised a special staining technique to produce a clearer picture of this snail-like structure. The cochlea started at the oval window (where the hammer, anvil and stirrup ended) and divided into three sections - the cochlear duct, scala vestibuli and scala tympani – within which lay the organ of corti (the seat of hearing), with the

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[32] Koenigsberger, *Hermann von Helmholtz* 158.

rods of corti, the hairs, the tectorial membrane and the basilar membrane. These discoveries provided Helmholtz with a tantalising clue for substantiating Ohm's theory of sound. He proposed that the differing strengths of corti's rods may be a factor in the sensation of different tones; "They are the most appropriate for executing vibrations on their own," he wrote.[34] He pictured a whole battery of vibrating bodies (like the individual piano strings) lining the organ of Corti, each responding to their own frequency.

This conception of the inner ear as a series of vibrating bodies that responded to specific frequencies was a direct application of the doctrine of specific nerve energies handed down to Helmholtz from his teacher Joannes Müller. In effect, each rod responded only to a specific sound vibration, making it very similar to a piano. "Now suppose," Helmholtz wrote,

> we were able to connect every string of a piano with a nervous fibre in such a manner that this fibre would be excited and experience a sensation every time the string vibrated. Then every musical tone which impinged on the instrument would excite, as we know to be really the case in the ear, a series of sensations exactly corresponding to the pendular vibrations into which the original motion of the air had to be resolved. By this means then, the existence of each partial tone would be exactly perceived, as the ear really perceives it. The sensations of tones of different pitch would under the supposed conditions fall to the lot of different nervous fibres, and hence be produced quite separately, and independently of each other. [35]

In *Sensations*, Helmholtz cited Müller's work as the basis for his key assumptions of how the two main sensory systems (hearing and sight) operate. It was Müller who showed, he wrote,

> that the difference in the sensations due to various senses, does not depend upon the actions which excite them, but upon the various nervous arrangements which receive them. We can convince ourselves experimentally that in whatever manner the optic nerve and its expansion, the retina of the eye, may be excited, by light, by twitching, by pressure, or by electricity, the result is never anything but a sensation of light....The same result is obtained for hearing by the hypothesis to which our investigation of quality of tone has brought us. The qualitative difference of pitch and quality of tone is reduced to a difference in the fibres of the nerve receiving the sensation, and for each individual fibre of the nerve there remains only the quantitative differences in the amount of excitement.[36]

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[33] Hermann Helmholtz, "Ueber die Vocale," *Archive für Holländischen Beiträge zue Natur- und Hiekunde* 1 (1857). See also Hermann Helmholtz, *Wissenschaftliche Abhandlungen*, vol. 1 (Liepzig: Barth, 1882) 395-96.

[34] Hermann Helmholtz, *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik*, 1st ed. (Braunschweig: Friedrich Vieweg und Sohn, 1863) 218.

[35] Helmholtz, *Sensations* 129.

[36] Ibid., 148.

Using Müller's doctrine, Helmholtz was able to create a strict, mechanical conception of the physiology and anatomy of the inner ear. This conception was based on a one-to-one correspondence between the elements of the inner ear and those of the physical world, the simple tones. It would go through minor modifications in lieu of new physiological findings in the 1860s,[37] and would remain the most comprehensive explanation of simple tone sensations until the 1930s and the work of Georg von Békésy (1899-1872) on the function of the basilar membrane.[38]

2.5 THE PSYCHOLOGICAL BASIS OF TIMBRE

There was one persistent obstacle for Helmholtz's one receptor/one tone hypothesis: in the presence of the strong fundamental tone, the upper partials were often difficult to hear. Shortly after Georg Ohm had proposed his Fourier analysis of sound, Seebeck criticized it on the grounds that some of the supposed simple tones could not be heard, and perhaps did not exist at all. For Helmholtz, however, this discrepancy with theory was not due to a flaw in the Ohmian conception of complex sound, nor with the physiological complement, but with the psychological aspects of sound perception. He wrote: "Seebeck, although extremely accomplished in acoustical experiments and observations, was not always able to recognise upper partial tones, where Ohm's law required them to exist. But we are also bound to add that he did not apply the methods...for directing the attention of his ear to the upper partial in question."[39] This method entailed the use of an instrument called the resonator (§2.6).

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[37] With the findings of Victor Hensen (1835-1924) in the 1860s, Helmholtz singled out the basilar membrane as the main substrate of sympathetic resonance. Hensen, like other physiologists of the time, had immediately set out to test the new ideas of Helmholtz upon reading Helmholtz's work. In his paper of late 1863, he singled out several potential candidates for our internal resonating systems and drew detailed diagrams of their structure, especially the basilar membrane. He performed ingenious studies observing the responses of the organ of Corti to a bugle, see Victor Hensen, "Studien über das Gehörogan der Decapoden," *Zeitschrift für Wissenschaftliche Zoologie* September (1863a). "Zue Morphologie der Schnecke des Menschen und der Säugethiere," *Zeitschrift für wissenschaftliche Zoologie* December (1863b). In the third edition of *Sensations* (1870), Helmholtz emphasised the importance of the basilar membrane in sensing different tones, but even with this significant change of emphasis, he stated that still "we cannot precisely ascertain what parts of the ear actually vibrate sympathetically with individual tones." Hermann Helmholtz, *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik*, 3rd ed. (Braunschweig: Friedrich Vieweg und Sohn, 1870).

[38] Beyer, *Sounds* 264-67.

[39] Helmholtz, *Sensations* 58.

A psychological factor, termed by Helmholtz an "unconscious inference," acted to distort basic sensations into what we end up seeing or hearing. For example, after many years of hearing human voices, the ear becomes accustomed to the combined (compound) sounds and perceives them as a fused whole, making it difficult to hear the individual components. One must concentrate to pick out the elements that habit has seemingly blended into one phenomenon. In the 1850s Helmholtz had applied the same principle to his work in optics. For instance, when looking at a point in space, he asked why we see one image instead of two (with two eyes, in slightly different positions, we should see two images). Some believed that the two optic nerves physically joined making a united image in the mind. Helmholtz, on the other hand, argued that the nerves were indeed separate, yet an unconscious blending made one point from two. A similar situation presented itself in sound, where a well-trained ear, with proper use of attention, could pick out the elements. He developed this perspective partly from his training under Müller who had emphasised the necessary separation between the sensory and attentional processes, and partly from the confidence he enjoyed as a musician. Musicians had long been trained in the art of picking out sounds that non-trained listeners could not detect. Helmholtz's friends, to take an anecdotal example, were amazed at "his extraordinary gift of observation." "When watching the play and splashing of a fountain at Sans Souci he heard melodies and chords in the murmur which they were unable to perceive, even when he drew attention to them."[40]

2.6 DETECTION OF SIMPLE TONES

Helmholtz invented his resonators to detect the elusive simple tones. If tuning forks were the first precision simple-tone *generators* for the new acoustics, the resonators became the first precision simple-tone *detectors*. These spherical brass or glass globes, which were tuned to respond to spe-

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[40] Koenigsberger, *Hermann von Helmholtz* 30. Helmholtz placed a very high value on attention for proper scientific observation. Good attention was deemed an essential laboratory tool in the nineteenth century. According to E.G. Boring, Helmholtz praised the "remarkable observational power" of the famed physiologist, Purkinje. Observers like Purkinje, Helmholtz claimed, displayed a peculiar gift of observing sensations and separating out the "imaginal supplements" that unconscious inference added. Edwin G. Boring, *A History of Experimental Psychology* (New York; London: The Century Co., 1929) 306.

cific frequencies, were held to the ear, thus allowing an observer to detect simple tones from complex tones in the surroundings. They were a mechanical means for uncovering the underlying basic sensations that had been distorted by mental processes. According to Helmholtz, when the skilful use of attention failed to uncover the partials, the resonators could "materially assist the ear in making this separation."[41] "The attention of the observer has generally to be drawn to the phenomenon he has to observe, by peculiar aids properly selected, until he knows precisely what to look for; after he has once succeeded, he will be able to throw aside such crutches."[42]

The resonators were to offer clear, unarguable proof of the existence of simple tones. In *Sensations* Helmholtz put it this way:

> We have rather to inquire, do these partial constituents of musical tone, such as the mathematical theory distinguishes and the ear perceives, really exist in the mass of air external to the ear? Is this means of analysing forms of vibration which Fourier's theorem prescribes and renders possible, not merely a mathematical fiction, permissible for facilitating calculation, but not necessarily having any corresponding actual meaning in things themselves.[43]

Helmholtz had already accomplished this with his experiments on the piano and his use of "tuned membranes" to detect partials and combination tones. In the winter of 1857 he introduced the resonators at a public lecture in Bonn, "the native town of Beethoven, the mightiest among the heroes of harmony."[44] The resonators were glass retorts or receptacles with two openings, one received the sound from the surroundings, the other had a glass tube that was inserted into the ear. In effect these receivers performed the same analytic task that the piano had performed in the vowel experiments, except they only responded to one simple tone.

According to Helmholtz, the piano strings, tuned membranes, rods of Corti and resonators all worked on the principle of sympathetic vibration. "You will all have observed the phenomena of the sympathetic production of tones in musical instruments, especially stringed instruments,"

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[41] Helmholtz, Sensations 7.

[42] Ibid., 49.

[43] Ibid., 35.

[44] Hermann Helmholtz, "On the Physiological Causes of Harmony in Music," in *Science and Culture: Popular and Philosophical Essays*, ed. David Cahan (Chicago: University of Chicago Press, 1995), 46.

Helmholtz said in his lecture at Bonn. "The string of a pianoforte when the damper is raised begins to vibrate as soon as its proper tone is produced in its neighbourhood with sufficient force by other means. When this foreign tone ceases the tone will be heard to continue some little time longer."[45] Piano strings vibrated in many modes making them difficult for experiments intended to detect one simple tone, and membranes were found not to be sensitive for fainter simple tones. On the other hand, a globe of air could be set into its natural vibration mode through sympathy with much more accuracy and strength "and the ear thus connected with it hears the corresponding tone with much increased intensity."[46] It was therefore much easier for someone to determine if a simple tone existed in the mass of tones making up a complex tone.

As we will see below when we discuss the more formal aspects of the theory of resonance, much work had been done on the study of aerial resonating cavities before 1857. These studies were mostly intended for refining the resonating aspects of musical instruments, or for studying the laws that govern aerial resonating tubes. Helmholtz, however, reconceptualised resonators as *tools* for *selecting* specific tones from a complex tone. This was a dramatic reinterpretation of resonators from tone *producers* to tone *detectors*. Ohm's theory and the physiological perspective provided the new context to reinterpret the use of resonators. In a vivid illustration of this reconceptualisation, Helmholtz attached a membrane to the open end of a bottle that responded to a specific frequency. When that frequency was present, a pith ball jiggled beside the vibrating membrane. This simple device served as a model for the glass resonators with two openings "for which the observer's own tympanic membrane has been made to replace the former artificial membrane."[47] The process by which Helmholtz invented the resonator was most likely not as neat as he described in the above example from his Bonn lecture, but his description highlighted the physiological context of his reinterpretation of the resonators as analytic tools. He had provided a

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[45] Ibid., 58-59.
[46] Ibid., 69.
[47] Helmholtz, *Sensations* 43.

new way to demonstrate and test the simple tones of Ohm's theory. As he wrote in *Sensations*, he had shown,

> that the simple partial tones contained in a composite mass of musical tones, produce peculiar mechanical effects in nature, altogether independent of the ear and its sensations, and also independent of merely theoretical considerations. These effects consequently give a peculiar objective significance to this peculiar method of analysing vibrational forms.[48]

In the same way that the prism came to define Newton's optics, resonators became the emblem of the new analytic conception of musical sound. In an 1881 portrait of Helmholtz by the painter Ludwig Knauss, a spherical resonator rests prominently on the table next to a tuning fork and prism.

Figure 2.1 Hermann von Helmholtz by Ludwig Knauss (1881). Pietsch (1901).

2.7 SYNTHESISING SOUND

Following a Congress of Natural Science in September 1857 at which Helmholtz presented a talk on acoustics, the King of Bavaria wrote to him offering to fund his proposed projects.[49] With this

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[48] Ibid., 36.

[49] Koenigsberger, *Hermann von Helmholtz* 162. At a later date the King of Bavaria told Helmholtz that he hoped that his acoustical discoveries could be applied to the architecture of public halls. Koenigsberger, *Hermann von Helmholtz* 178.

money, Helmholtz was able to construct his latest invention, the vowel synthesiser. This apparatus was designed to test specific features of his theory of timbre by reconstructing compound tones from simple tones. He presented the findings from this apparatus in April 1859 at the Bavarian academic conference in Munich in a paper entitled "Ueber die Klangfarbe der Vocale" ("On the Timbre of Vowel Sounds"). Most of Helmholtz's work on timbre derived from this talk, portions of which were published later that year in *Annalen der Physik* and the following year in English in the *Philosophical Magazine*.[50] It was the first public announcement of his theory of timbre.

Vowel sounds served as the ideal example of timbre. For example, two vowels "A" or "U" could be sung at the same pitch, yet sound quite different. Timbre had traditionally been ascribed to the shape of different waveforms. An "A" would have a different waveform from a "U." Helmholtz wanted to test this hypothesis in light of his new emphasis on upper partials and their role in timbre. He felt fairly sure that the proposition of Ohm gave a concrete physical framework (through the concept of simple tones) for discovering a more certain basis for timbre. If a complex note displayed the same pitch, he argued, the timbre must depend on the differing intensity of partials. On the other hand, if the waveform hypothesis were correct a difference of phase between the phase of simultaneous partials (which would result in different overall waveforms) would cause a different quality of tone. He set out to investigate the intensity and phase of the partials.

Helmholtz hypothesised that these questions could be answered through synthesis, or by producing sounds of different qualities by combining different simple tones. He went to the instrument maker Friedrich Fessel of Köln with the design for his "vowel synthesiser." By April 1858 he had the new instrument. He wrote to du Bois-Reymond: "I have now put together a complicated apparatus at the King of Bavaria's expense, by which one is able to control the vibrations of

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[50] Hermann Helmholtz, "On Vowel Sounds," *Philosophical Magazine* 19 (1860). Hermann Helmholtz, "Ueber die Klangfarbe der Vocale," *Annalen der Physik* 108 (1859).

a tuning-fork at will by an electro-magnet, with complete command of intensity and difference of phase. This is in order to regulate the production of timbre (Klangfarbe)."[51] The apparatus consisted of eight tuning forks which corresponded to B "in the deepest octave of a bass voice" and its upper partials as far as b2 "the highest octave of a soprano" comprising the notes B, b, f1, b1, d2, f2, a2 and b2.[52] Each fork was framed by a horseshoe electromagnet and connected in series to an interrupter tuned to 120 (the frequency of B) oscillations per second. The interrupter served to keep all the forks vibrating with regularity at their natural frequencies.[53] As he had done for the apparatus for combination tones described earlier, Helmholtz reinforced the tuning forks with "properly tuned" cylindrical resonator tubes of pasteboard.[54] The resonators could slide toward or away from the tuning fork so as to adjust the intensity of that tone. The mouths of each tube had a moveable cover hooked up by thread to a piano key. When operating the circuit, there was a slight hum to the electrical forks, but as soon as the cover was lifted from the resonator, the tone would be generated quite clearly.

By combining various partials Helmholtz claimed to reproduce the basic vowel sounds. He adjusted the intensity by moving the fork away or toward the resonator. The imitated vowels, he discovered, actually resembled those of the singing voice more than the spoken voice. "O" for example, was comprised of primary note B accompanied by its powerful octave, b. "E" was especially characterised by the third note f1, with a moderately sounded second note b and two very weak higher notes. (At the time he wrote his 1859 article, Helmholtz had not completed his studies for all the vowels because he did not yet have the high forks for some for the vowels. These

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[51] Koenigsberger, *Hermann von Helmholtz* 163.

[52] Helmholtz, "On Vowel Sounds," 84. Helmholtz calibrated his notes by a – 440. B (112 Hz) was the German notation for Si1 in the French notation, which was 240 v.s. (vibration simple) or 120 Hz. The French scale went by a 435 after 1858.

[53] Helmholtz was the first person to make use of an electromagnetic tuning fork, or a tuning fork maintained by intermittent electric currents that would keep the vibrations going at a regular rate. The series and the interrupter were based on the self-regulating current interrupter patented earlier by Helmholtz's friend, Werner Siemens, who used the oscillator to regulate the connections of a telegraph. Helmholtz modified this interrupter by using a tuning fork as the oscillator. Timothy Lenoir gives the details of this invention in Timothy Lenoir, "Helmholtz and the Materialites of Communication," *ORISIS* 9 (1994): 199.

[54] Helmholtz, *Sensations* 377.

were added by the time he published *Sensations*.)[55] Beyond the initial experiments with the synthesiser, Helmholtz was able to confirm his results with his glass resonators. He concluded that the distinctive quality of vowels depended on a certain number of partials and the intensity of each of those partials. One sound could have the same harmonics present, but each one could display different intensities making it sound quite different.

In the next series of experiments Helmholtz tested the effect of phase on the timbre of vowels sounds. This was a crucial test of the older waveform theory of timbre. In Ohm's theory, there would be no effect of phase because the same elements, with the same intensities, would constitute the same overall compound. Critics of Ohm argued that phase was important because a change of phase would lead to a different waveform, which in turn would cause a different timbre. But such a claim was contrary to the analytic conception of the ear. The ear did not respond to waveforms, it responded to simple tones.

Helmholtz manipulated the phase of the forks by adding wax to the prongs in order to temporarily throw off the vibrations and thereby alter phase. He also adjusted the opening of the resonator because the theory of resonators suggested one could cover a small fraction of the mouth of the tube to produce a slight shift in the phase.[56] After a series of experiments in which he kept the number and intensity of harmonics constant but shifted the phase, he concluded that the changes in phase did not have an effect on the timbre of the vowels.[57] This became a pivotal experiment for him, one that would face a serious challenge from Koenig in the 1880s (§4.7).

2.8 THE THEORY OF VOWELS

These studies on vowels were also contributing to a new theory of vowel sounds, which later came to be called the "fixed-pitch theory." Since 1857 Helmholtz's Dutch colleague, Franz Don-

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[55] Helmholtz, *Sensations* 121.

[56] Helmholtz was about to publish his article covering the mathematical theories of resonating tubes. Hermann Helmholtz, "Theorie der Luftschwingungen in Röhren mit offenen Enden," *Journal für die reine und angewandte Mathematik* 57 (1860).

[57] Helmholtz, *Sensations* 126.
Helmholtz, "On Vowel Sounds," 87.

Donders, had been conducting extensive tests on vowels and discovered, along with Helmholtz, that each vowel sound was dominated by a certain upper partial or small group of upper partials in a fixed region of the musical scale. In short, the cavity of the mouth was specially tuned for specific vowels. Therefore, no matter what note a person sang to produce a vowel sound, the mouth was shaped in a certain way and reinforced the same fixed region of harmonics giving the vowel a distinctive timbre.[58] Donders tested this idea with a curious whispering technique. He shaped his mouth cavity in the form of a specific vowel and produced a "windrush" that passed through the mouth and was transformed into a whistling sound. The vocal cords were closed and the windrush derived partly from the contracted glottis and partly from the forward contracted passages of the mouth. Helmholtz described the whispering sound as something similar to that of an organ pipe with a defective lip. "A noise of this kind," he wrote, "although not brought up to being a complete musical tone, has nevertheless a tolerably determinate pitch, which can be estimated by a practised ear."[59] Using this method Donders produced seven values for the vowels U, O, A, Ö, Ü, E, and I.[60]

Helmholtz used more than an attentive ear. He employed his new resonators to listen for the sounds, along with tuning forks to activate the resonance of the mouth cavity. He held a series of tuning forks to the mouth when it was in the shape of an "O" and discovered, by trial and error, the "characteristic pitch" of the resonant cavity. He then used the resonators to confirm the proper frequencies. For situations in which the mouth did not resonate well, and was therefore not conducive to the tuning-fork method, he sang through the notes of the scale, with his mouth in the shape of a specific vowel, and carefully observed a point where he sensed a peculiar tickling sen-

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[58] According to E.G. Boring, who has written one of the most comprehensive histories of vowels studies in psychology, the fixed pitch theory was in opposition to the relative pitch theory that stated that the distinctive vowel sounds derive from similar patterns of harmonics to the fundamental, no matter what the pitch of the vowel. See Edwin G. Boring, *Sensation and Perception in the History of Experimental Psychology* (New York; London: D. Appleton-Century Company, 1942) 367-75.

[59] Helmholtz, *Sensations* 108.

[60] Ibid., 109

sation caused by the vibrations of the drums in his ear. Using these methods, he came up with slight modifications of Donders findings.[61]

Helmholtz modelled his conception of the vowel production after the reed pipe, a vibrating tongue, rich in harmonics, that sounded differently depending on the shape of the chamber or tube to which it was connected. The human voice, through its vibrating vocal chords, produced a rich series of partial tones. The specific shape of the mouth then acted to reinforce and dampen some of these tones, making certain regions of the harmonics more prominent. "Under these circumstances the investigations of the resonance of the cavity of the mouth is of great importance," he wrote.[62] Refining the theory of resonance become crucial to the overall theory of timbre.

2.9 THE THEORY OF RESONANCE

Helmholtz's work on vowels coincided with a masterful exposition of the mathematics of aerial (resonant) tubes. It was these studies, he wrote to Ludwig in June 1859, that had led him to a definite theory of timbre.[63] One benefit was that he could now formally understand how the mouth acted as a resonator in shaping the distinctive vowel sounds that emerged from the vocal cords. Another advantage was that he could hone his formula for building precision resonators for the production and detection of simple tones. In March of that year, Helmholtz presented his paper at Heidelberg, "The Theory of Aerial Vibrations in Tubes with Open Ends" and later that year published his findings in Crelle's mathematical journal.[64] These studies of organ pipes and tubes were crucial for his theory of timbre, and with the clearer understanding of airflow and vibrations they would later serve as a foundation for a refined theory of hydrodynamics.[65]

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[61] Ibid., 105-10.

[62] Ibid., 104. The violin was also an inspiration for Helmholtz's model of how the mouth worked. In *Sensations*, Helmholtz cited Friedrich Zamminer's observations and calculations of resonance in violins. The violin chambers served as a model for the human voice in that the strings produced certain harmonics, similar to those produced by the vocal cords, although the violin cavity reinforced only a fixed range of these tones (similar to the cavity of the mouth). Ibid., 86-87. Also see Friedrich Zamminer, *Die Musik und die musikalischen Instrumente* (1855).

[63] Koenigsberger, *Hermann von Helmholtz* 178.

[64] Helmholtz, "Theorie der Luftschwingungen."

[65] Olivier Darrigol, "From Organ Pipes to Atmospheric Motions: Helmholtz on Fluid Mechanics," *HSPS* 29 (1998).

The enlightenment mathematicians, Bernouilli, Euler and Lagrange, had each produced an elaborate mathematical theory of the motion of air in open organ pipes. Formulas they derived for frequency, however, did not match well with experiment. Helmholtz believed that the previous writers had oversimplified the behaviour of air in the pipes. The conditions in the middle of the pipe, for example, were quite different from the conditions at the open end where the air particles interacted with free space. Using a powerful mathematical model called Green's theorem, Helmholtz was able to incorporate the complex boundary conditions at the open end of the pipe and derive a clearer picture of the conditions for aerial vibration -- motion at the nodes, intensity of the emitted sound and the phase relations -- and thereby greatly refine the formula for predicting the resonance-frequency in tubes and resonators. He compared his results with the extensive empirical studies of tubes by Guillaume Wertheim (1815-1861)[66] in France and Friedrich Zamminer[67] in Germany and found reasonable agreement for wide tubes, but remaining problems with narrow tubes.[68]

Based on these methods Helmholtz then formulated the resonance laws for the spherical resonators he had been using for his analytic experiments. Theory showed that with dimensions larger than the wavelength in question, and with small openings, these resonators reinforced one tone very powerfully. He derived his formula from theory and checked it with the observations on similar resonating spheres recently performed by Wertheim and Carl Sondhauss.[69]

In fact, Helmholtz relied on a wealth of empirical work. In the first half of the nineteenth century, mainly due to research on violins by the French physicist, Félix Savart, there had been much interest in resonating chambers. Koenig's predecessor, Albert Marloye, who had worked under Savart, invented a resonant box that reinforced and amplified the vibrations of a mounted tuning

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[66] G. Wertheim, "Mémoire sur les vibrations sonnores de l'air," *Annales de Chimie et de Physique* 31 (1851).

[67] Friedrich Zamminer, "Über die Schwingungsbewegung der Luft in Röhren," *Annalen der Physik* 97 (1856).

[68] An account of this work is found in Darrigol, "From Organ Pipes to Atmospheric Motions," 7-10.

fork.[70] As we saw above, Helmholtz made ample use of the extensive tests on various shapes and materials of resonating chambers by Wertheim, Zamminer and Sondhauss. He also used findings from music. Aristide Cavaillé-Coll, one of the premier organ builders of Paris at mid-century, developed several innovations in organ pipes prior to and during the early acoustical researches of Helmholtz.[71] In 1863, based mostly on Zamminer's measurements of frequency for narrow tubes and taking into consideration the influence of friction on aerial vibration, Helmholtz modified his theory of 1859.[72] As we will see later in this chapter, Koenig played an indirect role in the development of the theory of spherical resonators. The construction of the spherical resonators for the ear in the period 1859-1860 revealed the difficulties of constructing instruments based on theory alone. The resultant resonators set the boundaries for Helmholtz's later modifications to his formula. Work by Helmholtz and Sondhauss in the 1860s would eventually lead to the refinement of the theory of resonators by Lord Rayleigh in the 1870s.[73]

2.10 ANALYSING THE MOTION OF VIOLIN STRINGS

With his work on timbre and aerial resonance firmly established in experiment and with new instruments, Helmholtz set out to develop an analytic instrument for observing vibrating strings directly without recourse to the ear. To do this he utilised a technique developed in Paris by Etienne Jules Lissajous in the 1850s. Using two tuning forks with mirrors placed on the end of one of the prongs, Lissajous had invented an optical technique for combining the vibrations of the two vibrating bodies. A light beam bounced off the prong of one fork (vibrating up and down, creating, through persistence of vision, a vertical line on a screen). The first beam, in turn, bounced off another vibrating prong (vibrating sideways and therefore causing a horizontal mo-

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[69] Carl Friedrich Sondhauss, "Ueber den Brummfreisel und das Schwingungsgesetz der kubischen Pfeifen," *Annalen der Physik* 81 (1850). Wertheim, "Mémoire sur les vibrations."

[70] Miller, *Anecdotal History* 60.

[71] Helmholtz met Cavaillé-Coll in Paris during a trip in 1866. Koenigsberger, *Hermann von Helmholtz* 233.

[72] Helmholtz, *Wissenschaftliche Abhandlungen* 382-87. For a more detailed summary of these developments, see Darrigol, "From Organ Pipes to Atmospheric Motions," 21-23.

[73] Baron Rayleigh, *The Theory of Sound*, 2 ed., vol. 2 (London: MacMillan and Co., 1896), 170-235. For a summary of Rayleigh's work in acoustics, see Beyer, *Sounds* 83-102.

tion on a screen). The combined vibrations created characteristic geometric figures. For example, a pair of forks tuned an octave apart would create a figure-eight pattern. This new technique offered a dramatic improvement for precision tuning because the forks had to be exactly tuned with the prescribed interval to create the figure. The most precise application of Lissajous's method came in the form of what was called the vibration microscope, or "comparateur," that allowed one to study the vibrations of strings, tuning forks or any vibrating bodies. An objective lens rested on the end of a tuning fork and vibrated in one direction, and the object under study would be illuminated and vibrate in the opposite direction. Thus the vibrations combined to form the characteristic Lissajous patterns as seen through the microscope lens.[74] This was Lissajous's finest precision instrument for tuning and observing vibrating bodies.

During the year 1860 Helmholtz performed a series of studies on the motion of violin strings which his friend William Thompson communicated to the Glasgow Philosophical Society on December 19 of that year.[75] Helmholtz used a variation of the Lissajous vibration microscope for his studies. He placed the first object lens in a sturdy frame, with the other lens (lined up with a first lens) resting on the prong of an electromagnetic tuning fork. He then took the violin strings he meant to study, blackened them and placed starch powder on the place to be observed. A lamp, set beside the apparatus, illuminated the starch. The fork vibrated at 120 Hz, (kept steady by an electromagnet at 120 Hz), and the violin string at 480 Hz (a high "A" on the musical scale), making four vibrations for every vibration of the tuning fork.

Lissajous had used the vibration microscope as a precision tuner. Helmholtz, working in a different context, used the instrument to analyse a compound vibration into its simple components. To make this easier, Helmholtz imagined spreading the Lissajous patterns out via a rolling

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[74] For a description of Lissajous's first vibration microscope, see Jules Lissajous, *Instruction Pratique Relative a l'Emploi des Instruments d'Acoustiques* (Paris: Secretan, 1857) 10. For more on the history of Lissajous figures, see Steven Turner, "Demonstrating Harmony: Some of the Many Devices Used to Produce Lissajous Curves before the Oscilloscope," *Rittenhouse* 11, no. 2 (1996).

[75] Hermann Helmholtz, "On the Motion of the Strings of a Violin," *Proceedings of the Philosophical Society of Glasgow* 5 (1860).

drum to create a horizontal time axis. By establishing the necessary conditions of string vibrations[76] and by filling in the basic variables such as displacement, length of string, time duration of one vibration, and the position of the point under scrutiny on the string, he was able to calculate the velocity of the string's vibrations at certain points. He then carried out a Fourier analysis of all of the vibrations involved in the overall motion, such as the number and strength of harmonics in the string motion. [77] He also used this instrument to demonstrate shifting phase patterns in order to determine, in another way, that phase had no effect on timbre.[78] The Lissajous comparator thus became a core instrument in the new acoustics.

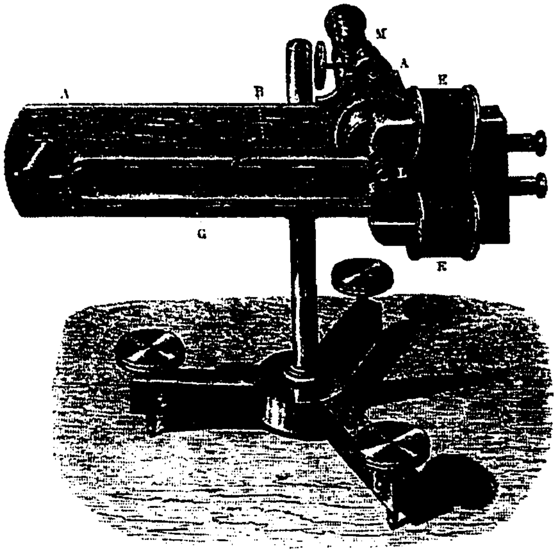

Figure 2.2 Lissajous comparator. Helmholtz *Sensations* 81.

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[76] Two conditions were necessary for determining the equation of the string's motion: First, that the strings of a violin, when struck by a bow, vibrate in one plane. Second, that every point on the string moves to and fro with two constant velocities. Helmholtz, "On the Motion of the Strings," 19.

[77] Helmholtz detailed the mathematics for this operation in Helmholtz, *Sensations* 384-87. On a qualitative level, he was able to judge the effects of different bowing techniques, and the uniformity of vibration. He found, for example, that the violin bow created two velocities in the string vibration, one during the striking of the string, the other during the return movement. The older violins, he noticed, produced a more regular, consistent effect with the bow stroke, making it easier to count the indentures of a given curve. "I find it a matter of importance to use a violin of the most perfect construction, and I had occasion to get a very fine instrument of Guadanini for these experiments." Helmholtz, "On the Motion of the Strings," 17-18. But all violin strings, if bowed in the same fashion, gave the same overall shape to the curve.

[78] Helmholtz, *Sensations* 126-27. He also used it to study the vibration of reed tongues, Ibid., 101.

2.11 THE SENSATIONS OF TONE

By 1860, with all the major elements for the reform of acoustics in place, Helmholtz wrote to his friend Donders: "I have decided to put my acoustic work together in a book. It will be a small volume, as popular in style as possible, so as to make it available to lovers of music. I think I shall be able to expound the physico-physiological basis of the theory of harmony."[79]

Die Lehre von den Tonempfindungen als Physiologische Grundlage für die Theorie der Musik (*On the Sensations of Tone as a Physiological Basis for the Theory of Music*) which first appeared in early 1863, tied together all of the above findings into a comprehensive analytic theory of sound. Harmonics or upper partials, which had been observed by musicians for centuries, were no longer ill-defined phenomena of music but the "elements of sound" with a strict mathematical, physical and physiological definition. Most importantly, as we saw earlier, Helmholtz created instruments that reflected his analytic thinking. *Sensations* was an introduction to resonators (for precision detection and analysis of simple tones), tuning forks with cylindrical resonators (for production of precision simple tones), the sound synthesiser (for producing complex vowel sounds from simple tones), and the Lissajous vibration microscope (for analysing the elements of vibrating bodies).

The second part of *Sensations* dealt with the way his fundamental findings applied to the structure of music as a whole. The interaction of upper partials, combination tones and beats explained, for example, the difference between flutes and violins. Minor chords, Helmholtz conjectured, obtained their distinctive character from slightly inharmonious but weak combination tones. He described the differences between various scales. The dissonances of the equal tempered-scale derived from "bad combination tones," he claimed. He invented what he called the "justly intoned harmonium," a special reed instrument, for experimenting with the scale of just intonation and the pure intervals. In his hands this instrument was an elaborate version of the polyphonic siren, designed for investigating the relations and effects of all the major scales at once.[80] It served as a powerful contrast to his piano: "when I go from my justly intoned harmonium to a grand pianoforte, every note of the latter sounds false and disturbing."[81]

Helmholtz argued in the third section of his book that musical preferences were ultimately determined by cultural taste. One culture, for instance, may not tolerate certain dissonances that another culture would view favourably. This was a radical position that recognised dissonance to be a matter of degree and not of kind, and it may have foreshadowed the freedom with which later composers made music, released from traditional notions of harmony.[82] With respect to this claim, he maintained that his contribution had been confined to establishing the "elements" and basic principles of musical sounds. Various cultures and traditions ultimately decided how these laws could be applied, he wrote, "but just as people with differently directed tastes can erect extremely different kinds of buildings with the same stones, so also the history of music shows us that the same properties of the human ear could serve as the foundation of very different musical systems."[83]

2.12 KOENIG AND THE NEW ACOUSTICS

By the time he published his second catalogue in 1865, Rudolph Koenig offered approximately fifteen instruments (out of 251) that derived from the work of Helmholtz. Some of them had been only slightly modified, others elaborated into related instruments, and a few significantly changed and improved. Koenig provided the means of spreading the theories and research of Helmholtz through these new instruments. For instance, in the 1860s he was the only maker who offered a model of the Lissajous comparator similar to Helmholtz's. In the latter part of the nineteenth cen-

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[79] Koenigsberger, *Hermann von Helmholtz* 194.

[80] Helmholtz had commissioned Messrs. J. & P. Schiedmayer of Stuttgart to make this instrument. Helmholtz *Sensations* 316. The Museo di Fisica at the University of Rome has a Harmonium built by Anton Appunn of Hanau.

[81] Ibid., 323.

[82] Hiebert and Hiebert, "Musical Thought and Practice" 303.

[83] Helmholtz, *Sensations* 366.

tury this instrument gained widespread use as an analytic research and demonstration tool.[84] Whereas Helmholtz had provided a new context and use for Lissajous's early invention, Koenig provided the means to perfect and distribute this instrument.[85] In Chapter Four we shall see how he transformed the comparator into the clockfork for calibrating precision tuning forks (§4.6).

The most important instruments related to simple tones, a conception that was not fully accepted even as late as 1880. Sceptical physicists thought of simple tones as mathematical fictions. The instruments, however, played a major role in making them a reality in practice. The Oxford physicist, R.H.M. Bosanquet, captured the essence of the new acoustics when describing his work on combination tones (§4.4). "These pure primes [tones]," Bosanquet wrote, "whether realizable or only ideal, are the elements by the combination of which all the composite notes of nature are formed; and, as all analysis depends on our knowledge of the elements whose presence we have to ascertain, the study of the properties of these pure prime tones is, in one sense at least, the foundation of all acoustics."[86]

2.13 THE DOUBLE SIREN AND COMBINATION TONES

The double siren was the first instrument that Koenig built from Helmholtz's studies. In fact, it was the subject of their earliest known correspondence in 1859 in which he thanked Helmholtz for a "detailed description" of his recent invention.[87] Koenig made his own double siren from this

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[84] Rudolph Koenig, *Catalogue des Appareils d'Acoustique* (Paris: Simon Raçon et Comp., 1865a) 107. For a description of how students used the one at Toronto, see W.J. Loudon and J.C. McLennan, *A Laboratory Course in Experimental Physics* (New York, London: MacMillam and Co., 1895) 107. There are currently Lissajous comparators at the National Museum of American History, Smithsonian Institution, cat. no. 315,724, Case Western Reserve University and the Museo di Fisica at the University of Rome. To view the one at the Museo di Storia Della Scienza in Firenze, see Giatti and Miniati, eds., *Acoustics and its Instruments* 106. For more on the origins, uses and transmission of this instrument see Turner, "Demonstrating Harmony," 34, 39-40.

[85] The comparator was the most refined instrument for studying the vibrations of bodies. Koenig used it to defend the purity of his tuning forks, in Rudolph Koenig, *Quelques Expériences d'Acoustique* (Paris: A. Lahure, 1882b) 199.

[86] R. H. M. Bosanquet, "On a Mode of Producing Continuous Notes from Resonators," *Proceedings of the Musical Association* 6 (1879): 15.

[87] See December 2, 1859, in Herbert Hörz, ed., *Brückenschlag zwischen zwei Kulturen: Helmholtz in der Korespondenz mit Geisteswissenschaftlern und Künstlern* (Marburg: Basilisken-Presse, 1997) 358.

description and sold it for 400 francs.[88] He included it in his 1865 catalogue in a small section devoted to the "coexistence of two or more sounds in the air."[89] He did not, however, make any major changes to the earlier model of Sauerwald (the maker of the first double siren).[90]

The double siren became an immensely popular instrument and showed Koenig's ability, even early in the 1860s, to facilitate Helmholtz's reforms. Even though it was relatively expensive, he sold it to several institutions large and small.[91] Professor Terquem at the École Normale Supérieure in Paris was one of the first researchers to use Koenig's double siren to test Helmholtz's findings.[92] Koenig himself used the double siren in his research, but eventually rejected it as a means for studying combination tones and developed a different series of instruments (§4.3). In the newly created teaching laboratories around Europe and North America, double sirens were used for a variety of demonstrations and exercises. Students at the University of Toronto used it for determining the pitch of an organ pipe.[93] At Dartmouth College, Professor Charles Emerson employed the double siren as a standard part of his lecture demonstrations on sound.[94] Father August Zahm used the double siren to illustrate the phenomena of beats and interference in his lectures on sound delivered at the Catholic University of America in 1891.[95] The double siren appeared in all the major texts on acoustics as a way for students and researchers to test and demon-

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[88] Koenig, *Catalogue (1865)* 9, 37.

[89] Ibid., 33-37.

[90] An original Sauerwald double siren as described by Helmholtz can be found at the Teyler's museum in Holland, signed by F. Sauerwald, purchased in 1865 from the maker at 65 Reichstahler in Berlin. Gerard L'E. Turner, *The Practice of Science in the Nineteenth Century: Teaching and Research Apparatus at the Teyler Museum* (Haarlem: Teyler Museum, 1996) 110. Another one can be found at the Johannes Müller Institut für Physiologie in Berlin, see Bartsch, Peter, ed. *Charité Universitätsklinikum der Humbolt-Universität zu Berlin historsche Instrumentensammlung, Katalogue. Johannes-Müller-Institute für Physiologie.* (Bonn/Berlin, 2000) 51.

[91] Presently, one can find examples of these sirens spread around Europe and North America - the Conservatoire National des Arts and Métiers in Paris, the University of Rome, the National Museum of American History, (cat no. 80.98.2), the University of Toronto, McGill University and Wesleyan College (the latter siren was catalogued by Tom Greenslade of Kenyon College, who has created a list of Koenig apparatus found in Colleges throughout the United States).

[92] A. Terquem, "Étude sur le timbre des sons produits par des chocs discontinus et en particulier par la sirène," *Annles Scientifiques de l'École Normale Supérieure* 7 (1870): 280.

[93] Loudon and McLennan, *A Laboratory Course* 102-03.

[94] Willis T. Sparhawk, "Notes on Sound, Optics and Electricity," in *Dartmouth College Archives, Willis T. Sparhawk, Notebooks 1891-95* (Hanover, New Hampshire).

strate combination tones, beats and interference phenomena.[96] After his death, the siren was still quite popular. The Max Kohl firm in Germany made an almost identical version.[97]

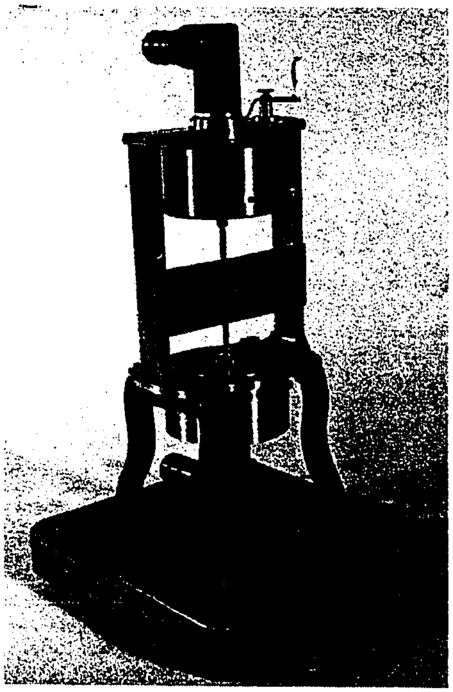

Figure 2.3 Double siren by Koenig, circa 1876. University of Toronto Museum of Scientific Instruments (UTMuSI).

Aside from copying the double siren of Helmholtz, Koenig performed his own research at this time and built another kind of siren that could do a wider variety of tasks. In the 1830s Seebeck and Opelt had invented sirens with changeable perforated cardboard disks of varying patterns to study the nature of tones, musical intervals and chords. Koenig made an improved and updated version of this siren with a new emphasis on controlling the individual tones of the disk. He used brass disks with varying patterns and a clock mechanism to regulate the rotation. He added ten wind-vents that could be moved to any desired position on the disk. He also made it

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[95] John Augustine Zahm, *Sound and Music* (Chicago: A.C. McClurg & Co., 1900) 402-05.

[96] Also see Franz Joseph Pisko, *Die neuren Apparate der Akustik* (Wien: Carl Gerold's Sohn, 1865) 49-54. Tyndall, John. *Sound.* 7 ed. London: Longmans, Green and Co., 1898) 74. Winkelmann, A. *Handbuch der Physik: Akustik.* vol. 2. (Leipzig: Johann Ambrosius Barth, 1909) 590.

[97] Max Kohl, *Catalogue of Physical Apparatus* (Chemnitz: 1909) 422-23. Max Kohl, *Catalogue of Physical Apparatus* (Chemnitz: 1928) 354. Kohl double sirens are found at the Museo di Storia della Scienza,

possible to adjust the intensity of each tone.[98] In the late 1860s Terquem used this instrument, along with other Koenig sirens, to study timbre and test the still contentious claims of Ohm, Seebeck, and Helmholtz.[99] Koenig advertised this instrument in his catalogue at the large sum of 800 francs (the third most expensive instrument in his catalogue).[100] In the 1870s the Seebeck siren became a springboard for alternative paths in Koenig's research on combination tones and timbre (§4.7).

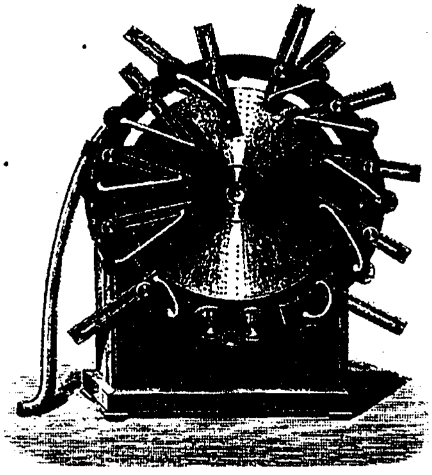

Figure 2.4 Seebeck siren by Koenig. Koenig *Catalogue (1865)* 7.

2.14 SYNTHESISER AND VOWEL STUDIES

The historian E.G. Boring described the Koenig/Helmholtz synthesiser as "a monument to the classical days of psychological brass instruments."[101] In brass and steel, with ivory piano keys, it provided a clear mechanical expression of Helmholtz's radical new physical and physiological conception of timbre. It was, perhaps, more of a monument to the teaching of his ideas. Frustra-

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Firenze, see Giatti and Miniati, eds., *Acoustics and its Instruments* 88., and the National Museum of American History (cat. no. 327, 651).

[98] Koenig, *Catalogue (1865)* 6-7.

[99] Terquem, "Étude sur le timbre" 279. A later version of this instrument, with ten different disks, can be found at the Museo di Fisica at the University of Rome.

[100] Koenig, *Catalogue (1865)* 6-7.

[101] Boring, *Sensation and Perception* 372.

tions with the synthesiser as a research instrument would greatly contribute to the dispute between Koenig and Helmholtz on the role of phase in timbre (§4.7).

In late 1859, around the same time that he received the description for the siren, Koenig read Helmholtz's article "Ueber die Klangfarbe der Vocale" ("On the Timbre of Vowels"). "Your work on the timbre of vowels has interested me so much, that I would be very pleased to have some detailed descriptions of the apparatus with the tuning forks... It would please me to have a full sketch with a few measurements of the main proportions. I would also be so thankful to you, if you would be so kind as to allow me to manufacture and occasionally distribute it [to clients]."[102] Having received no reply after a few months (Helmholtz's first wife died in December of that year), he wrote again at the end of February to ask again for instructions on how to build the synthesiser. He told him that a Russian professor, who had also read his article, inquired about the synthesiser, and wanted to know how much it would cost to make.[103] Not long afterward he received the reply and began building the instrument.

Koenig wanted the apparatus for his own experiments as well. Over a year later, in May 1861, he reported to Helmholtz that he had finished building the apparatus and had been performing some tests on it but was continually forced to stop on account of his business. "For some time now the apparatus has been finished and I ever so much regretted not having the honour of your visit as you came through Paris. I naturally would have very gladly shown you this work, in order to allow you to instruct me on improvements or alterations to the apparatus."[104] He was only able to replicate the basic effects of Helmholtz's original studies and was hoping for more conclusive tests in the future. "The forks all sound good with open resonators, and they were very little heard when the resonators were closed. One can also regulate the strength of each tone conveniently

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[102] See February 29, 1860, in Hörz, ed., *Brückenschlag zwischen zwei Kulturen* 361.
[103] See May 27, 1860, in Ibid., 362.
[104] See May 18, 1861, in Ibid., 362-63.

through the keys. In the little time that I could employ, however, sufficed only for the production of very incomplete vowels."[105]

By 1865 Koenig advertised the synthesiser in his second catalogue as "the grand apparatus for the composition of different timbre of sounds, notably the timbre of vowels, through the simultaneous production of a series of simple notes that form a progression of harmonics."[106] It cost 800 francs, making it the third most expensive instrument in the collection (along with the Seebeck siren). Whereas Helmholtz had used the eight notes of B and its harmonics, based on a different standard note, Koenig used the standard that he would use throughout his career, Ut3=256 Hz, from the physicist's scale, A = 426.6 Hz, which started at 2 Hz and proceeded by powers of two.[107] He claimed that his starting note, Ut2 (128 Hz), was only 8 Hz off from Helmholtz's starting note of 120 Hz. His forks began from what was called 256 v.s. and went to 1024 v.s. In addition, he used the common French notation: Ut3 (or the German c1, or middle c on the piano), Re3 (d1), Mi3 (e1), Fa3 (f1), SoL3 (g1), La3 (a1), Si3 (b1) and Ut4 (c2).

After seeing all of Koenig's new instruments at the London exhibition of 1862, the Vienna physicist Joseph Pisko became an enthusiastic promoter of his instruments, and therefore, indirectly, of Helmholtz's reform of acoustics. The synthesiser became one of the featured instruments of the new acoustics and Pisko singled it out for detailed discussion in *Die Neuren Apparate der Akustik* (1865).[108] The Koenig synthesiser pictured by Pisko in his book, with wooden square resonators, was quite different from later versions of the instrument, revealing that Koenig had most likely built more than one version. Later models, for example, had brass resonators and a secure mounting for the entire apparatus. In 1873 he added two more notes to the analyser Re5 and Mi5, reflecting changes Helmholtz had made during that time to his own apparatus. Helm-

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[105] See May 18, 1861, in Ibid.
[106] Koenig, *Catalogue (1865)* 10-11.
[107] In 1830 the German physicist Ernst Chladni adopted the physicist's scale for his research in acoustics. Zahm, *Sound and Music* 79.
[108] Pisko, *Die neuren Apparate der Akustik* 22-26.

holtz had had difficulty reproducing the "brighter" vowels and had added some higher forks.[109] Descriptions of this later model were found in several textbooks of the time.[110]

Although Helmholtz had claimed general success with his instrument, others had trouble reproducing the vowels. Students at the University of Toronto were told that it did not provide an accurate comparison of timbre, but that it "affords an instructive exercise for the student." Each tuning fork ran in series through an interrupter that had to be tuned perfectly (using a Lissajous mirror) to the lowest common frequency of 64 Hz. Any deviations from this frequency created changes in the intensity of various harmonics. The noise of the interrupting fork was considerable, as well, and it had to be moved into another room. Other researchers such as Zahm and Rayleigh had a difficult time replicating Helmholtz's findings.[111] Koenig's frustrations with the synthesiser led him to develop alternative instruments for synthesising vowels and timbre as early as the late 1860s (§4.7).

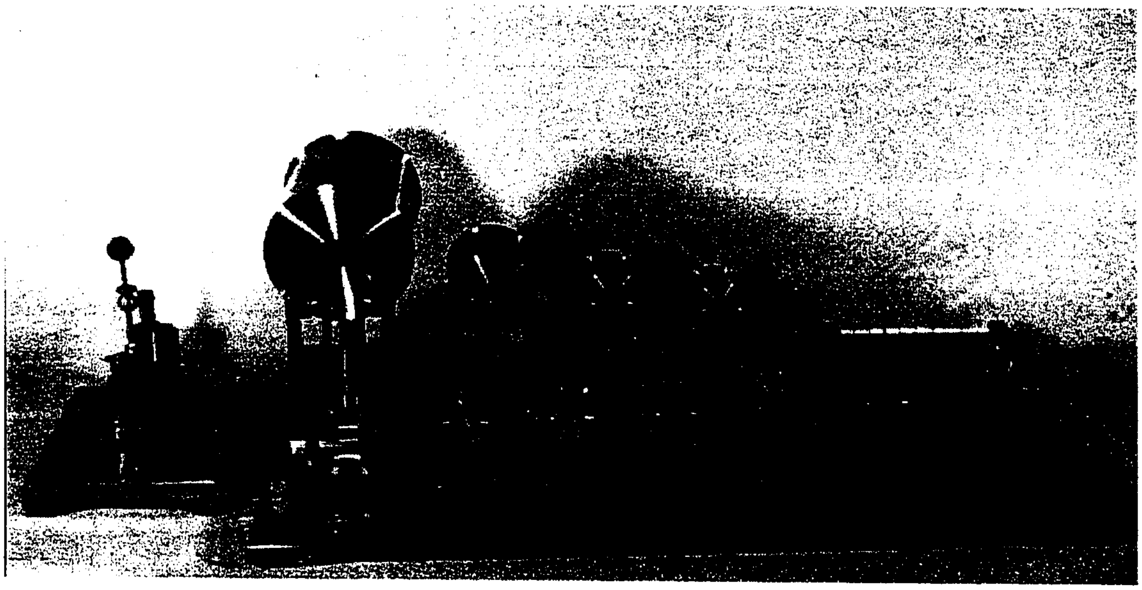

Figure 2.5 Helmholtz synthesiser by Koenig, circa 1876. UTMuSI.

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[109] Helmholtz, *Sensations* 123.
Rudolph Koenig, *Catalogue des Appareils d'Acoustique* (Paris: 1873a) 5.

[110] Adolphe Ganot, *Elementary Treatise in Physics*, trans. E. Atkinson, 14th ed. (New York: William Wood and Co., 1893) 239-40. Loudon and McLennan, *A Laboratory Course* 122. Zahm, *Sound and Music* 356-7.

[111] Dayton Clarence Miller, *The Science of Musical Sounds* (New York: MacMillan, 1916) 245-46.

For transmitting Helmholtz's theory, however, the synthesiser was a dramatic teaching apparatus.[112] At international fairs and in classrooms it served as a source of visual information of the mechanics of timbre. Following his first trials with the instrument in 1860, Koenig wrote to Helmholtz: "In the mean time, it was very interesting to show how the whole complex tone was altered when one changed a single harmonic, more or less, so I lent the apparatus to the Sorbonne and made there several such experiments in the course of Herr Professor Desains."[113]

Perhaps out of frustration with the synthesiser as a research instrument, in 1867-68 Koenig invented a radically new instrument called the wave siren.[114] It consisted of a cylindrical drum in a frame covered by a closely fitting revolving drum. The outside drum had sixteen levels of holes shaped as sinusoidal waveforms, the fundamental note at the bottom with an ascending series of fifteen harmonics. Each hole had a corresponding slit on the inner drum from which pressured air poured through. Piano keys allowed one to activate each level or tone. Koenig had spent almost ten years developing ways to represent sound waves graphically or with flame patterns; now he was reversing this process and modelling sound producers on waveforms. It marked his departure away from the abstract and analytic conception of sound, expressed by the regular perforated disks of a siren (with no resemblance to a sine wave), to a more visual method of reproducing sound. One of the first people to use it was Professor Terquem in Paris.[115]

2.15 CONSTRUCTING THE RESONATORS

The resonator was one of the most frequently used instruments in *Sensations*. It was used to demonstrate and test every aspect of the Helmholtz's acoustics – the theory of timbre, vowels, combi-

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[112] Teyler's museum in Holland also has a well-preserved model of Koenig's synthesiser. See Turner, *The Practice of Science in the Nineteenth Century: Teaching and Research Apparatus at the Teyler Museum* 116. The Science Museum in London and Harvard both have Koenig synthesisers. McGill University had a synthesiser in the late 19th century, but it is now missing.

[113] See May 18, 1861, in Hörz, ed., *Brückenschlag zwischen zwei Kulturen* 363.

[114] Koenig, *Quelques Expériences* 157. The only known picture of this instrument is from the 1876 Exhibition in Philadelphia, see Audrey B. Davis and Uta C. Merzbach, *Early Auditory Studies: Activities in the Psychology Laboratories of American Universities* (Washington D.C.: Smithsonian Institution, 1975) 3.

[115] Koenig, *Quelques Expériences* 157.

nation tones, beats, and the theory of resonance.[116] Yet in Helmholtz's preliminary studies (1855-1860) we find only a brief mention of these resonators. As we will see below, Koenig's significant improvement to the resonator was one of the reasons behind the new prominence of this instrument after 1860. Koenig played a valuable role in constructing and transmitting this instrument, which was to become the first precision detector of simple tones and the signature instrument of the new acoustics.

In *Sensations* Helmholtz claimed to have made his earliest resonators from "any spherical glass vessels that came to hand, as the receivers of retorts, and inserted into one of their openings a glass tube that had been adapted to my ear." "Afterwards," he wrote, "Herr R. Koenig, (maker of acoustical instruments, Paris, Place du Lycée Louis Le Grand 5) constructed a series of these glass spheres properly tuned."[117] Helmholtz most likely had heard of Koenig from his Königsberg connections. Koenig's work on the resonators, described in his letters to Helmholtz from late 1859 and early 1860, reveal that the tuning of the resonators was a very demanding job, requiring exceptional manual skill and creativity with sounds and materials. Similar to the phonautograph in 1859 (§3.4), the making of resonators could not have been done by an ordinary technician.

Koenig first had to face the delays and poor workmanship of the Paris glassblowers. Presumably he had instructed the glassblowers to do the preliminary shaping of the resonators. In December 1859 he informed Helmholtz that the desired resonators would be late because his first choice of glass manufacturer, who was supposed to provide a hollow glass sphere, took too long and provided a neck that was too thick for further manipulations. He wrote that he would go to another glassmaker who could to the job faster with better results. In the meantime, eager to extend his own research, and perhaps please his famous customer, he proceeded to do some experiments in order to create a series of resonators with a larger range of notes, "since I believe that it will certainly be desirable, with many kinds of investigations, to allow the resonators to go

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[116] Helmholtz, *Sensations*, 7, 43-44, 51, 52, 93, 103-119, 157, 167, 178, 216, 372-73.
[117] Helmholtz, *Tonempfindungen 1863* 561. Also see Helmholtz, *Sensations* 372-73.

through more tones, or through a complete series of tones."[118] He filled a large resonator/vessel with water and, as it leaked, he marked its sides with the specific notes that it had responded to at that level.

In theory, the key variables of the spherical resonators were the circular opening (where the sound entered from outside into the chamber) and the volume of the sphere.[119] The resonators therefore had to vary in size, but Koenig discovered, through practice, that manipulating the size of the opening was the most convenient way to fine-tune the resonator. As he did with tuning forks, he contracted the making of the main product and then did the fine-tuning himself. In his letter of February 2, 1860, to announce that he had finished the commission, he informed Helmholtz of the difficulties in achieving the desired product. He had gone through several trials with a glassblower, but none of them sufficed. Most of the circular openings had not been the appropriate size for the tuning procedure (which involved inserting a heater-tube into the sphere to manipulate the size of the opening), and the glassblowers had had great difficulty making the larger spheres. He therefore took the best they offered and improvised his own technique. He had them made with very large openings and a trimmed neck in order to insert the heater. He then delicately closed the opening until the desired tone was reached (a process which would have demanded a very well-trained ear). Some of the larger spheres still did not respond properly, so he crafted some wooden spheres, which he forwarded to Helmholtz for testing. The complete series included fourteen resonators covering a remarkable range of almost four octaves from "g" to "c4" (approximately 192 Hz to 2048 Hz).

Whereas Helmholtz's theory of resonance articulated centuries of artisanal knowledge about aerial vibrations, Koenig's efforts in the workshop provided Helmholtz with a clearer picture of the real-world boundaries of his theory.[120] His resonators, in effect, helped clarify Helmholtz's

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[118] See December 2, 1859, in Hörz, ed., *Brückenschlag zwischen zwei Kulturen* 359.

[119] Helmholtz, *Sensations* 373.

[120] D.C. Miller of Case School of Applied Science expressed the enduring tension between theory and practice in aerial resonating systems when describing Euler's elaborate theory of organ pipes: "These theo-

formula for the spherical resonators. Sondhauss's formula, Helmholtz wrote, which resulted from experiment, worked better when the openings were not too small. But when the diameter of the opening was smaller than one-tenth of the diameter of the sphere, Helmholtz's theoretical formula was closer to Wertheim's experiments. Using Koenig's resonators, Helmholtz determined experimentally that he had to use a slightly altered coefficient for his formula when the openings were between a fourth and a fifth of the diameter of the sphere.

Koenig's efforts also helped Helmholtz clarify his understanding of the role that openings played in the precision and amplitude of the resonators (the intensity and precision of the response).[121] In his technical appendix on resonators Helmholtz wrote of the sharpness of the resonator response:

> Resonators with a very narrow opening generally produce a much more considerable reinforcement of the tone, but then there must be a much more precise agreement between the pitch of the tone to be heard, and the proper tone of the resonator. It is just as in microscopes; the greater the magnifying power, the smaller the field of view. Reducing the size of the orifice also deepens the pitch of the resonator, and this gives an easy means of tuning it to the required pitch. But, for the above reason, the opening must not be reduced too much.[122]

Other variables such as the size of the spheres and the size of the neck went through slight transformations in Koenig's workshop for a few years after the original commission, thus revealing the amount of work it took to reach the standard form.[123] Making workable instruments took

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retical treatments [on aerial vibrations] suggest that the acoustic material was fed into a mathematical thrashing machine, where it is differentiated and integrated, and delivered in the form of clean acoustical grain or wheat in sacks, but the bread of acoustical life is not in it: the grain must still be ground, kneaded and baked before we can use the product. Strange as it may seem, there is not now any theoretical formula by which one can derive, *without the aid of empirical information*, the dimensions of an organ pipe which will give a specified tone. The flute is the simplest of wind instruments, yet one cannot approximately calculate the length of a flute tube which will sound a given note; one cannot by theoretical calculation locate any finger-hole on a flute tube which will produce a given tone. The difference between the "theoretical" and the actual length of the tube of a flute is more than two inches!" Miller, *Anecdotal History* 43

[121] Helmholtz described what we call today the "Quality factor" or "Q." This factor refers to the efficiency and sharpness of a resonating system, which is the energy stored divided by the energy dissipated. A high Q signifies a very efficient system that responds to a very narrow range of frequencies. Tuning forks, for example, have a very high Q; they display a sharp resonance and, due to their efficiency, continue to vibrate for a long time.

[122] Helmholtz, *Sensations* 374.

[123] The brass resonators measured at Toronto and the Smithsonian differed slightly from the original measurements of Koenig's glass resonators. The first glass resonator for "Sol3" measured 79 mm in diameter; the brass version measured 87 mm in diameter. The neck changed considerably from model to model. It

more than a clear theoretical blueprint, and more than skilled hands; they were just as much a product of Koenig's curiosity in the workshop. This creative process revealed that construction can be a form of experiment where the maker and clients learn something new about the world.

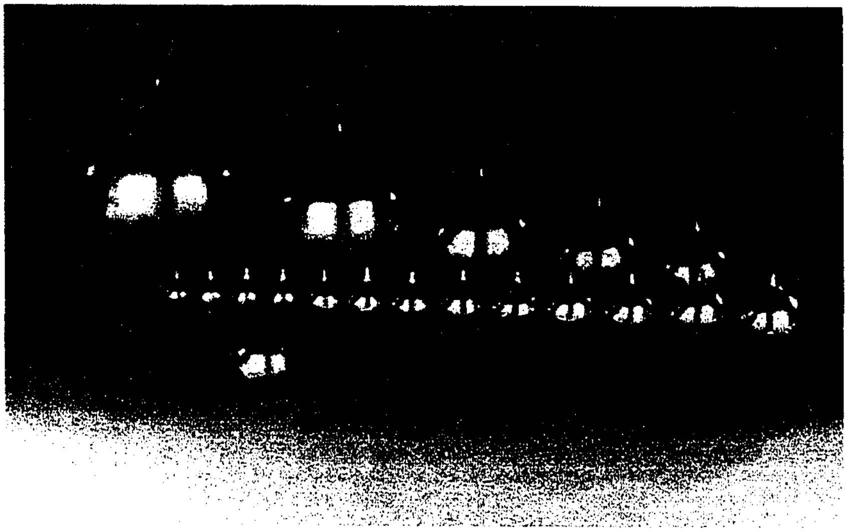

Figure 2.6 Koenig's brass resonators, circa 1890. Psychology Department, University of Toronto. UTMuSI.

Koenig's trials with materials had practical and theoretical implications as well. He made his first resonators of glass, but by 1865 he advertised brass resonators.[124] The glass resonators appeared in the first two editions of *Sensations*, 1863 and 1865. Helmholtz suggested in these editions that "perhaps it would be advantageous if the future larger spheres could be made of strong metal."[125] In his third edition, after learning of Koenig's brass resonators of 1870, Helmholtz remarked that recently Koenig had made them of "metal." Helmholtz had broken his glass resona-

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had an ambiguous existence in both theory and practice. Theory says that it should be one of the variables in the formula to determine pitch (along with the size of the opening and the volume), but early experimenters found that this formula "ceased to be applicable when the neck was very small." Wertheim, "Mémoire," 391-92. For this reason Helmholtz removed it from his formula. Koenig, however, clearly built resonators with necks that varied in size. Almost all of the images of resonators in texts and catalogues, even Helmholtz's image in *Sensations* 43, have a sizeable neck on the resonator. Koenig's brass resonators have smaller necks of varying size that appear to have been filed for tuning. A set of early brass resonators found at Oxford (from 1867) have rather large necks, compared to the later resonators from Toronto and the Smithsonian (1876). The necks served a purpose that was not accounted for in the formula.

[124] Koenig, *Catalogue (1865)* 10.

[125] Helmholtz, *Tonempfindungen 1863* 562. Helmholtz, *Tonempfindungen 1865* 562.

tors and ordered replacements.[126] Metal was obviously more durable and could survive the trains, carriages and shipping.[127] But metal also had theoretical implications. Brass resonators, "the most appropriate form of resonator," were mentioned in Helmholtz's last edition (1877) where brass was said to have the advantage of being "firm and smooth, to oppose the necessary resistance to the powerful vibrations of air which take place within them, and to impede the motion of air as little as possible by friction."[128] The changes Koenig had made were by then seen in light of Helmholtz's revised theory of resonance (the effect of friction) from 1863 (§2.9).

2.16 RESONATORS AND RESEARCH

Helmholtz made use of the resonators for a variety of researches into music and vowel quality. He coated the smaller funnel-opening with warm sealing wax and then inserted it into the ear so as to make it fit "air-tight;" he then plugged the other ear with sealing wax. When the resonator sounded the proper tone, "it brays into the ear most powerfully."[129] He used resonators to analyse the sounds of the piano, aerial pipes and the human voice.[130] He used them to confirm earlier predictions for harmonics, the existence of combination tones and beats, and, as mentioned above, to refine his theory of resonance. The most extensive use, however, was for his vowel studies. This is where his own powers of attention failed to pick out the rich and complex array of harmonics, and he was forced to rely on the resonators. "I must confess," he wrote, "that my own attempts to discover the upper partial tones in the human voice, and to determine the differences for different vowels, were most unsatisfactory until I applied the resonators."[131] Using Koenig's resonators he claimed to be able to detect up to sixteen harmonics from one vowel sound.[132]

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[126] Helmholtz, *Tonempfindungen 1870* 581.

[127] In his correspondence with James Loudon of the University of Toronto, Koenig was preoccupied with the details of shipping and packaging and was continually replacing glass pieces that had been destroyed in transit.

[128] Helmholtz, *Sensations* 372.

[129] Ibid., 43.

[130] Helmholtz, *Sensations* 7; 43-44; 51; 52; 93; 103-119; 157; 178; 216; 372-373.

[131] Helmholtz, *Sensations* 52. For a summary of the vowel studies, see Ibid., 103-19.

[132] Ibid., 103.

In the context of the drive to sharpen and purify the simple-tone producers and detectors, Alfred Mayer of the Steven's Institute in Hoboken, New Jersey, thought the resonators should be even more precise. [133] In an article reviewing a handful of methods for analysing sounds, Mayer raised the issue of the "want of precision" of the standard resonators.

> These facts concerning the lack of sharpness in the detection of pitch by means of resonators are not in accordance with the statements made in recent popular works on sound, where the resonator is described as remaining dumb until the exact pitch to which it is tuned is reached, when it responds to a suddenness which has been compared to an explosion! [134]

Despite this frustration, expressed by a friend of Koenig and a fellow devotee of the experimental master, Victor Regnault, the resonators were one of the most common research tools in the acoustics laboratory. In the midst of his work on combination tones, Koenig used them as a handy reference tool to verify the existence (or non-existence) of extremely faint harmonics in his tuning forks.[135] He also used them extensively for his vowel research.[136] Terquem in Paris used them for his research on timbre.[137] Whereas, in the early 1870s Koenig performed his most extensive studies of vowels with his manometric flame apparatus (§4.2), a student of Helmholtz, Félix Auerbach, performed a large-scale series of experiments using Helmholtz's set of resonators.[138] Even Mayer, who had complained about the "want of precision" of resonators, used Koenig's spherical resonators for experiments on the residual sensation of pitch.[139] Edward Wheeler Scripture used them to perform his famous experiments in phonetics.[140]

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[133] Alfred Mayer, "Researches in Acoustics: Six Experimental Methods of Sonorous Analysis Described and Discussed," *Philosophical Magazine*, (1874): 518. In applying a Koenig Ut3 resonator to the ear one discovers, in fact, that the resonator "brays" to a range of frequencies (+/- 16 Hz) above and below the prescribed tone to be selected. The braying varies in intensity, being much stronger when the exact note of the sound source (tuning fork) and the resonator match. With the 256 Hz (Ut3) resonator one does not hear any response after 288 Hz.

[134] Ibid.

[135] Koenig, *Quelques Expériences d'Acoustique* 151-52, 55, 60.

[136] Ibid., 42-46.

[137] A. Terquem, "Mémoire sur les sons produits par les ébranlements discontinus," *Comptes Rendus de l'Académie de Sciences* 73 (1871): 167.

[138] Félix Auerbach, "Untersuchungen über die Natur des Vocalklange," *Annalen der Physik* 8 (1878).

[139] Alfred Mayer, "Researches in Acoustics," *American Journal of Physics* XLVII, no. 277 (1894): 5, 8.

[140] Edward Wheeler Scripture, *Researches in Experimental Phonetics: The Study of Speech Curves* (Washington D.C.: Carnegie Institution, 1906) 112.

2.17 RESONATORS AND TEACHING

Resonators were mostly used for demonstrations, literally becoming an introduction to the ideas of Helmholtz. The resonators were, as Gaston Bachelard famously said of scientific instruments, "reified theories" that served to embody and propagate Helmholtz's theory of timbre.[141] They conveyed and substantiated the elemental view of sound phenomena and thereby made simple tones into a laboratory reality for students and professors. Dr. Siemens, a popular science lecturer at South Kensington, delivered what was a typical lecture on the analysis of sound in the early years of the new acoustics. In his demonstration he provided members of an audience with a series of resonators to hear the harmonics of his voice. "Even as I am speaking," he declared to the audience,

> if you take a few and try them, you will hear as I fall on the particular note in the inflexions of speech the tube reinforces it. The human voice is very full of harmonics, and if I sing the low C different persons holding the resonators will hear the upper partial notes that I unconsciously produce at the same time as the grave note that I am consciously producing.[142]

When Professor Thomas H. Core delivered a popular lecture on the analysis of sound at Hulme Town Hall, Manchester, on November 27 and December 4, 1877, he asked some of his own students to approach the stage and assist him with an experiment of timbre. "Sixteen students armed their ears with resonators, and stood in order from 1 to 16." The compound note of an organ pipe sounded and specific resonators responded. Another note sounded, and "seven students signified that they had detected their notes reinforced." "In this way the ear is armed with a powerful instrument for decomposing notes."[143]

In the student laboratory at Toronto, the demonstrators provided a brief theoretical overview of sound analysis and then described a series of experiments for testing these theories with the

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[141] Gaston Bachelard, *Épistémolgie* (Paris: Presses Universitaires de France, 1980) 137.
[142] Dr. Siemens, *Science Lectures at South Kensington* (London: MacMillan, 1879) 154.

resonators. In one experiment students stretched a steel string (a monochord) to vibrate at 256 Hz, and used the standard series of resonators (based on the harmonics of 128 Hz) that "recognise eighteen or twenty pure overtones of the harmonic scale."[144] They also compared the steel string with a copper string where "the third harmonic is often louder than the fundamental." Besides making the students familiar with Helmholtz's theory of sound quality, the experiment provided an everyday lesson on the appreciation of music in light of his theories; in this case, it nicely illustrated why stringed instruments, with such a complex array of harmonics, are so difficult to tune.

Koenig's brass resonators became a fixture of physical and psychological laboratories in the later part of the nineteenth century. At the University of Toronto, for example, there were two sets of Koenig's standard series of nineteen resonators – one for the psychology laboratory and another for the physical laboratory (in the 1890s the psychological laboratory was directly above the physical laboratory at University College). A full series of nineteen resonators cost a relatively modest 170 francs. The ideal psychology laboratory, according to the pioneer experimental psychologist, E.B. Titchener, should contain a standard set of Koenig resonators.[145] Titchener's neighbours at Cornell, Edward Nichols and Ernest Merritt of the Cornell physical laboratory, also used a set of Koenig resonators for their experiments on vowels.[146] Similarly, one finds resonators in both the physical and psychological collections at Harvard. Even in relatively small institutions, like Queen's University in Kingston, Ontario, one finds surviving Koenig resonators.[147] In Europe, resonators appear in almost every collection of historic scientific instruments from Co-

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[143] Thomas H. Core, "Modern Discoveries in Sound," in *Science Lectures for the People, Science Lectures Delivered in Manchester, 1877-78-79* (London & Manchester: 1877), 88.

[144] Loudon and McLennan, *A Laboratory Course* 115.

[145] E.B. Titchener, "The Equipment of a Psychological Laboratory," *American Journal of Psychology* 11 (1899).

[146] Ernest Merritt, "On a Method of Photographing the Manometric Flame with Applications to the Study of Vowel A.," *Physical Review* 1 (1894). Edward L. Nichols and Ernest Merritt, "The Photography of Manometric Flames," *Physical Review* 7 (1898). The Smithsonian Institution, National Museum of American History cat no. 314, 957, Case Western Reserve University in Cleveland, St. Mary's College (See Tom Greenslade's list) and Harvard have well-preserved sets of resonators.

[147] In Canada, one can also find a well-preserved set of universal resonators at McGill University.

Coimbra, Portugal to Moscow.[148] There were few acoustical instruments of the nineteenth century as ubiquitous as the resonator.[149]

The transmission of cylindrical resonators, those used for precision sound *production*, was also an integral part of bringing "simple tones" into the hands of students and researchers. The grand Helmholtz synthesiser, for example, used cylindrical brass resonators of different sizes in order to amplify the simple tones (tuning forks) meant to imitate a vowel sound. Koenig made quite large cylindrical resonators, four-feet in length, to be placed in front of his lowest frequency forks to amplify pure tones that were often not detectable without a resonator. He used large cylindrical resonators with adjustable openings (for pitch adjustment) to amplify tuning forks for his experiments with beats (§4.3). In addition, he sold the cylindrical resonators used to reinforce the standard tuning fork. These brass tubes comprised a massive family of precision sound production instruments based on Helmholtz's theory of aerial vibrations.[150]

The resonators were much like other analytic instruments of the time, spreading similar analytic notions in optics and chemistry. For example, we can compare the developments in this story to the spread of the precision balance in the wake of Lavoisier's reforms of chemistry and the refinement of the notion of chemical element.[151] One may also examine the rapid spread of the spectroscope (invented in 1859 by Gustave Kirchoff) as a counterpart to the resonator in op-

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[148] The University of Rome has twenty-three resonators in one series made by Koenig. As mentioned earlier, the Clarendon Laboratory at Oxford has an early set of Koenig resonators. For other sets, see Bartsch, *Katalogue. Johannes-Müller-Institute* 50. Giatti and Miniati, eds., *Acoustics and Its Instruments* 92. Turner, *The Practice of Science* 114-15.

[149] After Koenig died in 1901, E. Zimmermann in Berlin offered a more refined version of the universal resonator developed by Schaefer, called the "continuous resonator," for psychological laboratories. E. Zimmermann, *Psychologische, physiologische Apparate* (Liepzig; Berlin: 1928) 146-47. After 1901, Max Kohl made an identical series of resonators for psychological and physical laboratories in Europe and North America. Kohl, *Catalogue of Physical Apparatus* 449-50. An unknown instrument maker later in the nineteenth century made adjustable resonators based on the size of the opening. Instead of changing the volume, he extended the range of the resonators by offering a series of different sized openings that could be inserted into a larger opening of the spherical resonator. The University of Rome has a complete series of these resonators, consisting of a set of five spherical resonators with forty-eight different sized openings.

[150] Helmholtz, *Sensations* 377-279.

[151] Trevor Levere, "Balance and Gasometer in Lavoisier's Chemical Revolution," in *Chemists and Chemistry in Nature and Society, 1770-1878*, ed. Trevor Levere (Aldershot: Variorum, 1994).

tics.[152] Related to the spectroscope, there was also the spread of the diffraction grating earlier in the century, and before that, the prism of Newton. Comparisons between acoustics, optics and chemistry were quite common in the nineteenth century. Helmholtz himself made the comparison between his resonators and optical instruments.

> Hence every individual partial tone exists in the compound musical tone produced by a single musical instrument, just as truly, and in the same sense, as the different colours of the rainbow exist in the white light proceeding from the sun or any other luminous body. Light is only a vibrational motion of a peculiar elastic medium, the luminous ether, just as sound is a vibrational motion of the air....But the undulatory motion of light can also be analysed into the waves corresponding to the separate colours, by mechanical means, such as refraction in a prism, or by transmission through fine gratings, and each individual simple wave of light corresponding to a simple colour, exists mechanically by itself, *independently of any other colour.*[153]

In a series of lectures at the Catholic University in Washington D.C. in 1891, August Zahm spoke of the resonators in chemical terms:

> Such a series of resonant spheres or cylinders has been well likened to a set of chemical reagents. As such reagents enable the chemist to prove the presence of various elements and compounds, so do resonators afford the acoustician the means of analysing any compound note into its constituent partials.[154]

Not long after Helmholtz's death, the Scottish physiologist, John McKendrick, who had done important work in early phonetics and who claimed to have had the pleasure of once seeing Helmholtz's original resonators at his laboratory in Heidelberg, wrote that "this invention was of the greatest importance in practical acoustics, as it enabled the observer to sift a mass of sound, and it did for the ear what the prism of Newton did for the eye."[155]

2.18 RESONATORS USED IN OTHER APPARATUS

In his letter to Helmholtz in December 1859, while waiting to find a better glassblower and doing his own experiments, Koenig suggested that "it would certainly be desirable for several investiga-

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[152] Frank A.J.L. James, "Spectroscope," in *Instruments of Science: An Historical Encyclopedia*, ed. Robert Bud and Deborah Jean Warner (London; Washington D.C.: The Science Museum, London and the National Museum of American History in association with Garland Publishing, Inc., 1998).

[153] Helmholtz, *Sensations* 48.

[154] Zahm, *Sound and Music* 355.

[155] John Gray McKendrick, *Hermann Ludwig Ferdinand von Helmholtz* (London: T. Fisher Unwin, 1899) 146.

tions, to allow the resonators to go through more tones, through all the increments of tone."[156] These trials led to a wider range of resonators put on the market by 1865. In that catalogue, we find Koenig selling nineteen resonators as opposed to the original fourteen he had provided Helmholtz. His resonators were based on the harmonics of ut1 (64 Hz), even though ut1 itself could not be produced, it would have required too large a vessel. They started at ut2 (128 Hz) and went to mi5 (1280 Hz). In the late 1860s Koenig also conceived of a resonator that could be conveniently tuned to four or five simple tones. He did this by making two brass cylinders slide into each other to adjust the volume. A set of ten resonators, therefore, went from Sol1 to Ut6, covering over 65 notes.[157] Helmholtz first introduced Koenig's "universal resonator" in 1870, referring his readers to his appendix on the theory of aerial tubes for instructions of how to build them.[158]

Koenig also made a special set of resonators for vowel studies. By 1865 he had put on the market an apparatus to replicate, test and demonstrate Helmholtz's experiments on vowel sounds. It consisted of "five tuning forks with resonators tuned for the respective masses of air contained in the mouth cavity during the pronunciation of the vowels a, e, i, o, and ou." A student or researcher could listen for the characteristic tone in the vowel with the resonator and also verify its result with the tuning fork. "If a vowel is pronounced in a low voice, in holding the tuning fork before the mouth, one hears the mass of air strongly resonate."[159] These vowel resonators, along with the numerous other resonators mentioned in the above section formed the core of the new instruments for detection of simple tones.

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[156] Hörz, ed., *Brückenschlag zwischen zwei Kulturen* 359.
[157] Koenig, *Catalogue (1873)* 5.
[158] Helmholtz, *Sensations* 373.
[159] The University of Toronto and Harvard have good examples of this apparatus. Koenig, *Catalogue (1865)* 13. For more on the use of this apparatus, see Turner, *The Practice of Science* 115.

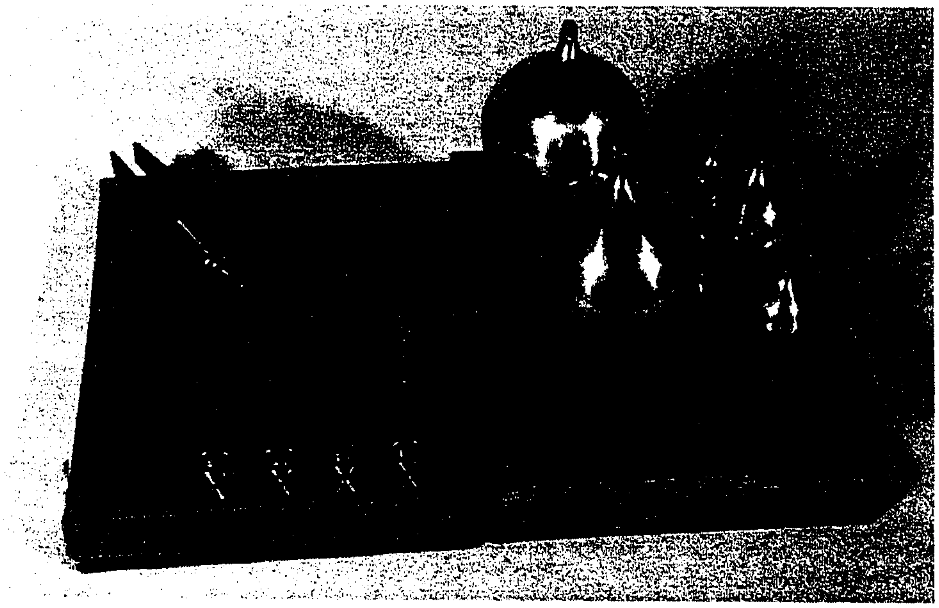

Figure 2.7 Tuning forks and resonators for studying vowels, circa 1876. UTMuSI.

The most popular elaboration of the resonator was the Koenig sound analyser. It was a combination of the resonators and his visual flame technique. If the synthesiser was a model of the voice in brass, steel and wood, the analyser was a model of the ear. This instrument first appeared in his 1865 catalogue. It dated from the period 1862 to 1865, and followed the invention of the manometric capsule. It had eight resonators marked with the French notes and starting with the fundamental tone, Ut2 (256 v.s. or 128 Hz) followed by the seven upper partials of that note, Ut3 (512 v.s.) or approximately middle c on the piano, Sol3 (768 v.s.), Ut4 (1024 v.s.), Mi4 (1280 v.s.), Sol4 (1536 v.s.), Si4 (1792 v.s.) and Ut5 (2048 v.s.).[160]

The analyser took musical sounds directly from the air, broke them down into their constituents and transformed these simple vibrations into a flame signal. A researcher sang or produced a musical note in front of the panel of resonators. These resonators picked up and reinforced specific frequencies within the complex notes, and the reinforced sound waves travelled through the back of the resonator and down the rubber tube into the manometric capsule. The membrane within the capsule vibrated in unison with the sound and communicated this vibration to a stream of gas entering from a tiny input. The gas would be lit at the end of this small jet tube and the resultant flame flickered undetectably to the naked eye. The reflection of the flickering flame would be spread out by the rotating mirror in a kind of strobe effect into a saw-toothed band of flame.

The analyser was a remarkable extension of Helmholtz's resonators. Most importantly, it made analysis visual and allowed for the *simultaneous* display of the strongest partials. Helmholtz praised it by saying it was now "possible to allow a large number of persons at once to determine whether or not a given tone is reinforced by the resonator."[161] Koenig's invention transformed analysis from being a cumbersome, potentially subjective experience to a demonstration shared by a number of witnesses. One could therefore "see" and compare the number, kind and relative strength of the harmonics during one act of observation, making the process more efficient and conducive to the increasingly social realm of research and teaching.

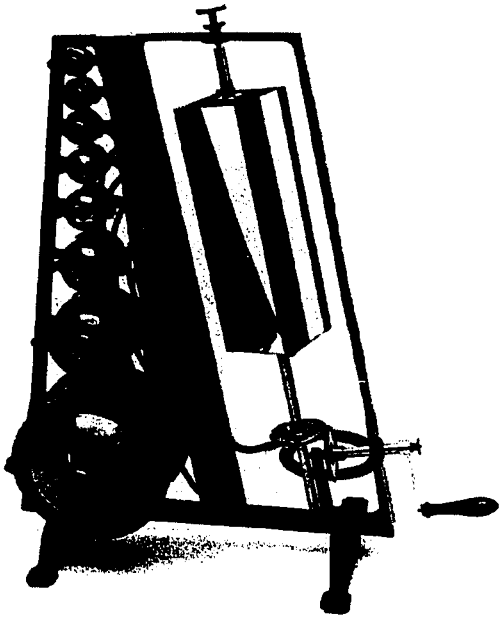

Figure 2.8 Koenig analyser with eight resonators based on the fundamental tone Ut2 (128 Hz), circa 1875. Smithsonian Institution, National Museum of American History, (cat. no. 314,583).

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[160] Rudolph Koenig, *Catalogue des Appareils d'Acoustique* (Paris: 1865) 6.
[161] Helmholtz, *Sensations* 374.

The first model, pictured in the 1865 catalogue, does not appear to have survived in any collection of historic instruments. Perhaps none, or only a few were made. It had a wooden frame and differed significantly from the later models. A second model, with a cast iron frame, distinct capsules and a reservoir for gas regulation appeared in several physical cabinets throughout Europe and North America in the 1870s. It is not known exactly when Koenig started making this model. Joseph Henry of the Smithsonian, for example, purchased his analyser in the early 1870s.[162]

The early models (with only eight spherical resonators) had certain limitations. "As this apparatus does not permit us to choose the fundamental tone of the vowel or any other sound which is to be analysed, it is adapted rather to demonstration than to further investigation," Koenig wrote.[163] A third model appeared in the catalogue of 1873[164] shortly after Koenig had returned from Germany where he had taken refuge during the Franco-Prussian War of 1870. This model, almost double in price, had fourteen resonators that could be adjusted to cover five octaves on the piano, with sixty-five notes marked, from approximately 40 Hz to 1300 Hz. In order to cover such a large range, Koenig invented an adjustable resonator (mentioned above), the "universal resonator," which he made from two brass cylinders that slid into each other. These tubes could be tuned and had two openings for insertion in the ear or to connect with the manometric flame. Markings on the cylinders showed the corresponding tone to be reinforced. The next two catalogues included the universal analyser as well as the second model.[165]

The third model was intended for research into a whole range of sounds and their elements, "particularly," he wrote, "those of the human voice." Unfortunately, he could not perform these experiments himself. By 1873 he had severely damaged his voice by performing too many vowel tests. He therefore did not publish any findings with his analyser, nor, it appears, did anyone else.

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[162] National Museum of American History, cat. no. 314,583

[163] Rudolph Koenig, "On Manometric Flames," *Philosophical Magazine* 45, no. 297 (1873c): 107.

[164] Koenig, *Catalogue (1873)* 12.

[165] Rudolph Koenig, *Catalogue des Appareils d'Acoustique* (Paris: 1882a) 29.

In fact, in the late 1860s and early 1870s, he performed his famous vowel researches with a single manometric capsule, speaking funnel and rotating mirror (§4.2).

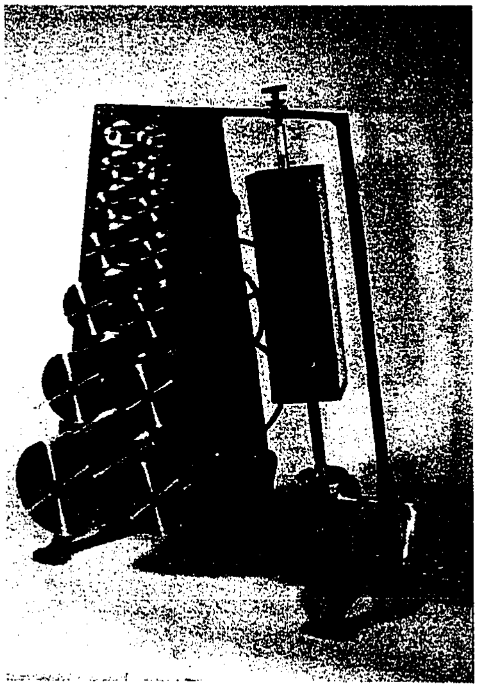

Figure 2.9 Koenig analyser with fourteen universal resonators, c. 1876. UTMuSI.

D.C. Miller of Case University used the universal analyser in his laboratory course as a means for demonstrating the analysis of sound. The analyser, he explained to his students, worked to "determine the number and relative intensities of the overtones present in the sound of an open and closed organ pipe."[166] He asked the students to blow a pipe in front of the resonators and note that "careful observation of the series of flames will determine what partial tones are present and what are their relative intensities." Demonstrators at Toronto, W.J. Loudon (nephew of James Loudon) and J.C. McLennan, described how students calculated the harmonics beforehand, adjusted the resonators accordingly, and then recorded the response of certain flames. "The instrument furnishes a useful means of observing overtones from any source of sound; but it must

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Rudolph Koenig, *Catalogue des Appareils d'Acoustique* (Paris: 1889) 86-87.

[166] Dayton Clarence Miller, *Laboratory Physics: A Student's Manual for College and Scientific Schools* (Boston: Ginn & Company, 1903) 152.

be adjusted with considerable care in order to perform its work with accuracy," they wrote.[167] August Zahm, claimed that the analyser could be used to demonstrate and investigate the "nature and composition of vowel-sounds." He provided a few examples, such as the *o* of "no" sung before the resonators to give "strong third and fourth partials, while the octave is weaker than in *u* ... No more beautiful nor convincing proofs could be desired than those furnished by carefully tuned resonators and manometric flames, that the different vowels, like all musical sounds of different quality, are the result, not of any peculiar action of the vocal cords, but depend solely on the varying admixture of certain partials, of varying intensities, with the fundamental."[168]

Above all, the analyser, like the resonators, served as an effective and dramatic introduction to the theories of Helmholtz. Thomas Core, a popular science lecturer in England, provided the clearest example of this role for Koenig's instrument. In the following quote from his public lecture of 1877 we find him using the analyser before he even described the theories of Helmholtz.

> But here is a curious point. I find that when a note is emitted more than one resonator will respond - sometimes, two, three or four. Now what does this show us? Since each resonator will only respond to a note of its precise pitch, neither more nor less - since three or four resonators respond simultaneously - it follows that the note emitted must contain all those notes. In other words, the note that I fancied was a simple one turns out to be a compound one, and this instrument has analysed it into three of four composite notes. [169]

The transparent nature of the instrument served an important function in the classroom and may explain some its wide-spread appeal. Even after the introduction at the turn of the century of more sophisticated techniques for analysing sound, people still used the analyser,[170] perhaps because the instrument itself seemed to serve as a source of information on the working of sound. The frame of the analyser resembled Helmholtz's diagrams of the tapering basilar membrane, and the resonators revealed to all the mechanical workings of sound analysis.

The analyser was, without a doubt, one of Koenig's more popular instruments. In 1865 it cost 250 francs, which was not overly expensive. A set of ten resonators, for example cost 100 francs.

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[167] Loudon and McLennan, *A Laboratory Course in Experimental Physics* 124.

[168] John Augustine Zahm, *Sound and Music* (Chicago: A.C. McClurg & Co., 1900) 356-357.

[169] Thomas H. Core, "Modern Discoveries in Sound," in *Science Lectures for the People, Science Lectures Delivered in Manchester, 1877-78-79* (London & Manchester: 1877) 84.

By 1873 the model with eight resonators had gone up to 300 francs, and to 325 francs by 1882. The model with fourteen resonators cost 600 francs in 1873 and 650 francs in 1882. The number of schools and museums that still possess a Koenig analyser is astounding. Western, McGill, and the University of Toronto own analysers. In the United States they are found in such large institutions as the Smithsonian and Harvard, and also in smaller colleges such as Dartmouth. They appear in the major museum collections of Europe – at Florence, Rome, Haarlem, Moscow, Paris, Madrid and London. Even such a small institution such as the Laboratoire d'Acoustique in Paris has a Koenig analyser resting in their reference library.[171]

2.19 TUNING-FORK TONOMETER

The preceding sections described the establishment of a whole array of precision instruments for *detecting* simple tones. An equally major part of the reform of acoustics, however, was the construction and proliferation of simple-tone *producers*. The tuning fork, which had been a relatively primitive instrument before Helmholtz's studies, became in the wake of *Sensations*, the central means of producing simple tones in the laboratory, and what was just as important, for instilling and spreading the analytic conception of sound into classrooms. Koenig was the premier maker of tuning forks; literally thousands of his forks spread to laboratories throughout the world. The history of the tuning fork involved many currents of theory and practice that came together in his work. In the early phase of these developments, his unique contributions came from a mixture of the Parisian context of his work (the experimental traditions and the precision instrument industry), and from the research of Helmholtz that put new demands of precision on simple-tone producers. The later phases of the development of the tuning fork derived from Koenig's controversial research into combination tones (§4.3). It was through the tuning fork that Koenig would have his greatest impact on the reform of the new acoustics.

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[170] At the University of Toronto, demonstrators used the analyser up to the 1970s.

[171] For more on the operation of the analyser, see David Pantalony, "Analyzing Sound in the Nineteenth Century: The Koenig Sound Analyzer," *Bulletin of the Scientific Instrument Society*, no. 68 (2001).

Koenig's masterpiece apparatus, one that he would work on and improve throughout his career, the tuning fork tonometer, first appeared in 1862. This was a series of precision tuning forks used for tuning and pitch measurements. Until his invention of the clockfork in 1882 (§4.6), the tonometer was the central means for making, tuning and calibrating all simple-tone producers. At 2000 francs the tonometer was by far the most expensive instrument in Koenig's catalogue of 1865.[172] By 1882 the price had risen to 3000 francs. By 1894, upon the completion of his last great tonometer the price had reached an astonishing 50,000 francs.

Helmholtz, as has been shown throughout this chapter, put great emphasis on the need for pure, precise, simple-tone producers for his experiments. When he began his studies, however, there was only one sure method, not really known or used by physicists, for precision tuning. In his studies of beats, combination tones and precision tuning, Helmholtz came to rely on the unique methods of Johann Heinrich Scheibler (1777-1837), a silk manufacturer from Crefeld in Rhenish Prussia with no scientific background but with a great love of music. In 1834 Scheibler had developed what he called the tuning fork tonometer as a more reliable means for tuning and setting a standard for pitch. He was frustrated, for example, that there were no dependable methods for determining pitch and he therefore set out to develop his own method.[173] Different pitch standards were being used in different locations, with varying emphasis on the quality and dependability of those standards. A concert "a" for example was sometimes below 400 Hz and at other times (or places) above 500 Hz. Today it is 440 Hz.

Furthermore, in the 1830s there was no magical black-box device, such as we have today, that could simply reveal the frequency of an instrument or tuning fork. All of the available methods ultimately depended on the judgement of the ear. Scheibler wanted to get rid of this source of error. His method relied on the comparison of sound sources by a method of counting beats, or the number of vibrations by which two sources differed. For his initial trials Scheibler used a fork

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[172] Koenig, *Catalogue, (1865)* 8. This would have been approximately one tenth the cost of outfitting a new teaching laboratory for that time.

for concert “a” of Vienna. He tuned a second fork to be one octave lower than this concert “a” fork. He ensured that the second fork was a true octave by using the beats of a known combination tone.[174] He then took a series of fifty-four tuning forks, the first one being four vibrations (or beats) sharper than the low "a" and the last one being approximately four vibrations (beats) flatter than the higher “a.”[175] The sum of the fifty-five sets of beats was the difference between the lowest and highest forks. Because lower “a” multiplied by two is the higher “a” or next octave, the sum of beats or difference was the actual frequency of the lower “a.” Similar experiments could be done with any other known ratio of the musical scale and, in fact, Scheibler developed quite sophisticated schemes for tuning instruments using beats and combination tones. As a result of his studies, Scheibler found the Vienna “a” standard to be 440 Hz. He presented these findings to the congress of physicists in 1834 at Stuttgart, and “a-440” came to be known as the “Stuttgart pitch.”

Considering the other methods of the time and their difficulties, Scheibler’s method represented one of the surest ways to produce a reliable, known standard of pitch; it would also create a new foundation for quantitative investigations of sound. Helmholtz, as we saw above, was the first to realise the value of these precision methods. He relied on Scheibler’s method of beats for several of his investigations into the previously uncharted territory of combination tones and upper-partial tones.

Scheibler’s ideas had been known before Helmholtz, but only to a handful of musical instrument makers. In Germany Zamminer had described the value of his method in his treatises. In Paris, where Scheibler visited in 1836, his ideas had been promoted by members of the Institute, but had not taken hold. Also in Paris, the organ builder, Cavaillé-Coll and the instrument maker

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[173] Heinrich Scheibler, *Physikalische und musikalische Tonmesser* (Essen: Bädeker, 1834).

[174] For example, if one were to match a fork of 100 Hz with one of 201 Hz, the difference tone (combination tone) of 101 would "beat" with the fundamental tone of 100 resulting in one beat per second. A perfect octave would produce no beats. According to Helmholtz, "There is no difficulty in hearing these beats, and hence it is possible to distinguish imperfect octaves from perfect ones." Helmholtz, *Sensations* 199.

Woelfel[176] had met Scheibler and "for quite some time had introduced his method into the workshops."[177] Woelfel appeared to be the first person to make a tuning fork tonometer in Paris using Scheibler's instructions.[178]

Until Helmholtz created a context to appreciate the scientific value of Scheibler's method, there was no interest among scientists for a tonometer. In addition, although Scheibler's method offered a remarkable means for determining a pitch number, the actual quality of the forks was still substandard. In Helmholtz's first experiments with combination tones, for example, we saw that forks were not necessarily dependable for producing pure single tones. He was forced to combine them with cylindrical resonators to purify the pitch.

The difference came with the new precision tuning methods of Lissajous developed in Paris in the late 1850's. Scheibler had provided a good way to determine the quantity of vibrations, and Lissajous provided a complementary means for refining the tuning methods. The combination of Scheibler's quantitative method, with Lissajous's visual method, made it possible by 1860 to make a truly dependable precision tuning fork. Koenig, who was exposed to both the German world of Helmholtz and Scheibler and the Parisian precision instrument scene of Lissajous, quickly saw the potential of combining these techniques to build a precision tonometer for the new acoustics. After a few years of arduous labour (tuning forks were the most demanding instruments to construct), he had built a tonometer by 1862.

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[175] According to Alexander Ellis, Scheibler used a metronome "corrected daily by an astronomical clock" to determine, as precisely as possible, the number of beats that separated each fork. Ibid., 445.

[176] Unfortunately, no other details are available about Woelfel.

[177] Rodolphe Radau, "Acoustique," *Cosmos: Revue Encyclopédique Hebdomadaire des Progrès des Sciences et de leurs Applications aux Arts et a l'Industrie* 21 (1862b): 109-12.

[178] Ellis has a slightly different version of this story than Radau: "Wölfel, - mentioned by Cavaillé-Coll as having constructed a tuning-fork tonomter on the model of Scheibler's without any other assistance but Scheibler's pamphlet, and quite as accurate as Scheibler's. It took him two years to construct." Ellis, "On the History of Musical Pitch" 34.

Figure 2.10 Twelve forks and resonator boxes from Koenig's sixty-five-fork tonometer, circa 1876. UT-MuSI.

Koenig displayed his first tonometer at the London International Exposition in 1862. It consisted of sixty-five precision tuning forks, comprising one octave, separated from each other by only four complete vibrations, and each mounted on a beautifully finished pine resonator box. Using his tonometer, he made three forks corresponding to the accepted scales of France, Germany and England. The standard tonometer that he advertised and sold was based on Ut3, or 256 Hz. The jury who had awarded Koenig a "médaille unique" commented: "By aid of this instrument, and a *practised* ear, very delicate gradations of pitch may be obtained."[179] They also held out the hope that "an authoritative establishment of international uniformity would confer an inestimable public advantage." Shortly following the exhibition, Rudolphe Radau, a Königsberger physicist living in Paris, introduced Koenig's tonometer to readers of the weekly scientific journal, *Cosmos,* claiming that his instrument would now make it possible to popularise Scheibler's invaluable method of tuning. Radau described how difficult it had been to produce a tonometer,

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[179] "Philosophical Instruments and Processes Depending on Their Use," in *International Exhibition 1862, Reports by Jurors* (London: William Clowes and Sons, 1862), 33.

and how Koenig had used the "resources of modern science" such as "the optical procedure of Lissajous" to finally make this quest a reality.[180]

Almost all of the tuning forks that Koenig made and spread throughout the world owed their precision to the tonometer. Physical and psychological laboratories of the nineteenth century carried his precision forks for graphical research, optical demonstrations, vowel tests, psychophysical threshold observations, timing experiments, beats and combination tone experiments, comparator studies, and the establishment of standard musical pitch. Being quite expensive, the tonometer itself was rarer than all of the above forks. It is difficult to assess how many universities and institutions bought his tonometer. Each series of forks were often broken up, and one finds forks from tonometers scattered throughout collections. The University of Toronto and the Smithsonian have 65 fork tonometers with finely finished wooden resonator boxes.[181] The tonometer, even if not present in university collections, also became an important part of the lore of physics laboratories of the time, showing how well it expressed the demands of the new acoustics. The tonometer embodied, more than any other instrument, the emphasis on pure simple tones. It was called Koenig's "crowning achievement," his "masterpiece apparatus," and a "fitting monument to its maker."[182] August Zahm wrote of Koenig's final grand tonometer (§1.3) that "nothing better could be desired, and certainly nothing more complete has ever been carried into execution."[183]

2.20 HELMHOLTZ'S IMPACT OUTSIDE THE SCIENTIFIC COMMUNITY

Although this thesis centres on the development of the science of sound, it is important to address briefly the relationship between music and science during this period. A difficult question pro-

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[180] Radau, "Acoustique 1862b," 112.

[181] Toronto has a complete 65-fork tonometer. The National Museum of American History has one with approximately 35 forks, cat. no. 315, 725.01-.45. The University of Rome has a complete 65-fork tonometer with smaller forks and no resonator boxes. It cost 1500 francs after 1882, half the price of 3000 francs for the complete set with resonator boxes. See Rudolph Koenig, *Catalogue des Appareils d'Acoustique* (Paris: 1882a) 6.

[182] For descriptions by Koenig's peers see C.L. Barnes, *Lessons in Elementary Practical Physics* (London: MacMillan and Co., Limited, 1898) 51. James Loudon, "Rudolph Koenig," in *Loudon Papers* (University of Toronto Archives: 1901). Loudon and McLennan, *A Laboratory Course* 96. Miller, *Anecdotal History* 89.

[183] Zahm, *Sound and Music* 75.

posed by the historians Erwin and Elfrieda Hiebert asks how we can "connect Helmholtz's contributions to the study of acoustics with the world of music?"[184] Whereas we were able to follow the reforms of Helmholtz into the laboratory, and even how problems in music fuelled lines of inquiry in the new acoustics, it is much more difficult to determine how these reforms made their way into the world of music. The Hieberts write of an immediate response to *Sensations* in the music journals after 1863 in which it was generally agreed that Helmholtz's work on the physiology of sound was novel and significant, but there were divergent opinions on how relevant it was for music. One critic, Moritz Hauptmann, dismissed it as not significant for the art of music.[185] On the other hand, there is evidence that Helmholtz's analytic conception of sound, in particular his theory of overtones influenced some key composers. One Czech composer Leo Janácek based his theory of chord connections on Helmholtz.[186]

In the world of musical instrument making there is evidence that Helmholtz had an influence on the development of the piano. The Hieberts conclude, for instance, "the effect of Helmholtz's studies on acoustics rippled through the piano workshops of Western Europe as well as America."[187] Helmholtz collaborated directly with Theodore Steinway, the great piano maker, providing some scientific guidelines for improving the harmonic structure of piano strings. Steinway, in turn, provided pianos for Helmholtz's experiments.[188] He also provided much new information on the striking and placement of the hammer and the science behind the structure of the string.[189] The Hieberts believe that some of these changes were reflected in the changes to the piano itself during the second half of the nineteenth century.

Some of these claims may be overemphasizing Helmholtz's influence on music, and the Hieberts admit that more work has to be done to fill in this history. D.W. Fostle has argued, to

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[184] Hiebert and Hiebert, "Musical Thought and Practice," 301.
[185] Ibid., 300.
[186] Ibid., 303-05.
[187] Ibid., 305.
[188] Ibid., 306-07.

take another side, that Steinway's art of piano making "was so far in advance of theory that even the most erudite scientific investigators could tell Theodore only a little about what he had done and nothing about what he might do."[190] Fostle claims that the hundreds of inventions and thousands of experiments carried out by the ambitious Theodore were not guided by the new science of acoustics at all. His connection to Helmholtz, and the use of his name for advertisements, was only intended to add prestige to their product in an age when science was starting to hold great currency with the general public. "In fact," Fostle concludes, "both William and Theodore [Steinway] seemed largely indifferent to, if not disinterested in, the developing science of acoustics. When acoustician Rudolph Koenig displayed his acoustical machinery at the Philadelphia Exposition [1876], it was considered by many to be the most impressive exhibit at the centennial. Nowhere does William record that either he or Theodore saw Koenig's machines."[191] On the other hand, Fostle does note that Theodore had used the Helmholtz resonators to listen for specific harmonics in his piano strings.[192] The latter point reveals that the influence of Helmholtz cannot be so easily dismissed, and may have come in the form of instruments.

Although it is hard to prove the influence of the new Helmholtzian concepts on the development of music, it may be easier, as with the above example of the resonators, to determine how the scientific instruments of the new acoustics changed musical practice. In this area it appears that the tuning fork led the way to major developments. The tonometer and clockfork were both used to standardise pitch in the second half of the nineteenth century. Koenig's clockfork standardised pitch in Russia, Austria, France and Italy. At Case University in Cleveland, D.C. Miller calibrated tuning forks for institutions and companies around the United States, among them Steinway & Sons and the Gaertner scientific instrument company (§4.6). In a sense the "tuning"

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[189] Ibid., 307. Another brief account of Helmholtz's contribution to the piano can be found in Richard K. Lieberman, *Steinway & Sons* (New Haven & London: Yale University Press, 1995).
[190] D.W. Fostle, *The Steinway Saga: An American Dynasty* (New York: Scribner, 1995) 289.
[191] Ibid.
[192] Ibid., 540.

of America took place using an instrument that had derived from the new *instruments* developed by Helmholtz and Koenig.

If there was one thing that was absorbed by both scientists and musicians in the wake of the new acoustics, it was the analytic conception of sound. Both Helmholtz's theories and Koenig's instruments reinforced the notion that the soundscape was constructed from building blocks or elements called simple tones. One musician lecturing to the Musical Association of London concluded that just as a "chemist would not hope to successfully evolve new combinations and results without an analytical knowledge of the derivations and affinities of the substances...a composer, like the chemist, must evolve new forms and new combinations possessing logical connection and affinities."[193] Even if it is difficult to assess Helmholtz's and Koenig's influence on the practice of music, it is not hard to see that their efforts changed the way musicians thought about sound. The copy of *Sensations* used for researching this chapter was bought in 1997 at the small bookshop of the Royal Conservatory of Music in Toronto.

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[193] Turpin, "Some Practical Bearings" 72.

CHAPTER THREE – THE MAKING OF A CRITIC, 1851-1866

> With Helmholtz, as is well known, Koenig had an endless dispute over the questions of the sounds of beats and of timbre. It may not be known, however, that Koenig began his researches in these questions with the object of supporting Helmholtz's theories, with the result, however, that he was led eventually to oppose them.[1]
>
> James Loudon.

3.1 INTRODUCTION

Rudolph Koenig played a crucial role in promoting and spreading the reforms of Hermann von Helmholtz, but he also became Helmholtz's main critic. The roots of his critical stance derived from his context in Paris. As a violinmaker he acquired an intimate knowledge of sounds and materials, which provided a foundation for his scepticism about Helmholtz's idealised view of sound. As a researcher, he placed great emphasis on visual techniques and instruments as a means for discovering new facts about sound. He was a pioneer in using graphical and optical methods for the study of sound and his use of visual techniques shaped his understanding of sound in ways that would eventually lead him to challenge Helmholtz. Above all, he was strongly influenced by the positivistic movement in Parisian scientific circles in the second half of the nineteenth century. He firmly believed that good experiments and observation were far more valuable than explanations based on hypothetical entities or abstract arguments. This attitude was best expressed by his devotion to honing his methods and instruments. In his early career we see Koenig developing his unique approach to acoustics through his exposure to these influences. In Chapter Four, I shall describe how these influences contributed to his disputes with Helmholtz.

3.2 CRAFTSMAN OF SOUND

> It was here [Vuillaume's workshop] that he [Koenig] first manifested an interest in acoustical problems, an interest so keen that, on Vuillaume's advice, he abandoned violin-making, at which he had become an expert, for the work of an acoustician. Koenig, however, never lost interest in the violin. His recollections of the great violin-maker

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[1] James Loudon, "Rudolph Koenig," in *University of Toronto Archives, Loudon Papers, B72 0031/016/05* (1901).

> [Vuillaume], who subsequently became a millionaire, were so interesting and entertaining that I more than once urged him to write a memoir.[2]

Not only did Jean-Baptiste Vuillaume make a lasting impression on the young Rudolph Koenig, but a glimpse at Vuillaume's workshop reveals a bustling place of diverse activities – precision woodworking, experimenting, innovating, and business – that became a model for Koenig's own career. The violin, in fact, was one of the instruments that Koenig came to know intimately and his counsel as an expert on violins continued to be sought long after his apprenticeship with J.B. Vuillaume.[3]

Jean Baptiste Vuillaume (1798-1875) has been called the most influential violinmaker of the nineteenth century.[4] He descended from a violin making family of Mirecourt, a small town in Vosges, which had been a flourishing centre of French violin making. During his early career in Paris he made his mark through imitation, being the first to successfully copy the old Cremonese masters with respect to tone quality and appearance. He made and repaired violins for the Italian,

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[2] Ibid.

[3] James Loudon recalled that later in Koenig's career a collector came to him to identify a violin and was surprised when he responded, "I made it myself!" The unique tailpiece, the signature of every violinmaker, had given it away, (Ibid). No known Koenig violins survive today. The one violin that has a direct connection to him, however, happens to be the most famous violin by Stradivari, "le Messie" (1716). This was reputed to be Stradivari's favourite violin and an example of his late style and perfected design. In 1827 it fell into the hands of the eccentric Italian violin collector, Luigi Tarisio, who guarded his prize in his apartment in Milan and often boasted of his possession on his selling trips to Paris. Upon the death of Tarisio in the spring of 1855, Vuillaume went to Milan and purchased the instrument from the unsuspecting relatives of the reclusive collector. He returned to his workshop in triumph to show his great prize to his workers where it was supposedly played for the first time. It was one of Koenig's favourite stories from his time in Vuillaume's shop (Ibid). Today "le Messie" rests in the Hill Collection of Musical Instruments at the Ashmolean Museum, Oxford. See Roger Millant, *J. B. Vuillaume: His Life and Work*, trans. Andrew Hill (London: W.E. Hill & Sons, 1972). William Alexander Silverman, *The Violin Hunter: The Life Story of Luigi Tarisio the Great Collector of Violins* (London: William Reeves, 1957).

[4] There was a recent exhibition of Vuillaume's life and work at the Cité de la Musique in Paris. Rémy Campos, ed., *Violins, Vuillaume (1785-1875): A Great French Violin Maker of the 19th Century* (Paris: Cité de la Musique, 1998). Also see, Charles Beare, "Vuillaume, Jean-Baptiste," in *The New Groves Dictionary of Music and Musicians*, ed. Stanley Sadie (London; Washington D.C.: MacMillan Publishers; New Grove's Dictionaries of Music, 1980). The Belgian composer, François-Joseph Fétis, wrote a book on the history and theory of Cremonese violins in collaboration with Vuillaume; it can therefore be viewed as a very close source for Vuillaume's views on science and violinmaking, see François-Joseph Fétis, *Anthony Stradivari, the Celebrated Violin-Maker, Known by the Name of Stradivarius*, trans. John Bishop (London: William Reeves, 1864).

Paganini, the Norwegian, Ole Bull, and the local French talent, Delphine Alard.[5] Outside of this involvement in the Parisian music scene, Vuillaume had an active interest in acoustics and earlier in his career (1830s) had collaborated with the French physicist Félix Savart (see below). He was also credited with many innovations, such as new instruments and bows, and was well known for his expertise concerning woods and varnish. He was an extremely successful businessman and by 1850 was conducting business in almost every country in Europe. In 1851, when Koenig joined his shop as a nineteen-year-old apprentice, Vuillaume had just won a gold medal at the London international exhibition. During this period, Vuillaume's workshop was a meeting place for many performers, dealers, clients, scientists and aspiring violinmakers.

Under Vuillaume's guidance, Koenig learned to master and control the relations between materials and sound phenomena. Later in his career, in fact, people would attribute Koenig's success to the fact that under Vuillaume he had been given a "solid instruction"[6] as a craftsman and had "acquired the skill of being able to perfectly finish wood that is so necessary in the construction of acoustical instruments"[7] Vuillaume was said to train his workers to a very high level and once they left his workshop he expected them to maintain the same high standards. His workers used precision tools and were taught that even the smallest change in thickness or size of material had a significant impact on sound quality. One of Vuillaume's former pupils, Delanoy, recalled his master's strict supervision:

> As far as his art was concerned he had an eagle's eye. Quite often as he was watching a workman's almost completed task, he would grab the instrument from his hand, and seizing a file, a rasp or a pocket knife, would start filing here and there to the great disgust of the workman who did not dare say anything, and when he was satisfied he would say to the man: "Fix those rough edges and polish." When this was finished the workman had to recognize that his work looked better and had more chic. Vuillaume would laugh and leave, pleased with himself.[8]

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[5] Alard, who became a son-in-law of Vuillaume, was a teacher at the Paris Conservatoire and one of the first musicians to introduce Parisian society to chamber music in the 1840s.

[6] François Napoléon Marie Moigno, "Hommage rendu au mérite," *Les Mondes, Revue Hebdomadaire des Sciences* 17 (1868).

[7] François Napoléon Marie Moigno, "Médailles décernées par la société d'encouragement dans un séance publique du 14 Juin 1865," *Les Mondes* 8 (1865): 534.

[8] Campos, ed., *Vuillaume* 33.

The signature of thorough, skilled and artful craftsmanship was especially prominent in Koenig's later scientific instruments of wood, such as his wooden resonators for tuning forks, sonometers and organ pipes. Inspection of these instruments today, reveals a beautiful finish, excellent construction and careful selection of woods.[9]

Life at the workshop included a special appreciation for those craftsmen, and especially Vuillaume, who exhibited a virtuoso eye, ear and feel for wood, glues, varnish, bow hair and strings. Apprentices were required to learn the minutest details of the materials with which they worked and the acoustical effects they produced. Vuillaume, for example, was well known among violinmakers for his excursions to remote parts of Europe to find a specific kind of wood of a certain age and density. He knew good sound through sight and could pick good wood from the unlikeliest places. He used pieces of old furniture that he came upon by chance and that he found to have excellent sonority.[10] The back, neck, sides and bridge of the violin were to be made from a specific kind of aged maple; the belly, bar, blocks and sound post were of pine.[11] He even invented a special oven to treat his wood.

> His final conclusion was that the best wood from the point of view of resonance is the wood that has been seasoned in planks for some thirty or forty years, of about 3 cm thickness, and, most important, that the seasoning should be carried out in the fresh air and under cover.[12]

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[9] In fact, Koenig's instruments are very easy to distinguish from any competitors (or copiers) merely on the basis of a quick glance at the finish, tight construction and quality of wood. The sound of his resonating boxes, or organ pipes is therefore of a noticeably higher quality. One fine example is Barbareau's grand sonometer used to demonstrate the formation of scales. The top is spruce with perfectly regular grains, the sides are mahogany with walnut ends, and the bridge is oak. There are even stylised sound holes, resembling the "f" holes of a violin (Smithsonian Institution, National Museum of American History, Cat. No. 314, 589). Another example of well-preserved Koenig craftsmanship can be found in the sixty-five-piece tuning fork tonometer at the University of Toronto. The wooden resonator boxes (white pine top with mahogany sides) are perfect examples of the high quality craftsmanship that went into even the smallest woodwork at his studio.

[10] Millant, *Vuillaume* 87. He once used the wood of an old bridge of Turin. Campos, ed., *Vuillaume* 25.

[11] In fact, there seemed to be no limit to the extent violinmakers would go to achieve the right sonority from their selection of wood. The violinmaker, John Broadhouse, claimed that for the best sound qualities and brilliance of tone, the tree should be cut in January or December, when no sap flows. He suggested cutting it from the south side of the tree, as the Italians did, and make sure it was seasoned for *at least* seven years. Judgement and experience were crucial. "Vuillaume, of Paris, travelled in Italy and Switzerland for the express purpose of procuring pine wood, and brought chairs, tables and other articles of furniture whenever he found the kind of wood he wanted." John Broadhouse, *How to Make a Violin* (London: William Reeves, 1890) 10.

[12] Millant, *Vuillaume* 87.

3.3 SAVART, VUILLAUME AND THE SCIENCE OF VIOLINS

There was a remarkable web of connections between the world of violin-making and early acoustical studies that doubtless had a significant influence on Koenig's career. Vuillaume collaborated with the French physicist, Félix Savart, on acoustical experiments on the violin.[13] Vuillaume saw acoustics as valuable for violin making and nurtured his connections to the world of science. In turn, Savart's lengthy studies on the violin over a twenty-year period gave birth to many new lines of inquiry regarding sound, which in turn gave birth to a small, but active community of acoustical researchers in Paris. Albert Marloye (1795-1874), for example, Savart's instrument maker, became the first scientific instrument maker to make acoustical instruments exclusively for teaching and research.[14]

There were two main reasons for Vuillaume's interest in science. In the first place, in order to improve his copies of Cremonese violins, Vuillaume desired to uncover their secrets. Above all he sought the unique quality of sound that characterised these violins. He believed scientific research could uncover the principles that had guided Stradivarius and other makers thus making it possible construct copies based on proven laws and guidelines.[15] Secondly, Vuillaume built violins at a time when performers were demanding new styles and more power. The violinmaker and historian, Carleen Hutchins, has argued, for instance, that there was a growing need in the nineteenth century for adapting the violin to the new (larger) concert halls and evolving playing styles. As a result, makers were looking to science for new insights.[16]

Savart, on the other hand, wanted to understand the mysterious nature of the violin for purely scientific reasons and also in order to improve violin making. He began seriously to study the

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[13] Thierry Maniguet, "Savart and Vuillaume," in *Violins, Vuillaume (1785-1875): A Great French Violin Maker of the 19th Century*, ed. Rémy Campos (Paris: Cité de la Musique, 1998).

[14] Paolo Brenni, "The Triumph of Experimental Acoustics: Albert Marloye (1795-1874) and Rudolph Koenig (1832-1901)," *Bulletin of the Scientific Instrument Society*, no. 44 (1995).

[15] Fétis, *Anthony Stradivari*, 77-92.

acoustical aspects of the violin in 1817 and much of his work for the next twenty-four years centred on every conceivable property of the violin – pitch, vibrations, and resonance. In 1819, he invented the trapezoid violin (a violin with a body made in the shape of a trapezoid), which struck a balance between mathematical theory and his experimental findings.[17] In his published memoir of 1819, Savart outlined what would become a theme for his research: "...the efforts of scientists and those of artists are going to unite to bring to perfection an art which for so long has been limited to blind routine."[18]

In the years 1838-39, Savart gave a series of lectures at the Collège de France summarising his latest research.

> It is thanks to Mr. Wuillaume (sic), distinguished Parisian instrument maker, that we could examine a great number of violins. He put several Stradivari, Guarneri, etc. at our disposal and showed much enthusiasm and helpfulness which we are happy to acknowledge.[19]

Vuillaume and Savart's means for uncovering the mysteries of "blind routine" centred on the new visual techniques for studying vibrating bodies. They took pieces of a violin – sound boards, and backplates. - sprinkled them with sand, set them in vibration with a bow and observed the distinctive nodal patterns that were formed.

By studying these patterns they claimed to discover previously undetectable properties of the Cremonese violins.[20] Thirty years before Vuillaume and Savart's collaboration, Ernest Florens

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[16] Carleen Maley Hutchins, "350 Years of Violin Research: Violin Development from the 16th through the 19th Century," in *Research Papers in Violin Acoustics: 1975 - 1993.*, ed. Carleen Maley Hutchins (Washington D.C.: Acoustical Society of America, 1997), 7.

[17] In his first catalogue of 1859 Koenig advertised an experimental trapezoid violin, which was a variation on Savart's famous trapezoid violin from 1819. This demonstration instrument appeared in each of his subsequent catalogues, and was the one instrument that had a direct lineage to Vuillaume's workshop. Rudolph Koenig, *Catalogue des Principaux Appareils d'Acoustique* (Paris: Bailly, Divry et Ce., 1859) 27. A Savart trapezoidal violin is presently displayed in the acoustical section, next to Koenig's apparatus, at the Conservatoire National des Arts et Métiers in Paris. Also, see Rudolph Koenig, *Catalogue des Appareils d'Acoustique* (Paris: 1882a) 18. *Catalogue des Appareils d'Acoustique* (Paris: 1873a) 10. *Catalogue des Appareils d'Acoustique* (Paris: Simon Raçon et Comp., 1865a) 30. *Catalogue des Appareils d'Acoustique* (Paris: 1889) 63.

[18] Carleen Maley Hutchins, ed., *Research Papers in Violin Acoustics: 1975 - 1993* (Washington D.C.: Acoustical Society of America, 1997) 18.

[19] Maniguet, "Savart and Vuillaume," 62. Félix Savart, *l'Institut* 8 (1840): 70.

[20] Fétis, *Anthony Stradivari*, 77-92.

Chladni (1756-1827) had invented this technique for demonstrating vibration patterns of various plates.[21] In these striking demonstrations, he sprinkled sand on vibrating plates and it congregated into distinct, and sometimes quite complex, geometric figures or nodal patterns. His efforts derived in part from romantic quests to seek symmetries and signs of hidden relationships.[22] Georg Lichtenberg's electrostatic figures of the late 18th century inspired Chladni's original investigations. Chladni's methods were made popular in France after he displayed his patterns to the emperor Napoleon.[23]

Koenig acquired an early appreciation of the power of visual techniques in Vuillaume's workshop. Vuillaume firmly promoted the view that his new techniques were a vast improvement on the methods used by other masters.[24] It is not surprising therefore that one of Koenig's first research papers was based on experiments with Chladni plates.[25]

Vuillaume was active in other scientific pursuits. Through these activities, Koenig developed an appreciation of the value of science for understanding music. In William Alexander Silverman's fanciful, yet historically based novel about the violin collector, Luigi Tarisio, Vuillaume is made to say: "Perhaps the world will not remember Vuillaume as a violinmaker, but as a scientist."[26] Vuillaume performed several detailed studies of strings, woods, "f" holes and bows.[27]

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[21] E.F.F. Chladni, *Traité d'Acoustique* (Paris: Courcier, 1809).

[22] For more on the context of Chladni's work, see Thomas J. Hankins and Robert J. Silverman, *Instruments and the Imagination* (Princeton, N.J.: Princeton University Press, 1995) 130-32.

[23] At Dartmouth College the demonstrators still use a set of Chladni plates made by Marloye and purchased by Professor Young in 1853. As Beyer notes in his history, Chladni plates were quite familiar to the educated public in the nineteenth century: "The strength of this fascination in the popular mind is reflected in the Civil War essay by Dr. Oliver Wendell Holmes *My Hunt After the Captain* (the search for his son, the future Supreme Court Justice, who had been wounded at the battle of Antietam), reprinted in Vol. VIII of *Holmes's Works*, Houghton Mifflin, Boston, Ma, 1891, p. 19: 'my thoughts...arranging themselves in curves and nodal points, like grains of sand in Chladni's famous experiment.' " Beyer, *Sounds*, 25.

[24] Fétis, *Anthony Stradivari*, 121-24.

[25] Rudolph Koenig, "Nouvelles reserches sur les plaques vibrantes," *Comptes Rendus de l'Académie de Sciences* 58 (1864a). Rudolph Koenig, "Theorie der Klangfiguren von Wheatstone," *Annalen der Physik und Chemie* 122 (1864b).

[26] Silverman, *Violin Hunter* 176.

[27] Fétis, *Anthony Stradivari*, 77-79, 121-24.

He was constantly redesigning parts for his violins.[28] He carried out experiments with other makers and players.[29] His workshop was viewed as a cutting-edge place to learn the secrets of the violin craft.[30] Above all, during his seven years in Vuillaume's shop, Koenig was exposed to a culture that sought the secrets and mysteries of distinctive musical sounds. In 1858 Koenig left Vuillaume's shop to seek answers to many of these questions in the world of science.

3.4 KOENIG'S FIRST COMMISSION – THE PHONAUTOGRAPH

In 1858 Vuillaume announced his semi-retirement. He closed his shop at rue Croix-des-Petits-Champs and moved to a country estate at Ternes, just outside the city. The business continued from the new location, but Vuillaume planned to remove himself from its day to day operations. The 1850s had been a time of economic expansion in Paris and Vuillaume had become a very wealthy man. While working in Vuillaume's shop, Koenig had devoted his leisure time to the study of mechanics and physics,[31] and sometime during this period he began attending the public lectures of the physicist and renowned experimentalist, Victor Regnault, at the Collège de France.[32] Koenig had established contacts in local instrument and scientific circles and was now prepared to put them to use. In 1858 he moved from the world of music to the world of science, by starting his own business as an acoustical instrument maker. Vuillaume encouraged him in this venture.[33] There was also a convenient niche for Koenig to fill. Savart's instrument maker, Albert

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[28] Malou Haine, "Jean-Baptiste Vuillaume: Innovator or Conservationist?," in *Violins, Vuillaume (1785-1875): A Great French Violin Maker of the 19th Century*, ed. Rémy Campos (Paris: Cité de la Musique, 1998).

[29] The Norwegian player, Ole Bull, used to visit Vuillaume's shop in the 1850s to do experiments on the soundboard. John Bergsagel, "Ole Bull," in *The New Groves Dictionary of Music and Musicians*, ed. Stanley Sadie (London: MacMillan, 1980).

[30] An often repeated story about Vuillaume, which Koenig told to James Loudon of Toronto, related to his famous Thursday afternoon varnish clinics, which where held for amateurs and professionals. Violin making was a very popular trade in Paris in the first half of the century and many young makers and dealers wanted to learn about Vuillaume's secret varnish. He sat at his workbench applying the varnish for all to witness his brushing technique and the session would end with sales of the coveted varnish. After the pupils left, to the amazement of his workers or close friends, Vuillaume would wipe the varnish off and apply his own varnish. James Loudon, "Rudolph Koenig," in *University of Toronto Archives, Loudon Papers, B72 0031/016/05* (1901).

[31] W. Le Conte Stevens, "Sketch of Rudolph Koenig," *The Popular Scientific Monthly* 37 (1890): 546.

[32] Loudon, "Rudolph Koenig."

[33] Ibid.

Marloye, had retired five years earlier leaving local scientists (and customers around the world) without a successor.

Koenig's first major project came as a commission from a local inventor, Édouard-Léon Scott, who wanted him to collaborate in the making of a phonautograph, a special instrument that recorded sounds graphically. The idea of recording sound graphically was quite novel at the time, offering many possibilities for musicians, instrument makers, inventors and acousticians. It was a very attractive project for the aspiring twenty-six year old instrument maker. In the end, Koenig was able to apply his unique skills and knowledge and construct a truly original instrument that would change the history of acoustics.[34]

Édouard-Léon Scott conceived of this apparatus as early as 1853. He wished to create an apparatus that would inscribe nature's own language of sound, a universal language unencumbered by conventions, and connected directly to the physical production of speech.[35] Scott, who had been a typesetter, wanted to reform stenography so as to record thoughts more efficiently in a natural, permanent form. He had been influenced by the idea of photography and wanted to create a similar record for sound. "Sound, just like light," he wrote, "can provide a lasting image at a distance."[36] He was also interested in the physics of sound, had studied under Regnault at the Collège de France, and knew other notable scientists who did research in acoustics. An important inspiration for Scott's idea came from a description of the mechanism of the ear in a physics textbook he had been editing. He immediately saw that if one wanted to create an "image" of sound, one should build a replica of the inner ear and connect this contraption to some form of inscrip-

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[34] Secondary sources on the development of graphical recording include: Robert Brain, "Kymograph," in *Instruments of Science: An Historical Encyclopedia*, ed. Robert Bud and Deborah Jean Warner (London; Washington D.C.: The Science Museum, London and the National Museum of American History in association with Garland Publishing, Inc., 1998). Robert Brain, "Standards and Semiotics," in *Inscribing Science: Scientific Texts and the Materiality of Communication*, ed. Timothy Lenoir (Stanford, California: Stanford University Press, 1998). Marta Braun, *Picturing Time: The Work of Etienne-Jules Marey (1830-1904)* (Chicago and London: University of Chicago Press, 1992). Paul Charbon, *La Machine Parlante* (J.P. Gyss, 1981). Hankins and Silverman, *Instruments and the Imagination* 133-140.

[35] For a summary of Scott's work, see Ibid., 133-37. Also see Silverman's dissertation, Robert J. Silverman, "Instrumentation, Representation, and Perception in Modern Science: Imitating Function in the Nineteenth Century" (University of Washington, 1992) 120-22. Charbon, *La Machine Parlante* 11-15

tion device.[37] The "sublime artist, God," led him to his goal by displaying "the marvel of all marvels, the human ear."[38]

Scott's first attempt indeed looked like an ear. In his application for a patent, submitted in 1857, Scott described his new invention for writing sound. It consisted of a bowl-shaped sound receiver and a tube with a thin membrane at the end. A writing stylus connected to the membrane rested on blackened recording paper secured on a plate. A weight mechanism pulled the plate at a uniform speed as the stylus recorded the vibrations.[39] Initially Scott had worked with the famous instrument maker Gustave Froment. Disappointed with this initial instrument, however, Scott made contact with Koenig, who had just started his business. They signed a contract in April 1859.[40]

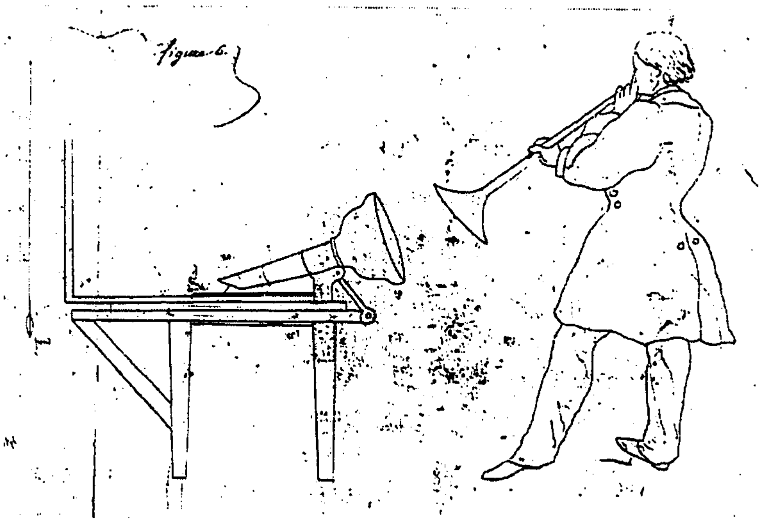

Figure 3.1 Scott's first phonautograph, 1857. Scott *Brevet* (1857).

In his first public announcement of his invention in 1859 Scott mentioned that during his efforts he had sought help in order to make sensitive membranes that closely resembled physiologi-

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[36] Édouard-Léon Scott, "Phonautographe et fixation graphique de la voix," *Cosmos* 14 (1859a): 314.
[37] Silverman, "Instrumentation," 122.
[38] Scott, "Phonautographe et fixation graphique de la voix," 315.
[39] Édouard-Léon Scott, "Brevet d'invention, No. 31470. Un procédéau moyen duquel on peut ecrire et dessiner par le son (acoustique), multiplier graphiquement les résultats obtenus et en faire des applications industrielles," in *Institut National de la Propriete Industrielle* (Paris: 1857).
[40] Charbon *La Machine Parlante* 13

cal membranes. He also sought help from practitioners who knew the principles of sound reinforcement, a "necessity for written speech." For developments that preceded his own invention, Scott paid homage to Félix Savart, Jean Müller, Jean-Marie-Constant Duhamel (1797-1872), Arthur Morin, Claude Pouillet, Guillaume Wertheim (1815-1861) and Jules Lissajous, each important figures in the local acoustics scene.[41] At the end of Scott's first announcement, the editor, Moigno added:

> We are happy to be able to announce that at this moment, M. Léon Scott, aided by the theoretical and practical artfulness of M. Rudolphe Koenig, just constructed a new apparatus that registers with the most clarity the vibrations of a tuning fork, up to a thousand of them a second. [42]

In fact, Koenig, with his refined craft and scientific knowledge, played a decisive role in turning Scott's ideas into reality. In July of 1859 Scott submitted a revised patent based on a very different instrument.[43] Koenig had made the second version with a rotating cylinder that could record the vibrations in a much smoother and uniform motion. He also added a graphic chronometer (tuning fork with stylus) to measure the duration of the various phenomena under scrutiny. He designed a new ellipsoid drum to receive the sound more efficiently. Scott modified the membrane structure so as to imitate more faithfully the workings of the ear. The phonautograph was first displayed in 1859 in London at a meeting for the British Association for the Advancement of the Sciences.[44]

In their contract, Scott had given Koenig, the constructer, the rights to the design of the instrument. When Scott suggested making further changes to the membrane, Koenig refused. Scott had wanted to try a new way of arranging the frame of the membrane in order to imitate the anat-

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[41] Scott, "Phonautographe," 320.

[42] François Napoléon Marie Moigno, "Phonautographe et fixation graphique de la voix," *Cosmos* 14 (1859a) 320.

[43] Édouard-Léon Scott, "Certificat d'addition à un brevet d'invention du Mars 28 1857, no. 31470. Un procédéau moyen duquel on peut écrire et dessiner par le son (acoustique), multiplier graphiquement les résultats obtenus et en faire des applications industrielles," in *Institut National de la Propriete Industrielle* (Paris: 1859). The address on the second application, Louis le Grand, 5, was very similar to Koenig's address at that time, Place Lycée Louis le Grand, 5. Perhaps it was the same studio.

[44] François Napoléon Marie Moigno, "Sur la phonautographe," *Cosmos* 15 (1859b) 677.

omy of the ear even more closely than in the previous design, but Koenig wanted it simpler. The two men thus had a falling out over the future of their novel instrument.[45]

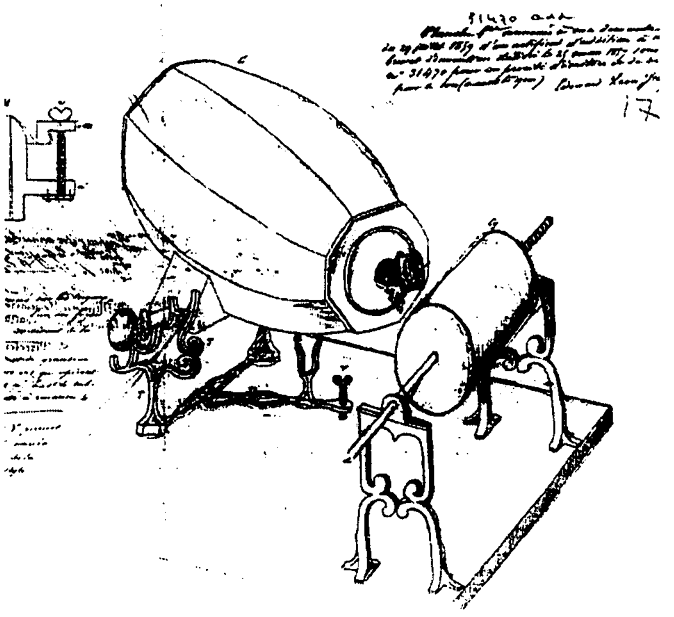

Figure 3.2 Scott and Koenig's first phonautograph. Scott *Certificat* (1859).

During the next few years, working independently of Scott, Koenig made further changes to the original design. He transformed the collecting drum from an ellipsoid shape to a parabolic shape with better resonant qualities. He made the collecting drum of zinc, whereas Scott had originally used a strong form of "plaster of Paris" (starken Gipswänden).[46] Koenig also simplified Scott's membrane and frame arrangement significantly. Scott had set the membrane at an angle, for a faithful imitation of the membrane of the ear, which he claimed was "thin, tight, and inclined." As we saw above, he had also placed the membrane in contact with an adjustable tube that connected to the focal point of the ellipsoid chamber. After many trials, Koenig found the appropriate tightness of membrane (he constructed a special frame for it), and connected this frame directly to the focus of the parabola. The final membrane was described as "very tight and

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[45] Charbon *La Machine Parlante* 14

[46] Franz Joseph Pisko, *Die neuren Apparate der Akustik* (Wien: Carl Gerold's Sohn, 1865) 71-77. Also see, Silvanus P. Thompson, "Rudolph Koenig," *Nature* 64, no. 1669 (1901).

very homogeneous."[47] He experimented with membranes of thin paper (vegetable), hide-glue, goldbeaters skin, and parchment paper.[48] By 1865 he had also developed an electric tuning fork chronoscope that he believed was much more convenient and precise for measuring time intervals on the phonautograph.

Koenig therefore had not only improved the quality of the tracings, he had transformed the phonautograph into a quantitative instrument. The original phonautograph of Koenig and Scott could reproduce and measure vibrations in the range of 256 to 1024 vibrations a second, which was viewed as a "*tour de force incroyable*" for that time. When these drawings were first shown at the London meeting in 1859 Moigno wrote: "these tuning forks, pipes, human voices, alone or together, that automatically write hundreds and thousands of vibrations executed per second created a true enthusiasm."[49]

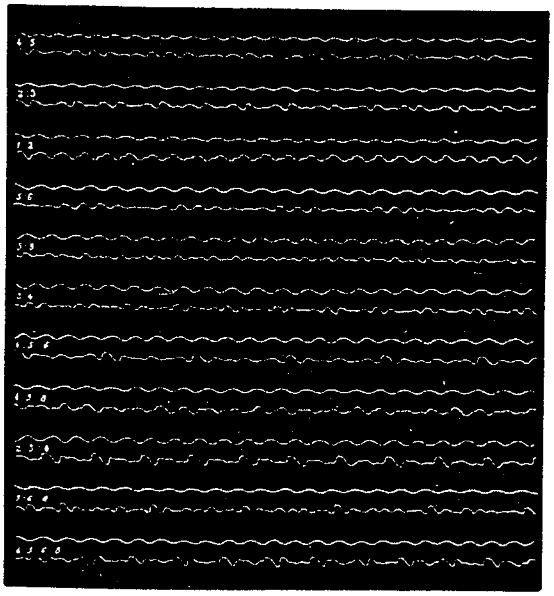

Figure 3.3 Phonautograph tracings of different harmonic combinations of organ pipes (bottom of each pair), compared with a standard tuning fork (256 Hz) (top tracing of each pair). Koenig Quelques *Expériences* (1882) 26.

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[47] Moigno, "Sur la phonautographe," 677.
[48] Pisko, *Die neuren Apparate der Akustik* 73.
[49] Moigno, "Phonautographe,"417.

In 1865 Koenig sold the phonautograph for 500 francs and it became a fairly popular instrument.[50] The Dutch physiologist, Franz Donders, was one of the first researchers to use it for his early vowel research in the 1860s.[51] Even as late as the 1870s, we find Koenig using it to verify the existence of the disputed combination tones (§4.5). It also entered the scientific imagination as a definitive, objective test of even the subtlest, controversial phenomena. In his attempt to show that science had now caught up with even the most farfetched claims, William Crookes wrote: "The spiritualist tells of tapping sounds which are produced in different parts of the room when two or more persons sit quietly round a table. The scientific experimenter is entitled to ask that these taps shall be produced on the stretched membrane of his phonautograph."[52] Koenig never envisioned the phonautograph as a sound reproduction instrument, such as the Edi-

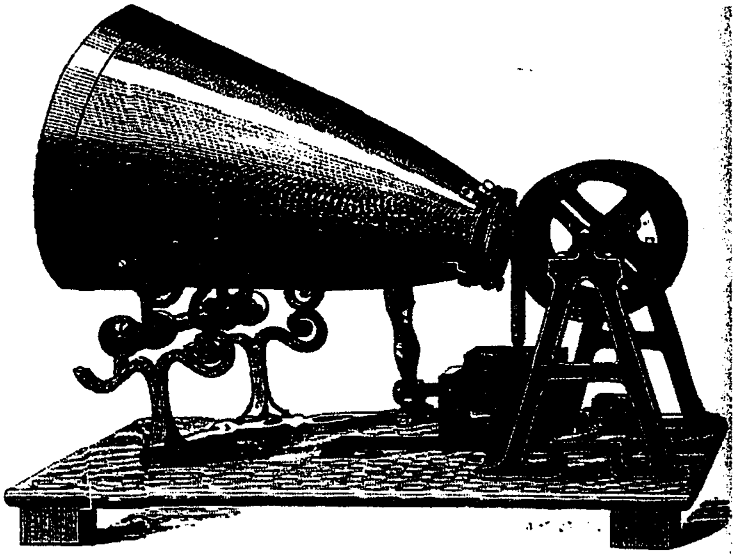

Figure 3.4 Koenig's second phonautograph. Pisko *(1865)* 72.

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[50] Koenig, *Catalogue, (1865)* 39. The National Museum of American History (Smithsonian Institution) has one of the original Koenig phonautographs, acc. no. 215, 518. Joseph Henry purchased it in 1865, see Joseph Henry, "Letter to J. Swain, December 9," in *Smithsonian Institution Archives, outgoing correspondence, office of the secretary 1863-1878* (Washington D.C.: 1865). The Teyler's museum has another phonautograph from 1865, see Gerard L'E. Turner, *The Practice of Science in the Nineteenth Century* (1996) 135-36. Another phonautograph has recently been found by Paolo Brenni at the Museum of Physics at the University of Coimbra, Portugal. Columbia College and Harvard both owned phonautographs in the nineteenth century.

[51] F.C. Donders, "Zur Klangfarbe der Vocale," *Annalen der Physik* 123 (1864).

[52] William Crookes, *Quarterly Journal of Science*, July 1870.

son phonograph developed from the same principles twenty years later. He only saw it as a new graphical method. When S.P. Thompson asked him if he or Scott had ever foreseen an instrument like Edison's while working on their invention, he replied: "No, the idea never occurred to either of us; we never thought of anything but recording."[53]

3.5 "LIKE ASTRONOMY BEFORE THE INVENTION OF THE TELESCOPE"

In the last chapter, I described how the theories of Helmholtz were a major event in the history of sound and music. The phonautograph had an equally profound impact on the history of acoustics and music from a methodological point of view. People could now study sound independent of its source, in a permanent, visual record. This dramatically altered the need for the "expert ear" and provided a tool with substantially extended powers of observation and analysis. One need only take note that the ear is seldom used in modern acoustical studies to realise the significance of this development.

Koenig, one can argue, was a leader of the movement to replace the expert ear with an automatic recording instrument. He attached a small pamphlet to his 1859 catalogue praising the revolutionary methods ushered in by the phonautograph. The title read, "The phonautograph, apparatus for the graphic recording of noises, sounds and the voice, invented by Édouard-Léon Scott and constructed by Rudolph Koenig." Underlying much of this essay was a deep faith that the new graphical method would completely revolutionise acoustics.

> Most of the sciences founded on observation and experiment already have in possession a set range of special instruments, suitable to provide a precise and thorough knowledge of certain phenomena, because our senses, it is known, are only capable of providing certain sensations, most often defective, irreducible and variable from one individual to another. Astronomy and optics have instruments of great variety that provide a vast extension or an extraordinary subtlety to sight. The natural sciences have their means of observation in chemical analysis and in the microscope that reveals a world that seems intended to elude us through its smallness. These instruments, genuine tools of scientific work, have opened a path of inexhaustible richness to experimentation, and have made progress of unexpected reach in the sciences and the arts.[54]

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[53] Thompson, "Rudolph Koenig," 630.

[54] "Le phonautographe, appareil pour la fixation graphique des bruits, des sons, de la voix, inventé par M. Édouard-Léon Scott et construit par M. Rudolph Koenig," in *Catalogue des Principaux Appareils d'Acoustique* (Paris: Bailly, Divry et Ce, 1859), 1.

Acoustics, its author argued, had not followed the lead of the other sciences. The study of sound had been until recently like "astronomy before the invention of the telescope; it languished in waiting without its instruments of observation for measurement and analysis." Acousticians desperately needed a "microscope to see sound, and better, to save the imprint." "The phonautograph fills this gap." The pamphlet then described how the inventor (Scott) laboured for over six years developing his new tool and, at times, even presented some of his new experiments on noises, the voice, song, and musical instruments to other scientists but he was not fully satisfied with the results.[55]

> Happily, another person came to him. M. Rudolph Koenig put himself to the task for the complete implementation of the phonautograph. M. Scott owes a lot to this skilful instrument maker for the proper use of the instrument, the arrangement of the diverse parts with good acoustical conditions, and the ingenious construction that allows the apparatus to figure prominently in a physical cabinet.[56]

Inscription devices were quite the vogue in Paris in the early 1860s. Aside from the work of Scott and Koenig, the young Parisian medical researcher, Etienne-Jules Marey (1830-1904), who was just two and a half years older than Koenig, made his reputation at almost the same time for the same reason – his invention and use of graphical instruments. Marey had obtained his interest in graphical techniques from his studies in Germany where he learned the "organic physics" of Helmholtz, Brücke, du Bois Reymond and Ludwig. In the late 1850s he returned to France to pursue pure physiological research with Claude Bernard at the Collège de France. In 1859 he introduced the sphygmograph or "pulse writer" for inscribing the pulsation of the heart. He then worked with Auguste Chauveau to produce a new form of cardiograph in 1861. In the 1860s he went on to develop a number of other graphical instruments. Koenig and Marey most likely met at this time and became lifelong friends.[57]

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[55] "Ibid.," 3-4.

[56] "Ibid.," 2.

[57] Koenig and Marey cited each other in later works. Marey's classic treatise of 1878 displayed several of Koenig's drawings and traces, see Etienne-Jules Marey, *La Méthode Graphique en Sciences Expérimentales* (Paris: G. Masson, 1878). They even shared the same artist, a fellow named Perot, the artist who assisted Koenig with his famous manometric drawings. Both were mechanically inclined and saw graphical

In the above discussion, we find much emphasis on revolutionising instruments and methodology, with almost no mention of a specific acoustical theory. It was the new instrument that would revolutionise the study of sound and not necessarily a grand theory. Moigno, for example, wrote that the phonautograph would "at least lift the corner of the veil that covered the mysteries of the mechanisms of the human voice."[58] Like photography, it was seen as a faithful recorder of all varieties of sound. Before 1860 there is no mention of the phonautograph in relation to the theories of Helmholtz. In fact, Helmholtz's most important article on timbre was not published until late in 1859 (§2.7). The phonautograph then took on a different role.

3.6 EXPERIMENTS AT THE ACADEMY OF SCIENCES

In the early 1860s Koenig's new graphical studies merged, for the first time, with the work of Helmholtz. Koenig's studio during this period was a "plaque tournante"[59] for ideas, people and traditions. We find him involved with education,[60] medicine,[61] and music.[62] We find him doing his own research and collaborating with local scientists.[63] It was also, as we saw in the last chap-

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instruments as a way of discovering truths hidden from the senses. In his history of acoustics, Koenig summarised the need of certain instruments to extend and fortify defective senses, which was "Marey, très condense!" After the Franco-Prussian war, Marey was the only Parisian scientist who continued to be on good terms with Koenig (see Chapter One).

[58] Moigno, "Sur la phonautographe," 679.

[59] I borrow this phrase (turning plate in a train round house) from the French historian, Christine Blondel, who has made a similar characterisation of the electrical instrument makers in nineteenth-century Paris. Christine Blondel, "Electrical Instruments in 19th Century France, Between Makers and Users," *History and Technology* 13 (1997).

[60] Koenig developed a number of attractive demonstration devices during g this period. For more on Koenig's wave machines, see Julian Holland, "Charles Wheatstone and the Representation of Waves," *Rittenhouse* 13, no. 2 (2000).

[61] From 1864 to 1877 Koenig worked at 30 Hautefueille, around the corner from the medical faculty. Louis Auzoux's anatomical model shop was also around the corner on rue de l'École-de-Médecine. Koenig sold Auzoux's famous models as early as 1859 Koenig, *Catalogue, (1859)* 31. In addition he invented two new diagnostic instruments, the "dynascopic tuning fork" and a stethoscope with rubber tubes. François Napoléon Marie Moigno, "Diapason dynamoscopique," *Cosmos* 20 (1862). François Napoléon Marie Moigno, "Nouveau stéthoscope," *Cosmos* 25 (1864).

[62] Koenig invented a device that could measure the homogeneity of a violin string. François Napoléon Marie Moigno, "Phonoscope," *Cosmos* 20 (1862): 700.

[63] In 1862 a local physicist, Prof. Faye, collaborated with Koenig to create a new instrument to measure the speed of sound. Rudolph Koenig, "Appareil pour la mesure de la vitesse du son," *Comptes Rendus de l'Académie de Sciences* 55 (1862). François Napoléon Marie Moigno, "Séance, Lundi le 29 Septembre 1862," *Cosmos* 21 (1862). Koenig performed novel research on Chladni plates. He designed a special set of rectangular plates that produced theoretical figures predicted by a theory of Charles Wheatstone. Koenig, "Nouvelles reserches sur les plaques vibrantes." Koenig, "Theorie der Klangfiguren von Wheatstone."

ter, a time when he introduced Paris to the works of Helmholtz. Following Helmholtz's article on vowels in 1859, Koenig's studio became a cutting-edge, well-equipped laboratory for demonstrating, transmitting and testing these theories. In the early 1860s he built all of the core instruments of Helmholtz's new acoustics -- the resonator for studying timbre, the double siren for studying combination tones, the tuning-fork synthesiser for studying the creation of vowels, Scheibler's tuning-fork tonometer for studying beats, and the Lissajous comparator for studying vibrating bodies (See Chapter Two). In May 1862, for example, Radau introduced his readers to Helmholtz's new ideas on timbre by describing the resonators and vowel synthesiser, "which we have been able to admire at Koenig's place."[64] Each of these instruments appeared in the 1865 catalogue, and those scientists fortunate enough to be in Paris could see them at Koenig's. By 1865 his studio became known as a place for learning about Helmholtz, because he had been "able to maintain continued relations with the scientists of that country [Germany], permitting him to gather and realise, in a convenient form, research and demonstration instruments unknown in France before him."[65]

Between 1858 and 1862 Koenig performed tests of Helmholtz's ideas using his new graphical instrument. It is here that we see the merging of the Parisian taste for graphical techniques with the ideas coming out of Heidelberg. In the summer of 1861 the Academy of Sciences viewed Koenig's latest graphical work for the first time. On June 10 (at the weekly Monday session of the Academy) Claude Bernard presented the work of a young Hungarian anatomist, Adam Politzer, who had recently conducted a series of experiments on the tympanum in order to verify some of Helmholtz's claims about the working of the inner ear.[66] Using the heads of freshly killed dogs,

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Charles Wheatstone, "On the Figures Obtained by Strewing Sand in Vibrating Surfaces, Commonly Called 'Acoustic Figures'," *Philosophical Transactions*, (1833).

[64] Rodolphe Radau, "Acoustique," *Cosmos* 20 (1862a): 623.

[65] Moigno, "Médailles décernées par la société d'encouragement," 534.

[66] François Napoléon Marie Moigno, "Séance, Lundi, le 10 Juin 1861," *Cosmos* 18 (1861).

dogs, chickens and a human,[67] Politzer had used a form of manometer (pressure-gauging device) to demonstrate the workings of the tympanic membrane and its associated muscles. At the end of his presentation of Politzer's work, Bernard displayed, with the help of Koenig, some recent "automatic" graphical traces showing related experiments obtained from Koenig's studio. He had connected a stylus to the hammer, anvil and stirrup of the inner ear and recorded the responses to various simple tones and combinations of tones. For those in the audience, this display was a stunning graphical display of Helmholtz's ideas on physiology, harmony and beats. François Moigno, the editor of *Cosmos*, wrote that the tracings recorded in these experiments were "an incomparable perfection; they prove that the membrane of the tympanum is largely superior to the best artificial membranes of the physicists. M. Helmholtz, the eminently skilful physicist had tried, but in vain, the experiment that worked so well in Paris."[68]

Two weeks later, after experimenting with Koenig, Politzer himself presented a continuation of his experiments on the inner ear to the academy.[69] This time, Politzer did the anatomical preparations and Koenig did the graphical work for a live demonstration of the automatic inscriptions.[70] They used a form of the phonautograph with a blackened roller, stylus and, again, fresh parts of the inner ear, bones and membrane to demonstrate some of Helmholtz's findings of beats and simple tones. The novelty of Politzer and Koenig's experiments caused a small controversy. Politzer, realising that he had been part of an important event, made a point of correcting statements of the past week that Helmholtz had tried these experiments and failed.[71] He apparently

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[67] The use of animals for experiments was apparently a constant source of troubles for Bernard. The local police commissioner was not pleased with his experimental habits, and neither was his wife. See J.M. D. Olmstead and E. Harris Olmstead, *Claude Bernard & the Experimental Method in Medicine* (London: Abelard - Schuman, 1952) 42, 113.

[68] Moigno, "Séance, Lundi, le 10 Juin 1861," 669.

[69] François Napoléon Marie Moigno, "Séance, Lundi, le 24 Juin 1861," *Cosmos* 18 (1861).

[70] For Koenig's brief description of these experiments see Rudolph Koenig, *Quelques Expériences d'Acoustique* (Paris: A. Lahure, 1882b) 29.

[71] There is no evidence that Helmholtz did attempt these experiments, but he had done several graphical experiments early in his physiological career (related to muscular movement), see Frederic L. Holmes and Kathryn M. Olesko, "The Images of Precision: Helmholtz and the Graphical Method in Physiology," in *The Values of Precision*, ed. M. Norton Wise (Princeton, N.J.: Princeton University Press, 1995).

wanted to protect the image of his master and preserve his own claim to his and Koenig's experiments in the face of such enthusiasm.[72]

Édouard-Léon Scott, still upset by his falling-out with Koenig, did claim priority for the method used in these experiments and he was unhappy with not being credited. At a séance a few weeks later Scott reminded the academy that this recent series of experiments resembled ones he had done on his own a few years earlier. To prove his point, he asked that a sealed package detailing these studies dating from 1857 be opened and read to the academy.[73] The commissioners at Scott's presentation (1862) included Victor Regnault, Claude Bernard and the physicist, Claude Pouillet. In introducing his sealed package, Scott commented that recently a "foreign savant with the aid of an instrument maker" had presented to the academy a series of inscription-type experiments with the inner ear of a decapitated animal, and he wanted to let everyone know that he had already done this research. In his address to the academy, he reminded the audience of his senior credentials. He thanked Duhamel[74] for the original discoveries relating to his graphical research, and his "former master," Regnault, for his support at the Collège de France. He went on to detail his research related to recording graphically the responses from parts of the inner ear and his attempts to create an imitation of these functions in his recent invention, the phonautograph.

Scott failed to appreciate the entirely new context that was opening up for graphical studies. Politzer and Koenig may have been doing similar experiments to Scott's in method, but they were testing Helmholtz's theories, something that Scott had never (nor could have) considered in 1857.

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[72] In fact, Helmholtz sited these experiments in his book the next year, see Hermann Helmholtz, *On the Sensations of Tone as a Physiological Basis for a Theory of Music*, trans. Alexander J. Ellis (New York: Dover Publications, Inc., 1885) 136, 66. I suspect, however, that the original statement about Helmholtz came from Koenig, who may have communicated such a statement to Moigno in order to underline the significance of his discoveries. This incident, therefore, may have been the start of tensions that grew between Koenig and Helmholtz.

[73] François Napoléon Marie Moigno, "Séance, Lundi, le 15 Juillet 1861," *Cosmos* 19 (1861).
Édouard-Léon Scott, "Inscription automatique des sons de l'air au moyen d'une oreille artificielle," *Comptes Rendus Hebdomadaires des Séances de l'Académie de Sciences* 53 (1861).

[74] Duhamel was a senior professor at the École Polytechnique. In the 1830s he invented a novel graphical instrument called a vibroscope. It consisted of a rotating cylinder and a vibrating writing stylus, see Sigalia Dostrovsky, "Jean-Marie-Constant Duhamel (1797-1872)," in *Dictionary of Scientific Biography* (New York: Scribners, 1970).

At this time Koenig was becoming the recognised leader of the new graphical movement with his invention and promotion of new instruments and Scott was most likely jealous of the young German whom he had helped bring into the scientific world in the first place.

3.7 POSITIVISM AND ACOUSTICS

Koenig's graphical studies of Helmholtz's ideas revealed his early desire to seriously test the theories of the great physicist. It was also part of a broader program he had initiated to develop and hone graphical methods for testing, calibrating, timing and demonstrating many acoustical phenomena. Ultimately, Koenig dedicated himself to improving the graphical method, so that no matter what his instruments were used for, they would present a faithful picture of nature. In fact, he was often more interested in studying his instruments than studying sound itself.

Science in Paris during the Second Empire (1851–1870) had its own style, approach and attitudes to teaching and research.[75] There was a strong faith in experiment, along with widespread scepticism of theories that strayed from the observable. As a complement to this culture, Paris had the largest and most talented population of precision instrument makers in Europe, an inheritance from the great years before 1840. Koenig thrived in this context.

Those who did research in Paris did so in a culture that regarded methods and experiment as the surest path to certain knowledge. The historian Robert Fox has described Victor Regnault as a master experimentalist, but when it came to the bigger picture, generally "unimaginative" and "lacking any bold theory."[76] Claude Bernard, the pioneer of experimental physiology in France, is

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[75] For more on French Science in this period, see Matthias Dörries, "Easy Transit: Crossing Boundaries between Physics and Chemistry in Mid-Nineteenth-Century France," in *Making Space for Science. Territorial Themes in the Shaping of Knowledge.*, ed. Crosbie Smith and John Agar (Basingstoke: MacMillan, 1998). Robert Fox, *The Caloric Theory of Gases from Lavoisier to Regnault* (Oxford: Oxford Press, 1971). Robert Fox, *The Culture of Science in France, 1700-1900* (Aldershot, U.K.: Variorum, 1992).
Robert Fox, "The Savant Confronts His Peers: Scientific Societies in France, 1815-1914," in *The Organization of Science and Technology in France, 1808-1914*, ed. Robert Fox and George Weisz (Cambridge: Cambridge University Press, 1980). Robert Fox, "Scientific Enterprise and the Patronage of Research in France, 1800-70," *Minerva* 11 (1973). Harry W. Paul, *From Knowledge to Power: The Rise of the Science Empire in France, 1860-1939* (Cambridge, New York: Cambridge University Press, 1985). Alan J. Rocke, *Nationalizing Science: Adolphe Wurtz and the Battle for French Chemistry* (Cambridge, Massachusetts: The MIT Press, 2001).

[76] Fox, *The Caloric Theory of Gases* 295-302. For more on Regnault, see Dörries, "Easy Transit."

said to have told an American student, "why think, when you can experiment!"[77] Alan Rocke has shown in his studies of chemists from this period, that many scientists were positivist/empiricists (or in the least very cautious), in the sense that they were reluctant to discuss anything that could not be made observable in the laboratory (such as atoms). As we will see in his later disagreements with Helmholtz, Koenig fully adopted this approach to science.

In his unpublished history of acoustics, Koenig claimed to have devoted the first years of his business from 1858 to 1862 "specially to the perfection of this method [graphical]"[78] By 1862 he had created a spectacular album of his key graphical experiments that he displayed at London along with his apparatus. The album consisted of seven sections (sixty-four tracings, "les phonogrammes," on blackened paper), showing the main areas to which the graphical technique could be used. This is where he made his mark both as a scientist and businessman. He displayed his "masterpieces of patience and skill" to great admiration at the London Universal Exposition of 1862, winning a "médaille unique."[79] Visitors to the exhibition marvelled at Koenig's pictures of sound.

> M. Koenig showed a wonderful collection of instruments applied to the illustration of the theory of the conduction, undulation, and vibration of sound. By the most ingenious but simple instrument -- a common glass cylinder coated with fine lampblack, and applied, turning, to a tuning-key when vibrating -- M. Koenig makes sound its own printer. From the impression left on this printer all the different vibrations and undulations of sound between A and G are here recorded from the outset to their latest tone, have been made to register themselves, and from the records thus left a most beautiful series of acoustic charts has been drawn out.[80]

The album was so popular that Koenig made and sold reproductions for 400 francs.[81] He would also complain in his 1882 book that several people had reproduced his coveted pictures in

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[77] Olmstead and Olmstead, *Claude Bernard* 69.

[78] Rudolph Koenig, "Quelques Notes," in *University of Toronto Archives, Loudon Papers B72-0031/017(05)* (1901).

[79] Radau, "Acoustique," 659.

[80] John Timbs, *The International Exhibition. The Science, & Art of the Age: or, the International Exhibition of 1862 Popularly Described from Its Origin to Its Close; Including Details of the Principle Objects and Articles Exhibited* (London: Lockwood & Co., Stationers Hall Court., 1863).

[81] Koenig, *Catalogue (1865)* 42.

"a large number of physical texts, most often without any indication of their origin."[82] He reproduced some of them himself in his 1865 catalogue and several more in his 1882 book. The instruments themselves, mostly consisting of sets of tuning forks with a special graphical stylus attached to the end of one prong, spread throughout the scientific world.[83] The most popular device related to the graphical Lissajous trials (see below). Each fork cost on average 100 francs.

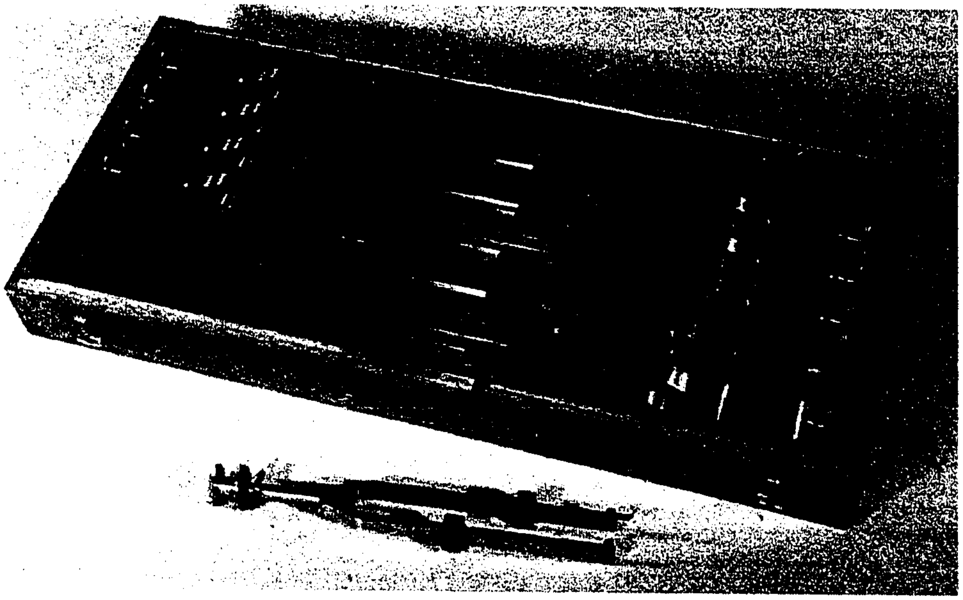

Figure 3.5 Graphical tuning forks with stylus and sliding weights, ranging from Ut1 to Ut 3, see Koenig *Catalogue* (1882) 27. UTMuSI.

Koenig's display of tracings was a grand exposition of the new graphical method, as well as a dialogue on methods in general. The album consisted of seven sections: one large section on counting vibrations and timing; one section for Lissajous type combinations of two different "parallel" vibratory movements (e.g. two tuning forks at different pitches forming a musical in-

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[82] Koenig, *Quelques Expériences d'Acoustique* 1. Copies of Koenig's tracings can be found in W.J. Loudon and J.C. McLennan, *A Laboratory Course in Experimental Physics* (New York, London: MacMillam and Co., 1895) 109-10. Pisko, *Die neuren Apparate der Akustik* 55-93. A. Winkelmann, *Handbuch der Physik: Akustik*, vol. 2 (Leipzig: Johann Ambrosius Barth, 1909) 150-52. John Augustine Zahm, *Sound and Music* (Chicago: A.C. McClurg & Co., 1900) 421-22.

[83] Koenig's graphical forks are found at the National Museum of American History, Smithsonian Institution, cat. no. 134, 593, 314, 594, 315, 720 and 315, 721. The University of Toronto has a complete set of ten graphical tuning forks, ranging from Ut1 (64 Hz) to Ut3 (256 Hz). Graphical forks can also be examined at Harvard and Case Western Reserve. Also see Turner, *The Practice of Science* 131.

terval); one section for vibratory motions (harmonics) within one body (e.g. a stringed instrument, organ pipe or slender tuning fork); two sections for special rectangular patterns related to musical intervals (Lissajous combinations but with the forks placed perpendicular to each other); one for comparing tuning forks put into vibration by different means -- the stroke of a violin bow or sympathetic vibration; one for recording different phonautograph experiments; and, finally the phonograms produced with Politzer using real animal parts.

Koenig's close attention to reducing potential errors in his instruments was clearly demonstrated in his experiments with his timing apparatus. He investigated the nature of different-sized inscribing forks, the effect of different rates of drum rotation, the friction of the styluses, and modifications on vibration rates due to changes in current. When it came to counting vibrations, he believed that his original method, using a small escapement chronometer that marked the roller every six seconds, was flawed because the act of marking could retard the rolling movement. For this reason he developed a special tuning-fork chronoscope that displayed the vibrations of a tuning fork of known frequency on a paper roller for comparison. He also developed a method whereby an electric signal, marking the beginning or end of an event, was recorded beside the known vibrations in order to measure the exact timing of an event. This allowed him to see and compare, with great precision, and without the awkward disruptions of the chronometer, the vibrations per time interval.[84] He intended this timer to be used with the phonautograph, but it was also sold separately for other precision-timing experiments.

One series of Koenig's experiments led to the development of his famed precision-timing apparatus, the Regnault chronograph. Through his graphical studies, he became aware of tiny, cyclical perturbations in the frequency of the electrically-driven fork he used for his timing apparatus. He tested several different-sized forks (graphically) and noted their different patterns of deviations. This problem created another source of possible error, namely, that one would have to operate a second chronometer to keep track of the irregularities of the chronograph. His articulation of these problems led to Regnault's invention (see below) which used a seconds-pendulum to calibrate directly the number of vibrations per second and thus reduce the error of counting successive seconds over a long period of time.[85]

Koenig investigated how different methods for exciting the forks created potential variations in the quality of vibrations. In section six, he used the graphical method to show that tuning forks excited by violin bows (a common technique in the laboratory) revealed different variations of amplitude from those excited by sympathy (using another vibrating fork to stimulate a fork). Such a demonstration showed the power of the graphical method for "seeing" something that would have been undetectable to the ear. At the same time, it provided information about various methods and possible sources of error in acoustical experiments.[86]

Koenig also made specific studies of the potential problems with membranes used in his phonautograph. He studied the tracings of combined sounds from different sources (e.g. two organ pipes played together) and discovered that the membrane of the phonautograph did not represent equally the intensity of various simple tones that had been *played* with equal intensity.[87] This finding would lead to his main complaint with the phonautograph in light of Helmholtz's theories, namely that it failed to represent accurately intensities of tone (§3.8).

Such modifications and changes seemed natural to the culture of experiment in Paris that focussed on honing instruments and methods. It appeared that Koenig was determined to avoid any potential criticism of his instruments from every angle. In fact, many passages in his book read like a dialogue with potential critics.[88] If a critic suggested that the method for counting vibrations was fundamentally flawed because of the weight and friction of the stylus, he responded: "But this is not serious, because nothing is more easy than to determine with precision this little altera-

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[84] Koenig, *Quelques Expériences d'Acoustique* 2-6.
[85] Ibid., 11.
[86] Ibid., 21-22.
[87] Ibid., 23-24.
[88] Koenig's chapter on the development of the standard tuning fork is the high point of the "dialogue" style he adopts. Ibid., 172-83.

tion that the intervention of the stylus causes to the vibrations."[89] And yet he did take it seriously. As a remedy he simply compared the free fork with the writing fork using beats and a Lissajous comparator to calculate the precise amount of deviation. Future experiments could simply factor in this variation. To take another example, if anyone was worried about the effect of the rolling drum on counting the vibrations, Koenig conducted a series of tests to show that changes in drum speed did not affect the overall outcome.

Some of these experiments were done in his studio with members of the local physics community. In the section showing his experiments on the phonautograph, Koenig and Lissajous recorded the vibrations of a tuning fork placed in front of a phonautograph membrane, and compared these tracings to the tracings of an identical tuning fork inscribed directly (with stylus) on a rotating drum. They found that the tracings were in fact very similar.[90] Again the point was not to look for anything that would reveal the nature of sound, but to show that the representations of the phonautograph "faithfully" reproduced those of the tuning fork and could therefore be trusted.

Not all of the studies were intended to explore sources of error. Koenig also developed a set of instruments to display graphically the beautiful Lissajous patterns produced when two vibrating bodies were combined through one apparatus. He discussed Lissajous's and Professor Desains first attempts to do this in 1860, and his subsequent improvement of this method two years later. Aside from the tracings, these instruments were a marvel themselves. They consisted of a large and very heavy cast iron frame (38 x 12 inches) with two adjustable steel mounts for the tuning forks. One fork held a blackened glass plate on its prong with a counter balance on the other prong; the other fork had a small writer on the end of the prong that moves slowly and smoothly backwards as it rested on the vibrating glass plate of the adjacent fork. The combined

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[89] Ibid., 6.
[90] Ibid., 24-25.

movements created distinctive graphical curves on the glass plate. For more elaborate geometric patterns, the writing fork was placed at different angles to the fork in relation to the glass plate.[91]

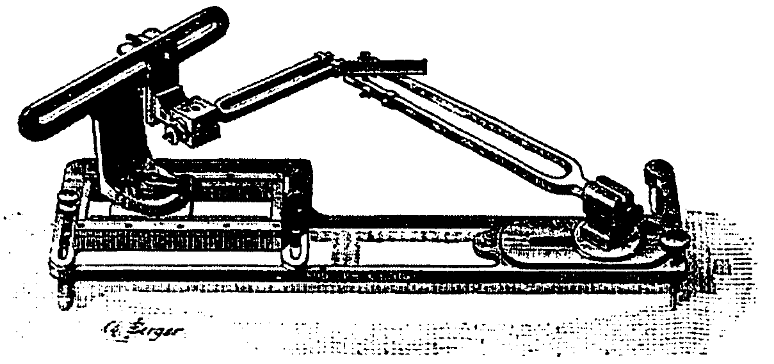

Figure 3.6 Apparatus for graphically compounding two vibratory movements at any inclination. Koenig *Catalogue* (1889) 80.

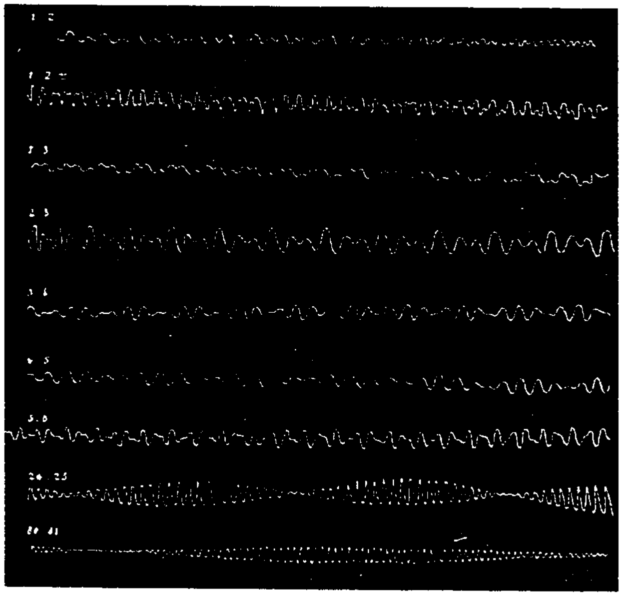

Figure 3.7 Tracings from the above apparatus. The second from the bottom clearly shows what beats look like in graphical form. Koenig *Quelques Expérience* (1882) 13.

3.8 OPTICAL INNOVATIONS

"The most curious of all his inventions, one that we already all know here [Paris]," declared the Société d'Encouragement when they awarded him the gold medal in 1865, "is without a doubt

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[91] Koenig, *Catalogue (1865)* 40. The University of Toronto has a set of ten tuning forks used for these graphical studies. The National Museum of American History (Smithsonian Institution) has a complete

the one that uses gas flames as a means for revealing the vibratory movements of air."[92] Radau first reported this invention in August 1862, describing how Koenig "showed us an attractive apparatus that had a lot of success at London, and that is destined to demonstrate one of the laws that follow the vibrations for a column of air contained in an organ pipe."[93] The manometric capsule and a whole family of related instruments, developed between 1862 and 1866, were developed on the heels of Koenig's graphical innovations. By 1866 these optical instruments, along with the graphical instruments and the instruments associated with Helmholtz came to define Koenig's business. In an introductory letter to the American physicist, Joseph Henry of the Smithsonian Institution, Koenig underlined these two aspects of his collection:

> Admirable work [in acoustics] has been executed in the last few years and since the illustrious Helmholtz published his admirable treatise on physiological acoustics everyone has been occupied with these researches and acoustics has finally been established as a science. The instruments that serve to demonstrate its phenomena are just as indispensable to a cabinet of physics as all the others that one meets there. Examination of my collection will show you that the causes that previously occasioned the neglect of this science no longer exist. In effect, if the greater part of scientists had recoiled from acoustical researches for fear that their ear, little exercised, would encounter insurmountable obstacles, we are today in possession of such admirable methods that permit the study of sound without the assistance of the ear.[94]

Koenig made the visual part of his collection a major aspect of his formal advertising. His visual instruments especially appealed to the new laboratory teachers. He entitled the longest and totally new section of his catalogue of 1865, "methods for observing the vibration of sounds without assistance from the ear." It also had more illustrations than the other sections. As we saw with the London Exhibition of 1862, fairs were an ideal venue to display, demonstrate and sell these instruments. Prof. Robert Clifton of the Clarendon laboratory at Oxford, who had just been granted financing to equip a physical cabinet, purchased a number of Koenig instruments for

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apparatus for creating combined figures, see catalogue No. 314, 596. The Teyler Museum also has a copy of this instrument, see Turner, *The Practice of Science* 130.

[92] Moigno, "Médailles décernées par la société d'encouragement," 535.

[93] Rodolphe Radau, "Acoustique," *Cosmos* 21 (1862b): 147.

[94] See October, 1865. Koenig, Rudolph, "Letters to Joseph Henry, 1865-1878b." In *Smithsonian Institution Archives, Office of the Secretary, 1863-1879, Incoming Correspondence, Record Unit 26, Box 8, Folder 15.* Washington D.C.

classroom lecture/demonstrations during a visit to the Paris Universal Exposition of 1867.[95] Koenig won a gold medal at this exposition where his displays consisted of pictures produced by his optical and graphical studies.[96] For this exposition and the Natural History Society meeting in Dresden the next year, Koenig prepared a large number of paintings of his manometric studies for display at his booth.

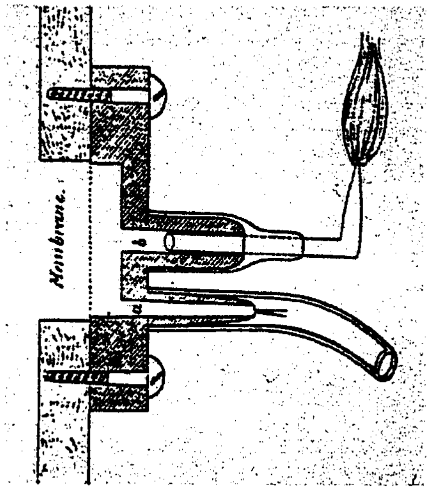

Figure 3.8 Manometric capsule. Koenig (1864c).

The manometric capsule itself revealed Koenig's mechanical ingenuity and his constant quest to make subtle effects fully observable and controllable. The capsule held a thin membrane divided into two parts: one part was open to the sound source under study; the other was closed to a flow of gas that came in through an input and exited via a gas jet. The burner was lit creating a tiny candle-sized flame. The membrane picked up vibrations in the air and transferred these vibrations to the gas, which caused the flame to flicker. A rotating mirror revealed through persistence of vision the otherwise undetectable flickers to the observer.

Koenig first applied this technique in observing the fluctuations of air in an organ pipe. In London he displayed his manometric pipe with three capsules at three nodal positions along the

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[95] John Sanders, "The Clarendon Laboratory Archive in Oxford," *Bulletin of the Scientific Instrument Society*, no. 54 (1997): 12.

length of the pipe.[97] (A node of vibration corresponded to a place where there was changing density or pressure, yet no longitudinal vibration. For example, at the centre of the pipe two longitudinal segments vibrate into each other creating a dead zone in the middle. The continuous squeezing and pulling back create the pressure changes, and cause the flame to vibrate). The middle capsule corresponded to the node of the fundamental and the outer two capsules corresponded to the nodes of the octave. When the pipe sounded with the fundamental note, one saw the middle capsule vibrate strongly, since it was located at the node of vibration, while the other two vibrated less strongly, being halfway between the node and the ventral sections. When the higher octave sounded one saw a strong response at the two outer capsules, because they were at the nodes of vibration, while the middle capsule did not vibrate at all being at a ventral segment. This instrument cost 30 francs in 1865 and 45 francs in 1882.[98]

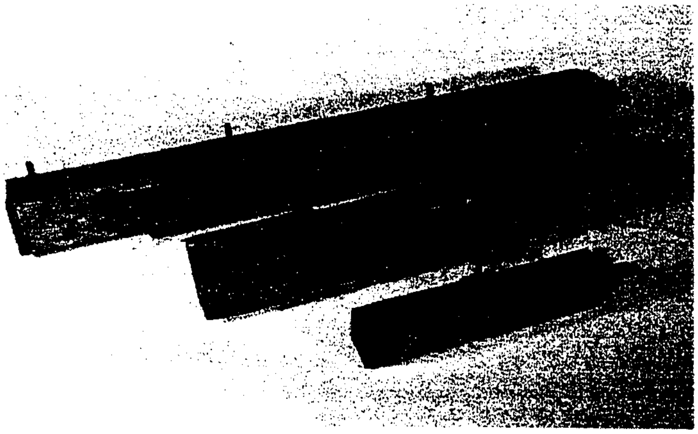

Figure 3.9 Manometric organ pipes, Koenig *Catalogue (1889)* 85. UTMuSI.

This manometric demonstration apparatus derived, like many of Koenig's early instruments, from a clever combination of existing devices. The use of the membrane came from a fairly modest, yet well-known demonstration of Savart showing the existence of nodes in an open-ended

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[96] For a detailed description of Koenig's exhibit see William P. Blake, "Section on Acoustics," in *Reports of the United States Commissioners to the Paris Universal Exposition, 1867*, ed. William P. Blake (Washington: Government Printing Office, 1870).

[97] Koenig, *Catalogue (1865)* 43. Rudolph Koenig, "Ueber ein mittel den wechselnden Dichtigkeitszustand der Luft in tönenden Orgelpfeifen sichtbar darzustellen," *Annalen der Physik und Chemie* 122 (1864c).

organ pipe. A thin membrane, framed by a wooden ring and sprinkled with fine sand, was lowered by a very light string, into a sounding pipe.[99] At various points, depending on the movement of the vibrating air molecules, one heard the sand dancing on the membrane; at other points, it was quiet. In this way the nodes and the ventral segments of the speaking tube were mapped out.[100] Koenig's manometric pipes were intended as an improvement on this demonstration.

The idea of using a gas flame, in place of the sand, came from the recent discovery of something called "the sympathetic flame."[101] In America, the physicist Le Conte first noticed this phenomenon at a musical party in 1857. As a trio by Beethoven was played on a violin, piano, and violoncello, Le Conte noted the rhythmic flickers of a gas burner on a nearby brick wall.

> This phenomenon was very striking to every one in the room, and especially so when the strong notes of the violoncello came in. It was exceedingly interesting to observe how perfectly even the trills of this instrument were reflected on the sheet of flame. *A deaf man might have seen the harmony.*[102]

The sympathetic flame seemed to be a variation on the singing flame, an acoustical phenomenon known since the 1830s, where a jet of gas, usually hydrogen, covered by a tube of glass, emitted a musical note of great force and purity. Faraday, Rayleigh and Tyndall had all tried to explain this mysterious phenomenon. They concluded that it resulted from the periodic, rapid pulsation of gas leaving through the tiny orifice. The bite and release, through friction at the orifice, created unnoticeable bursts of flame that the resonator tube amplified to produce a sound. To prove that the flames were indeed in a state of flux, Tyndall used a twirling mirror that picked up the image of the bouncing flame and projected it onto a dark screen. According to Tyndall, "were the flame silent and steady, we should obtain a continuous band of light: but it quivers, and emits at the same time a deep and powerful note. On twirling the mirror, therefore, we obtain, instead of

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[98] These organ pipes were quite common in physical collections. For a good example, see Turner, *The Practice of Science* 121.

[99] Both Marloye and Koenig sold this instrument. Koenig, *Catalogue, (1859)* 14. Albert Marloye, *Catalogue des Principaux Appareils d'Acoustique et Autres Objets*, 3rd ed. (Paris: Bonaventure et Ducessois, 1851) 41.

[100] For a description of this demonstration, see Zahm, *Sound and Music* 226.

[101] John Le Conte, "On the Influence of Musical Sounds on the Flame of a Jet of Coal-Gas," *Philosophical Magazine* 8, no. 4 (1857).

a continuous band, a luminous chain of images."[103] Tyndall's rotating mirror created a strobe effect, capturing and suspending specific moments in the fluctuations of the flame or spark.[104]

Koenig took this idea of the sensitive flame and the detecting mirror and connected it to a vibrating membrane and a continuous flow of gas. He then connected the manometric capsule to a hole in the side of the organ pipe. The membrane vibrated causing undetectable flickers in the jet flame. The mirror suspended these flickers in order for the eye to see the undulations clearly. In this small but clever contraption, Koenig had taken the sympathetic flame of the concert hall and turned it into a useful, controlled effect for the laboratory. The capsule produced a flame that was responsive to a well-defined sound source (such as an organ pipe or resonator), not the undefined surroundings of a music hall.

Koenig's optical innovations took on new life when he started to question the value of his phonautograph. *Cosmos* reported in May of 1862 that he had verified the most general claim of Helmholtz about timbre (that compound notes contain other harmonics) with "several phonographic tests that we have seen at his place." [105] But he was beginning to question the ability of the phonautograph to represent faithfully the true complexities of timbre. Cosmos reported:

> It is unquestionable that the researches of Helmholtz have opened a sure path from which the timbre of sounds must be engaged. For some time, it was hoped that the phonautograph served to clarify this question; but M. Koenig has arrived, through his experience, at the definitive conviction that the vibrating membranes fitted with styluses will never give anything but the *number of vibrations* of notes...and that it is impossible to receive from them [the phonautograph studies] a profit for studying the *quality* of sound. [106]

Two weeks later Radau explained further that Koenig had one key problem with the use of a membrane for analysing complex vibrations – he believed that the membrane actually favoured certain notes, thereby making it very difficult to assert any claims about amplitude or intensity. For example, one could not adequately claim that the timbre of a certain compound note was due

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[102] Ibid., 473.

[103] John Tyndall, *Sound*, 3rd ed. (New York: D. Appleton and Co., 1896) 250.

[104] As Thomas Greenslade has pointed out, Wheatstone first used the rotating mirror to calculate the velocity of an electric spark across a gap. Thomas B. Greenslade, "The Rotating Mirror," *The Physics Teacher* April (1981).

[105] Radau, "Acoustique."

to the strength of a particular harmonic, if this effect was merely the result of the membrane favouring that tone. We saw that Koenig came to this conclusion after finding in his own series of graphical tests that the membrane favoured certain notes more than others did.[107] These tests derived from a series of tests done in 1860 by two French scientists, Bouget and F. Bernard. They had conducted several experiments on Koenig's improved membranes (using his phonautograph), independent of the ideas of Helmholtz, to test Savart's hypothesis that membranes would *respond to all tones equally*.[108] They found, as Koenig had found, that Savart was wrong and that the phonautograph was not able to represent intensities of sound in a faithful way. After viewing a particular graphical tracing of a complex tone one could not, for example, claim that the octave of a complex note was indeed stronger than the fifth, if the membrane naturally favoured the octave. Based on this major doubt about the functioning of the membrane, Koenig seemed to give up on the phonautograph. It was also quite likely that his troubles with Scott further motivated Koenig to focus on his manometric methods.

That summer, at the London Exposition, Koenig demonstrated his new manometric capsule with organ pipe.[109] Following the introduction of this new device, and in the context of his growing concerns about the phonautograph, he developed a manometric sound analyser, the "apparatus designed to decompose in a visible manner the timbre of sound into its elementary notes by means of manometric flames."[110] Using the analyser, one could gauge the intensity of a harmonic through the brightness of the flame.[111] Koenig believed that the intensity issue that had proven

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[106] Ibid., 624.

[107] Koenig, *Quelques Expériences 23-24,* 28.

[108] Savart had claimed that membranes respond to all harmonics equally, instead of favouring certain notes (revealing a natural frequency of vibration). Bouget and Bernard wanted to test this claim with Koenig's improved membrane and graphical methods. They concluded that membranes did in fact distort the physical reality of tones, and did not, as Savart claimed, respond equally to all tones in the surrounding. François Napoléon Marie Moigno, "Vibrations des membranes," *Cosmos* 17 (1860).

[109] "Class XIII, Philosophical Instruments and Processes Depending on Their Use," in *International Exhibition, 1862. Reports by the Juries on the Subjects in the Thirty-Six Classes into Which the Exhibition Was Divided* (London: William Clowes and Sons, 1862), 33.

[110] Koenig, *Catalogue (1865)* 46.

[111] The most detailed descriptions of these experiments can be found in Rudolph Koenig, "On Manometric Flames," *Philosophical Magazine* 45, no. 297 (1873c): 106.

troublesome for the phonautograph, was not an issue for the capsules which responded to one note only.[112] In addition, the sound analyser offered a much more dramatic optical demonstration of timbre (§2.18).

Koenig quickly found other uses for the manometric capsule. He applied his invention as yet another way to display the relations of musical intervals based on the optical-tuning methods of Lissajous. Instead of using the vibrations of two tuning forks for making comparisons, he used two adjacent pipes connected to manometric capsules.[113] Both pipes rested vertically in a windchest and each had a capsule attached to the middle of the pipe. Each capsule had a rubber gas input tube and an output tube that connected to a stand for the burners, which were placed one on top of the other. A rotating mirror sat adjacent to the stand in order to pick up the signal from the burners. Two Ut3 pipes, for example, displayed identical flame signals. Other combinations dem-

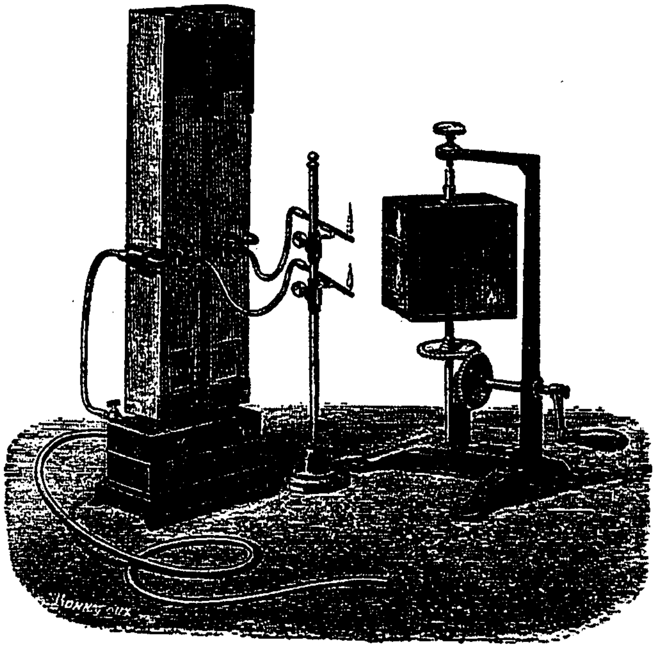

Figure 3.10 Apparatus for compounding and comparing the vibrations of two air columns by the method of manometric flames. Koenig *Catalogue* (1889) 84

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[112] Koenig *Quelques Expériences* 48

[113] Koenig, *Catalogue (1865)* 45.

onstrated the differences between octaves, thirds, fifths, etc. Koenig also built a burner that combined the lines from both pipes. Such a set-up created specific harmonic patterns, for example, the characteristic pattern of an octave, or third, etc. He saw this not only as a good demonstration of basic musical intervals, but as "exceedingly useful for tuning."[114]

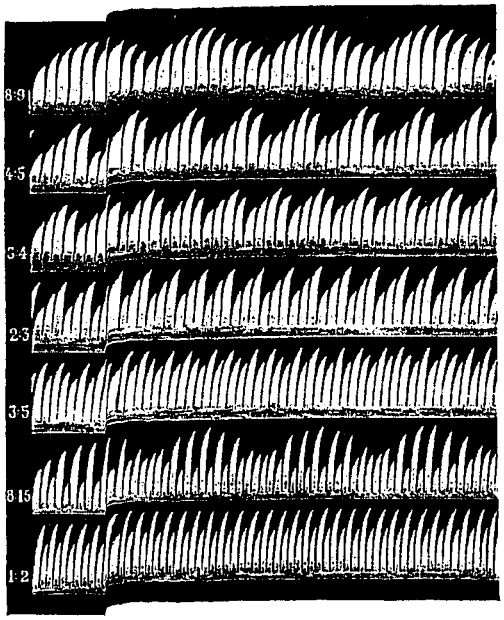

Figure 3.11 Flame patterns from above apparatus. Koenig *Quelques Expériences* (1882) 54.

Related to his musical goals, Koenig invented a simple way to use the capsule for studying violin and vocal sounds that he called a manometric apparatus for the "representation of sounds." This consisted of a small rotating mirror, a capsule attached to a stand and gas input, and a rubber tube connected to either a stethoscope (for pressing against the sounding-post of a violin) or a handheld speaker tube into which one sang vowels or musical notes.[115] With this instrument, he was able to draw and analyse the distinctive flame patterns that came from complex sounds. In the next chapter, we will see the exhaustive and inventive way he used this apparatus in his famous vowel studies.

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[114] Koenig, "On Manometric Flames," 6. Also see Turner, *The Practice of Science* 119.
[115] Koenig, "On Manometric Flames," 13.

The manometric capsule could also effectively demonstrate beats and interference phenomena. Koenig invented what he called his manometric interference apparatus to provide a new optical method for showing and studying these phenomena. A resonator and tuning fork produced a known frequency that was sent along two parallel sets of brass tubing. One of the tubes could be adjusted like a trombone to extend or shorten its length by a measurable amount. The two sound vibrations met in a joined capsule to produce a combined flame signal. If, for example, the waves met when in perfectly opposite phase, they would cancel each other completely and produce an unmoving band of flame. Students at the University of Toronto used it as a "striking" demonstration of interference.[116] It was also used as a precision instrument for measuring the wavelength of certain notes in different gases, and for calculating the velocity of sound. The wave length could be measured quite accurately by slowly adjusting the tubing until it was "visibly" out of phase; at

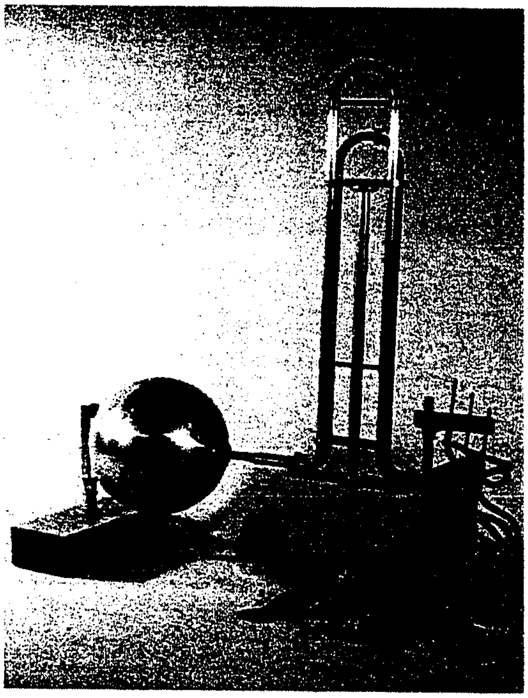

Figure 3.12 Manometric flame interference apparatus, Koenig *Catalogue* (1889) 88. UTMuSI.

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[116] Loudon and McLennan, *A Laboratory Course in Experimental Physics* 128.

such a point the tube had been moved half a wave length.[117] This instrument is currently found in several physics collections.[118] It cost 250 francs in 1882.

3.9 COLLABORATION WITH REGNAULT

> I remember Koenig pointing out to me the door by which he used nightly to enter the sewers to make his solitary way through the swarming rats to the place of experiment.[119]
> (James Loudon)

The last part of Koenig's training as a scientist, the one that formally cemented his positivistic approach to acoustics, came in 1866 when Victor Regnault asked Koenig to join him as a collaborator in his "sewer" experiments in Paris. Since 1862 Regnault had been carrying out an exhaustive series of experiments that would prove to be the definitive set of experiments on the velocity of sound. Regnault, who had taken Savart's place at the Collège de France in 1841, was one of the more revered experimentalists of his age. He had started his career in chemistry (for a short time he trained under Liebig in Germany) but by the 1840s had moved to precision experiments in physics. He became known for his tireless efforts to perfect his methods and control every angle of the experimental conditions, especially sources of error with human origins. He was something of loner, and did not have a team of students, but instead he had "collaborators," who helped him in his demanding projects. At the Collège de France, he had also inherited a world-class collection of laboratory instruments.[120]

Regnault had initially planned to carry out his series of experiments on the speed of sound in 1855. He applied for and was granted a large sum of money from the Academy to undertake these experiments, but he had to wait until 1862 for what he termed "favourable conditions." Those conditions arrived in the form of Haussmann's renovations of Paris, which were carried out be-

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[117] Dayton Clarence Miller, *Laboratory Physics: A Student's Manual for College and Scientific Schools* (Boston: Ginn & Company, 1903).

[118] The University of Toronto, National Museum of American History (Smithsonian Institution) (cat. no. 314,594), Harvard, and the University of Rome. Also see the apparatus at Florence and the Teyler Museum, Anna Giatti and Mara Miniati, eds., *Acoustics and Its Instruments: The Collection of the Istituto Tecnico Toscano* (Firenze: 2001) 95. Turner, *The Practice of Science* 134.

[119] Loudon, "Rudolph Koenig."

[120] Dörries, "Easy Transit," 256. Fox, *The Caloric Theory of Gases* 295-302.

tween 1852 and 1870.[121] The laying of new gas pipes and water lines provided a perfect opportunity for Regnault to make use of long pipes for his experiments on sound. He conducted his experiments in various sewers throughout Paris using seven pipes varying in length from seventy to 4900 meters. Aside from coming up with a new value for the speed of sound at 0 °C in open air (330.7 m/s), Regnault's memoir reporting his experiments serves as a monument to his rigorous and highly inventive experimental method.[122] He did a series of experiments under every possible condition – different-sized pipes, different modes of producing sound, and in different mediums. One of his novel findings was that the velocity of sound increased in small pipes (e.g. those only 11 cm in diameter). In larger pipes, over a meter in diameter, the value reached a limit that was the same as if the waves were traveling in open air.

In an earlier attempt to measure the speed of sound, scientists fired a cannon and compared the light flash (almost instantaneous) with the time it took for the sound to reach them. Regnault eliminated the potential "personal error" in this process, and other methods that had been used, by automating the whole process.[123] In order to carry out these time-measurements, Regnault invented an ingenious instrument using Koenig's tuning fork chronograph in conjunction with a series of electric signals. Regnault's chronograph (as it came to be known after Koenig began making and selling it)[124] consisted of an electromagnetic tuning fork held upright in a heavy rigid frame. A small brass stylus attached to the end of one prong and rested on the roll of smoked pa-

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[121] For more on Baron Haussmann's reshaping of Paris, see David P. Jordan, *Transforming Paris: The Life of Baron Haussmann* (Free Press, 1995).

[122] Victor Regnault, "Experiénces sur la vitesse de propagation des sons," *Mémoires de l'Académie des Sciences de l'institut Impérial de France* 37 (1868).

[123] In his history of acoustics, Koenig describes the earlier attempts by the French scientists, Mersenne, Laplace, Prony, Arago,and Gay-Lussac. Koenig, "Quelques notes." Also see Robert T. Beyer, *Sounds of Our Times: Two Hundred Years of Acoustics* (New York: Springer-Verlag, 1998) 4-7, 33-37. Dayton Clarence Miller, *Anecdotal History of the Science of Sound.* (New York: MacMillan Company, 1935) 65-66.

[124] Koenig, *Catalogue (1873)* 11. McGill University has one of the finest surviving examples of this apparatus on display at Rutherford Hall. Other good examples exist at Case Western Reserve and the Conservatoire National des Arts et Métiers in Paris. The National Museum of American History (Smithsonian Institution) has a sample of this instrument in fairly poor condition, see cat. no. 314, 597.

per drawn continuously by a handle at the rear.[125] With a tuning fork of known vibration one could easily calculate a time by counting the vibrations. Two other styluses rested on the each side of the tuning fork writer; both styluses were hooked up to an electric circuit and run continuously unless their circuit was broken, at which instant a small mark was recorded on the paper. In Regnault's experiments, he attached one of these styluses to a seconds-pendulum in order to calibrate the potential errors of the tuning fork. The other stylus recorded the events under study. A break in the circuit registered the original report (a trumpet blast) and after travelling through a series of reflections in the pipes (to make distances of up to 20 km), the sound wave activated a

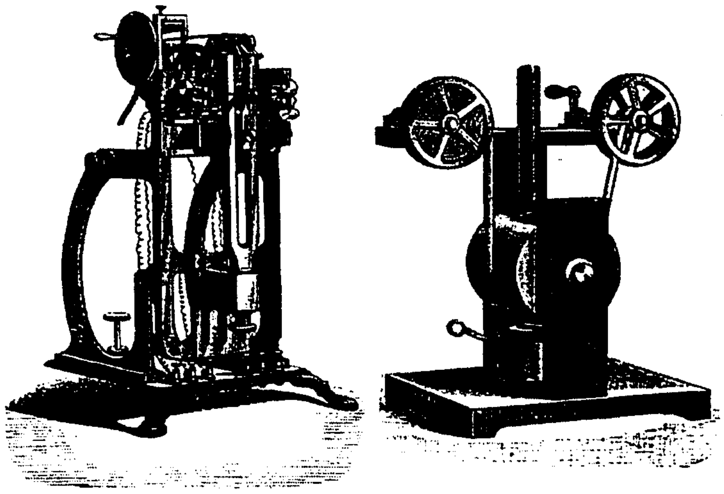

Figure 3.13 Regnault chronograph (left) with a special apparatus to blacken the rolling paper (right). Koenig *Catalogue* (1889) 79.

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[125] The Regnault chronograph at Case has a rather elaborate roller showing that a fair amount of attention was given to this part of the apparatus (for uniform recording). Koenig developed many small features, i.e. adjustment screws connected to the wheelwork, in order to control the smoothness of revolution. These are not found on Regnault's original instrument as illustrated in his memoir. Koenig's model also allowed for the frame to swivel from the perpendicular to the horizontal position. For comparison, see Koenig Catalogue (1889) 79 and the plates in Regnault, "Experiénces sur la vitesse de propagation des sons." Koenig also sold a special instrument that accompanied the Regnault chronograph for making the blackended paper. Koenig, *Catalogue (1889)* 79. The creation of these papers was an art in itself and the subject of a lengthy letter from Koenig to James Loudon at Toronto in 1878. His main concern was that the blackening process run as smoothly as possible so as to have a uniform product. Rudolph Koenig, "Koenig Letters (1878-1901)," in *University of Toronto Archives, Loudon Papers, B72-0031/004*. Case Western Reserve University has a fine example of this blackening apparatus.

membrane that broke the circuit. The chronograph, being connected to the circuit, recorded all of these events on the blackened roller paper.[126]

Koenig's collaboration with Regnault was not limited to the use of one of his instruments. Toward the end of his series of experiments, in 1866, Regnault undertook to measure the velocity of sounds made by musical instruments. In particular, he wanted to know if different sounds of the musical scale had the same velocity of propagation. But he soon encountered insurmountable obstacles. According to Regnault, the main problem was that musical sounds, being composed of a "series of isochronous undulations, whose intensities are unequal," could not be properly registered by the membranes that triggered the telegraphic circuit. For example, it was often the case that a wave of maximum intensity would follow a succession of weaker waves, making it difficult to determine an exact measurement. Regnault tried to overcome this by making adjustments to the membranes and the circuit, and even using Helmholtz resonators to amplify the sound waves, but nothing seemed to work. He was forced to abandon his cherished automatic signal system and get an "attentive observer" to mark the arrival of the waves. "M. Koenig, our skilful constructor of acoustical instruments, eagerly accepted this mission."[127]

These "insurmountable obstacles" are noteworthy, because Regnault's conception of the insensitivity of the instrument derived directly from his Helmholtzian conception of complex sound waves. His use of the resonators revealed clearly that, whatever theoretical commitments he may have harboured, simple tones were a physical reality to be manipulated in the laboratory. This shows another intersection between the ideas of Helmholtz and the Parisian scientific community mediated by one of Koenig's instruments. In this case, the resonators may have helped define Regnault's conception of error.

Koenig's actual role in the experiment became that of the "attentive observer." In the great pipe of the St. Michel sewer system, which was one metre in diameter and 1589.5 metres long, a

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[126] For the development and use of the Regnault chronograph, see Koenig, *Quelques Expériences d'Acoustique* 11-12. Loudon and McLennan, *A Laboratory Course in Experimental Physics* 117-18.

trumpet sounded, causing the membrane to begin the telegraphic signal. Koenig, who was placed at the other end, put his ear to the board covering the pipe and broke the signal when he heard the sound arrive. He did several practice trials to gain as much skill and speed of reflex as possible. Aside from establishing "definitive" results about the differing velocities of high and low notes, Regnault and Koenig concluded form this experiment that the timbre of a sound, being composed of several simple sounds, was not preserved and actually decomposed during propagation in a very long tube.

These experiments were a high point in Koenig's formative career. They would constitute the last part of his unorthodox apprenticeship in Paris. In this latter opportunity, he became fully indoctrinated into Regnault's world of thorough experimentation. His training as a craftsman of sound, his pioneering efforts to create visual methods and his tireless interest in honing instruments and methods became the foundation for several disputes he became involved with very shortly.

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[127] Regnault, "Experiénces sur la vitesse de propagation des sons," 429.

CHAPTER FOUR- DISPUTES

> What many of them learned is that their true love was
> not star watching, but telescope minding[1]

4.1 INTRODUCTION

By 1867 Koenig had developed a distinctive approach to science that eventually brought him into conflict with Helmholtz and other scientists. He had obtained a specialised training as a craftsman of sound that gave him a strong sense of confidence when experimenting. He had spent much of his early career developing visual instruments that shaped his conception of sound phenomena. He developed firm convictions about the limits of theory and the values of experimentation. Above all, he spent his days with instruments. He thought through his instruments, made a living from his instruments, and tried to solve disputes through instruments. Science for Koenig, was in the instruments.

4.2 MODIFICATIONS TO HELMHOLTZ'S VOWEL STUDIES

Koenig's vowel studies constituted his first albeit minor attempt to modify the findings of Helmholtz. They were an indicator that science was practised differently in Koenig's studio: he had the ability to make, improve and invent instruments as his research progressed; he was exceedingly meticulous and thorough as an experimenter; he used visual techniques in a conscious move away from too much reliance on the "expert ear." His vowel studies were the result of over five years of laborious research. Victor Regnault presented the first series of these findings to scientists at a session of the Academy of Sciences in Paris on April 25, 1870. At that time, Koenig claimed to have obtained his results earlier, but he had waited to verify the results with "eminent physiologists, whose support encouraged me to publish them today."[2] As we will see below, he was particularly concerned with obtaining exact figures for the "characteristic pitch" of a vowel (§2.8) and more than once delayed publication to seek further verification.

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[1] Stephen Strauss, "Chile Observatory May Take a Hike," *Canada's Globe and Mail*, Wed. Jan 21, 1998.

[2] Rudolph Koenig, "Sur les notes fixes caractéristiques des diverses voyelles," *Comptes Rendus Hebdomadaires des Seances de l'Académie de Sciences* 70 (1870): 933.

At first Koenig used Helmholtz's tuning fork and resonator method for his experiments on vowels, but he soon asserted what he believed to be his technical superiority in the laboratory by improving upon Helmholtz's original instruments. He agreed with Helmholtz's findings for the vowels A (Si4 flat), O (Si3 flat) and E (Si5 flat), but for "I" and "U", the higher and lower notes respectively, he came up with different results. For the vowel "I," Helmholtz did not have a tuning fork of high enough pitch and had used the "whispering" method of Donders to determine that the characteristic tone to be Re6 (2304 Hz). Through his own experience, Koenig believed that even this tone was not high enough. "By constructing tuning forks higher and higher" Koenig found that Si6 flat (3584 Hz) was the characteristic pitch for the vowel "I," quite a bit higher than Helmholtz's value. For the vowel "U," Helmholtz had resorted to a method in which he sensed a peculiar tickling in his throat at the right note to find the value Fa2. Koenig in an attempt to reduce Helmholtz's findings to a simpler rule, believed that each of the vowels seemed to follow a law of jumping one octave in the note of "Si" or "b" flat, so he hypothesised that "U" or the French "OU" would be characterised by the note Si2 flat.[3] "I verified this hypothesis in a meticulous manner, with the aid of a tuning fork whose pitch could be varied with sliders."[4] These sliders, a recent invention by Koenig, reflected how his instruments were continually developing along side his thinking (and experiments), giving him great flexibility in the laboratory. Unlike other researchers, Koenig did not have to wait for an instrument maker to make him a special instrument.

Koenig transformed these findings into an instrument of five forks and resonators tuned to the five main vowels (see figure 2.7). The first apparatus, which appeared in the 1865 catalogue, was modelled after Helmholtz's figures for the vowels ("U" Fa2, 175 Hz, "O" Si3 flat, 466 Hz, "A"

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[3] Koenig was clearly excited at uncovering and communicating a new law of vowels, a law that separated the characteristic tones by an octave each. He hoped that it would be possible to discover eventually a physiological cause within these simple relationships. Just as one finds the same musical intervals in the music of many peoples, he argued, one finds the same five vowels in different languages. Ibid.

[4] This is the first mentioning of sliding weights on tuning forks. Ibid., 932.

Si4 flat, 932 Hz, "E" Si5, 1976 Hz, and "I" Re6, 2349 Hz). As a result of his research in the late 1860s, Koenig changed these figures to 224, 448, 896, 1792, and 3584 Hz.[5]

In his next round of experiments, Koenig further sought an independent course through the thoroughness of his research and his visual methods. He set out to confirm the above results with an extensive series of vowel studies using his manometric flame technique. He used a funnel-shaped speaking tube, a single manometric capsule and a rotating mirror to create the flame patterns representing specific vowels. Koenig was the first to study the character of each vowel in a wide range of pitch conditions. He was also able to achieve quantitative results from the elaborate figures that he produced, which represented a considerable refinement of the manometric technique. His original intentions had been merely qualitative, to show the "great difference in the appearance of the sound of the five vowels, sung on the same note, as well as to show the manner of the change of the flame-pictures of the same vowel from one note to another."[6] But with some

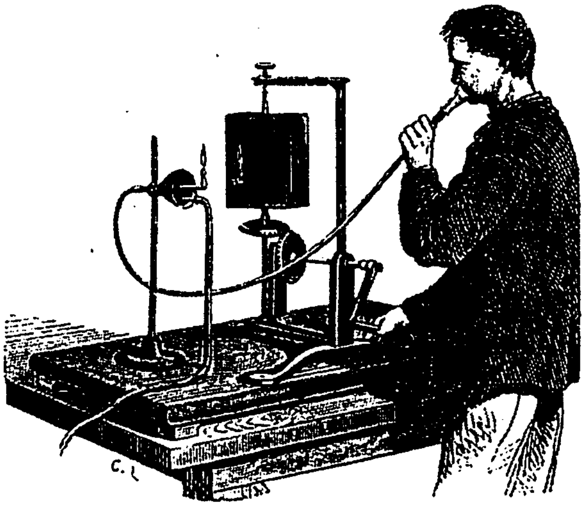

Figure 4.1 Manometric vowel tests. Radau *Acoustique* (1870) 253.

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[5] The actual figures in 1870 were 225 (U), 450 (O), 900 (A), 1800 (E), and 3600 (I). But Koenig switched most of his instruments to the physicist scale at this time making it correspond to Ut3 256 Hz. Rudolph Koenig, "Die manometrischen Flammen," *Annalen der Physik und Chemie* 146 (1872): 179.

[6] Rudolph Koenig, "On Manometric Flames," *Philosophical Magazine* 45, no. 297 (1873c): 12.

clever control experiments, he discovered a means of assigning frequencies to the patterns. He thus produced a thorough confirmation of his earlier work on vowels, and a convenient visual reference to vowels.[7]

Making the manometric flame pictures entailed an elaborate series of control experiments. Koenig took known, controlled phenomena, created by organ pipes and resonant boxes, and used them as standards for comparison. He therefore first studied the patterns produced by simple tones. He then studied combinations of these tones with the apparatus consisting of two manometric organ pipes. From these combination he was able to note distinctive patterns for specific musical intervals, such as a combination of an octave and its lower fundamental, or a third harmonic and a fundamental. From these patterns one could determine the simple tones that combined to form the overall pattern.[8] As a test he studied the patterns emitted by a violin. He placed a rubber hose into the "f" hole and connected a stethoscope to the soundboard and analysed the patterns.

This process enabled Koenig to associate specific combinations of sounds to specific patterns. He sang each vowel in fifteen different notes ranging from Ut1 (64 Hz) to Ut3 (256 Hz).[9] "While I sang into the apparatus, an artist drew the picture which he saw in the mirror. I also drew the same picture independently: and if both our drawings were identical they were looked upon as correct; if, however, there were discrepancies, I repeated the experiment until the error was discovered."[10] Once he had recorded a set of drawings for each vowel he analysed the drawings for the location of characteristic tone. If, for example, he sang the vowel at a particular pitch and observed that the resultant pattern was that of a fundamental combined with a third harmonic, he

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[7] Koenig was quite aware that his pictures appeared in several physical texts, and he complained that some writers had used them without permission. Rudolph Koenig, *Quelques Expériences d'Acoustique* (Paris: A. Lahure, 1882b) 61. Good examples of these drawings appeared in Koenig's article of 1873, his book, and August Zahm's book. Ibid., 53-65. John Augustine Zahm, *Sound and Music* (Chicago: A.C. McClurg & Co., 1900) 352-61. Koenig made many of these pictures as early as 1867, and first exhibited samples of them at the meeting of the Association of Natural Philosophers at Dresden in 1868. Koenig, "On Manometric Flames," 12.

[8] Ibid., 7.

knew that the characteristic tone must be in the range of the third harmonic of the fundamental tone. After going through the whole range of tones, he determined the location of the characteristic frequency for each vowel.

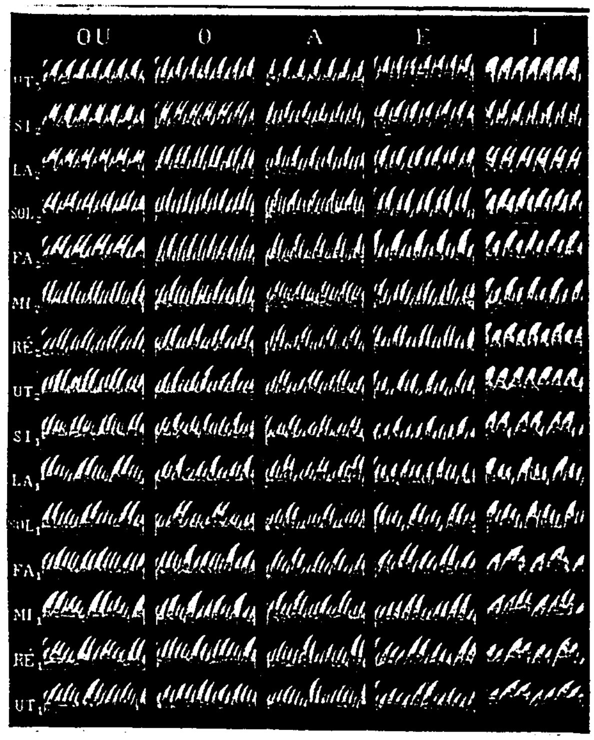

Figure 4.2 Vowel figures from manometric flame studies. Koenig *Quelques* (1882b) 63

Each cell in the above table took an enormous amount of time, skill and concentration.[11] There was the constant positioning and readjustment of the mouth; the effort to maintain the vowels at one steady pitch; and the meticulous observation and drawing of the wave patterns. In fact, it took over five years to complete the whole set of values for publication.

> I delayed their publication until now because I wished to revise them with precision, but was always prevented by the delicate state of my throat, which did not permit me such fatiguing experiments. But now, since I can no longer hope to recover, I have used my best endeavours to make the pictures correct, and give them forth, not indeed as absolutely perfect, but as nearly so as it was possible for me to make them.[12]

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[9] Rudolph Koenig, *Catalogue des Appareils d'Acoustique* (Paris: 1882a) 65-66.

[10] Koenig, "On Manometric Flames," 11.

[11] Part of my appreciation for these experiments derives from my own recreations of the manometric vowel experiments on August 23, 2000 at the University of Toronto Physics Department.

He made large paintings of these drawings for fairs and lectures and displayed a complete set of them at the International Exhibition of London in 1872.

4.3 HELMHOLTZ'S COMBINATION TONES VS KOENIG'S BEAT TONES

As his manometric research was coming to completion, Koenig began to concentrate increasingly on experiments with tuning forks and beats. He believed that Helmholtz had been too hasty in developing his combination-tone theory. Basically, Koenig thought that Helmholtz's original experiments were not reliable and that he had developed unnecessary abstractions in order to explain combination phenomena. Koenig's positivistic attitude became central in the ensuing dispute. He firmly believed that thorough experiments and perfected instruments created a body of evidence that would speak for itself and reveal the rules that govern the so-called combination tones. One outcome of this position was an intense focus on the purity of his instruments. His reliance on visual methods also shaped the debate. He came to think of his graphical representations as a mirror of nature, and this kind of thinking directly influenced his conception of sound and the kinds of instruments he made for further investigations.

It has been discovered in the twentieth century that there are in fact a multiplicity of combination-tone effects created at the sound source, in the transmission medium and in the ear, dependent on several variables that were not well understood in the nineteenth century (and still are not fully understood today), which put all of the experiments described below on an impossibly slippery foundation.[13] I am more interested, however, with *how* Koenig and others dealt with the un-

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[12] Koenig, "On Manometric Flames," 12.

[13] In the late 1890's Sir Arthur W. Rücker and E. Edser created a completely isolated system for detecting some of Helmholtz's combination tones on an objective basis. A.W. Rücker and E. Edser, ***Philosophical Magazine*** 39 (1895). In the late 1910s Erich Waetzmann devised an elegant series experiments that tied together the results of both Koenig and Helmholtz. He created a membrane loaded with a weight on one side, and discovered, after sounding two simple tones near the membrane, that the resultant waveform resembled that of Koenig's beating waveforms, but due to an asymmetrical restoring force, the whole waveform had shifted above the horizontal of the curve. A Fourier analysis of this curve showed a number of combination tones and harmonics. Erich Waetzmann, "Versuch einer Versöhnung der Helmholtzschen Theorie der Kombinationstöne und der R. Königschen der Stosstöne," ***Zeitschrift für Physik*** 1 (1920b). Erich Waetzmann, "Verzerrung von Schwingungen infolge unsymmetrischer Verhälnisse," ***Zeitschrift für Physik*** 1 (1920a). For summaries of Waetzmann's contributions, see Arthur Taber Jones, ***Sound: A Textbook*** (New York: D. Van Nostrand, 1937) 258-61. E. G. Richardson, ***Sound: A Physical Text-Book*** (Lon-

known, than with *what* they knew or did not know. The following is about the choices scientists make when faced with troublesome phenomena.

In December 1875 Koenig published an extensive series of studies on "combination tones."[14] His experience suggested that many of Helmholtz's combination tones simply did not exist and he saw instruments as the key to unravelling the confusion. The reed-pipe harmonium and the double siren that had been used by Helmholtz had in Koenig's opinion too many partial tones or harmonics. These contaminant tones mixed with the fundamental to create unwanted artefacts, or what Helmholtz thought to be combination tones. In the first paragraph of his landmark paper Koenig stated that he had been careful in these experiments to select sources of sound that only produced the simplest possible notes.[15] Later in the article he emphasised again that if "we wish to be sure that we really have to do with combination-notes of simple primary notes, we must set aside both the many-voiced siren and the reed-pipes, and only make use of simple tuning forks."[16] This emphasis by Koenig marked the beginning of an intensive campaign to purify simple-tone production.

A number of the forks used by Koenig for these researches can now be found at the Physics department in the University of Toronto. They represent one of Koenig's most intensive efforts to produce indisputably pure tuning forks. Some came from Paris directly; others came via Philadel-

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don: Edward Arnold, 1953) 60-63. A.B. Wood, *A Textbook of Sound* (London: G. Bell and Sons LTD, 1964) 400-02. For a brief summary of the debate up to Waetzmann, see Deiter Ullman, "Helmhotz-Koenig-Waetzmann und die Natur der Kombinatiöne," *Centaurus* 29 (1986). For developments after Waetzmann, especially those related to physiology, see Edwin G. Boring, *Sensation and Perception in the History of Experimental Psychology* (New York; London: D. Appleton-Century Company, 1942) 352-59.
E.B. Newman, S.S. Stevens, and H. Davis, "Factors in the Production of Aural Harmonics and Combination Tones," *Journal of the Acoustical Society of America* 9 (1937). S.S. Stevens and H. Davis, *Hearing: Its Psychology and Physiology* (New York: Wiley, 1938). Good historical summaries appeared in R. Plomp, "Detectability Threshold for Combination Tones," *Journal of the Acoustical Society of America* 37 (1965). R. Plomp, "Beats and Mistuned Consonances," *Journal of the Acoustical Society of America* 42 (1967). For more recent accounts in physics texts, see Richard E. Berg and David G. Stork, *The Physics of Music*, 2 ed. (Englewood Cliffs, N.J.: Prentice Hall, 1995). Juan G. Roederer, *Introduction to the Physics and Psychophysics of Music*, 2 ed. (New York: Springer-Verlag, 1979).

[14] Rudolph Koenig, "Ueber den Zusammenklang zweier Töne," *Annalen der Physik und Chemie* 157 (1876a).

[15] Rudolph Koenig, "On the Simultaneous Sounding of Two Notes," *Philosophical Magazine* 1, no. 6 (1876c): 417.

phia after the centennial exhibition. There are approximately fifty-six forks ranging from 64 to 4096 Hz (almost the whole range of the piano). Koenig made the branches of the forks extremely thick to ensure that the forks produced fewer "impurities" or needless harmonics. Thinner branches often vibrated like strings, in several modes at once and thus produced several harmonics. The prongs of the lowest fork, for example, are 35 mm in thickness, 55 mm in breadth and 75 cm in length. The higher forks have extremely stout bottoms, which taper near the tops of the branches. Koenig added adjustable brass sliding weights to the larger prongs in order to tune by degree to the note of the next fork. Precision markings on the prongs provide the proper placement for each note. Previously, people working with tuning forks used pellets of wax to change the frequencies. Koenig employed his sliding weights to alter the frequency with great ease and precision. Massive cylindrical brass resonators, over one meter in length and 30 cm in diameter, amplify the weaker low notes. The larger forks are supported before the resonators in heavy cast iron stands. The lowest five forks alone, without their stands and sliding weights, weigh almost 130 kilos.

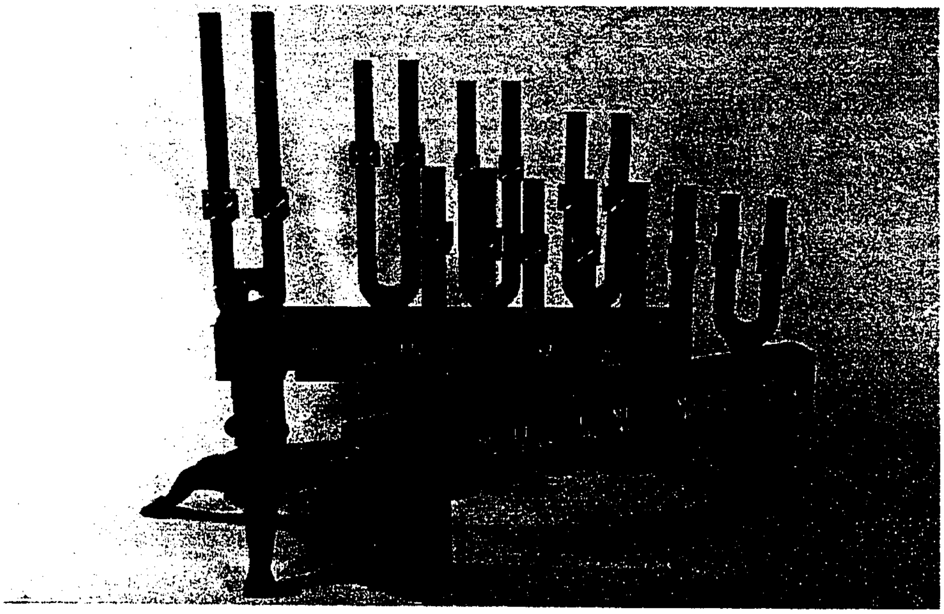

Figure 4.3 Large tuning forks for studying beats and beat tones, circa 1876. UTMuSI

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[16] Ibid., 513.

For a more compact version of these instruments, intended for research and especially demonstrations, Koenig built the "tuning forks of variable pitch." [17] This apparatus consists of two massive tuning forks (128 Hz) in a cast iron stand, each placed before large brass resonators (something like the low forks described above). The forks are driven by an electromagnet. The prong of one of the forks is hollow with mercury inside. An adjustable screw allows one to change "at will" the level of mercury, and therefore, the pitch. Each fork has as well two simple weight mechanisms which are used to alter the phase of the vibrating forks. Lissajous mirrors on the tops of the prongs allow one to make precise phase adjustments. Koenig first showed this apparatus to "several scientists" in 1874. He claimed that it allowed one to conduct Helmholtz's beat and combination-tone experiments with pure, simple tones, while having the capability to make easy, fine-tuned adjustments.[18]

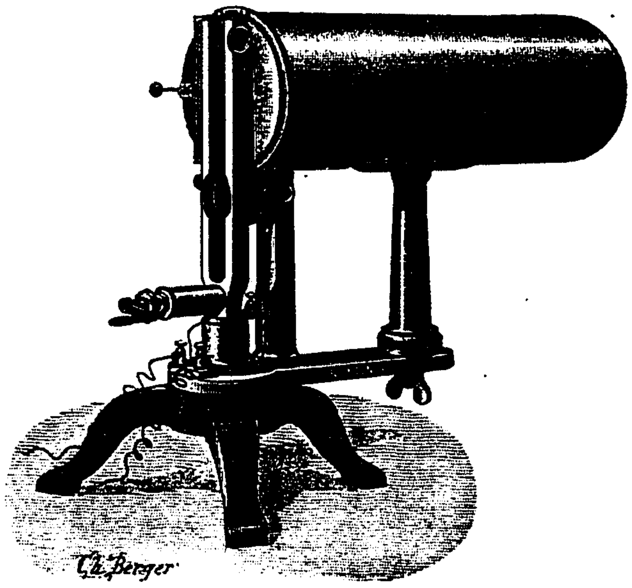

Fig. 94 (h. = $0^{m},55$) (N° 189).

Figure 4.4 Tuning forks with mercury adjustment. Koenig *Catalogue* (1889) 67.

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[17] Koenig, *Quelques Expériences* 84-86. Rudolph Koenig, "Stimmgabel mit veränderlichem Tone," *Annalen der Physik* 157 (1876b).

In his 1876 study, Koenig presented a whole array of data over a large range of notes and developed simple mathematical rules for predicting the behaviour of what he called primary beats. For example, he produced the tones 74 and 40 Hz simultaneously and discovered the appearance of 34 beats per second; this series was called the *inferior beat.* He also claimed, however, that such a combination produced six beats per second, which came from the "negative remainder," since 40 goes into 74 twice with six left over (80 – 74 = 6); this series was called the *superior beat.*

By keeping one note low and extending the other note through several octaves, Koenig discovered levels of quickening and slowing of beats within different *periods.* In these situations he found that the primary beats were always calculated within one octave of each other, so that, for example, the two tones 100 and 512 Hz created two series of beats, 12 and 88. 100 went into 512 five times with 12 left over (inferior beat); 100 went into 512 six times with 88 left over (600 – 512 = 88)(superior beat). Not all of these beats were audible, and Koenig discovered a further rule to describe which set of beats could be heard.[19]

Koenig extended these rules for beats to cover what he called "beat-tones," which often occurred in the same location on the scale as combination tones. The beat tones were simply a rapid succession of beats that blended into a tone. Thomas Young (1773-1829) first made this suggestion and now Koenig believed he had "overthrown" the theory of Helmholtz by re-establishing Young's old theory.[20] For example, Koenig discovered a beat tone of 256 Hz when he struck two forks, 2048 and 2304 Hz. As with the lower frequency forks, there were two sets of beats, the inferior and superior beat tones. In effect, the beat tones were a substitute for the system of com-

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[18] McGill University has a well-preserved example of this apparatus made by Koenig. They probably came to Canada in 1882 when Koenig visited Montreal. The National Museum of American History (cat. No. 327, 654 and 327, 655) and Case Western Reserve both have a set of these forks made by Max Kohl.

[19] The inferior beat was audible when it was less than half of the lowest tone; the superior beat was heard when the inferior beat was greater than half of the lowest tone.

[20] In 1879 John Tyndall recalled that "some years ago, Koenig was ardently engaged on these questions [combination tones]... and he then understood Koenig to be of the opinion that he had overthrown the theory of Helmholtz with regard to combination tones, and established the old theory of Thomas Young." See

bination tones created by Helmholtz. In the first period, the inferior beat (the mathematical difference of the two tones), was identical to Helmholtz's "difference tones." The beat-tones were also capable of creating "secondary" beats when they interacted with other tones, similar to the way that Helmholtz's combination tones could beat with partial tones. The two systems, however, predicted vastly different tones in other areas. Helmholtz predicted summation tones (the mathematical sum of the two prime tones) and several higher-order combination tones based on his combination tones; Koenig predicted superior-beat tones and tones from the higher periods. The apparent contradictions were almost unresolvable by experiment because the disputed tones (on both sides of the debate) were very difficult to hear and confirm.

Koenig argued that Helmholtz's combination tones did not exist, or were at least so weak that they were insignificant. "These combination tones were as little reinforced by the resonators as the beat-tones," he wrote.[21] Beat tones, he stated, could not be detected by resonators either, but they could be proven to exist through graphical diagrams. He pointed out that by studying the

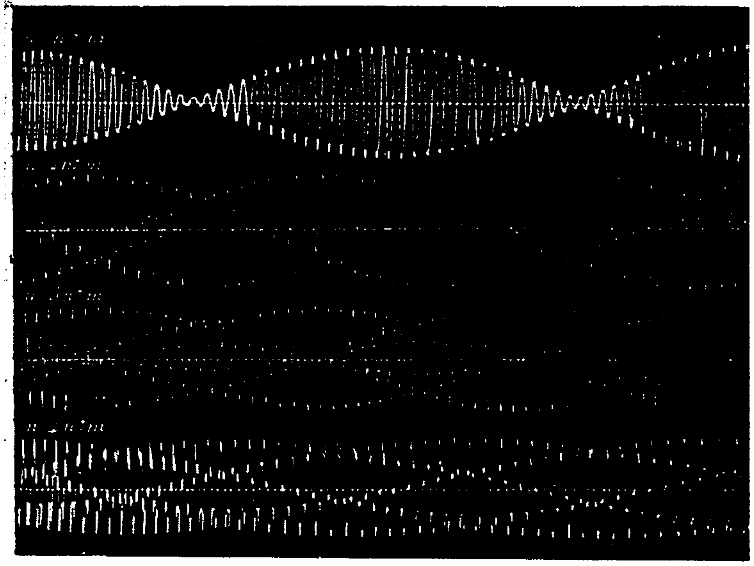

Figure 4.5 Graphical drawings representing beats. Koenig *Quelques* (1882b) 97

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the discussion among members of the British Musical Association in William Spottiswoode, "On Beats and Combination Tones," *Proceedings of the Musical Association* 5 (1879): 125.

drawings of various combinations of tones, one saw the beat patterns in the waves. It was enough to see in the diagrams that the compressions and dilations of beats were not much different from "ordinary sound-waves."[22] Somehow, the ear or the mind detected these changes as beats and beat tones. But being cautious, Koenig left those types of issues for the physiologists and psychologists to resolve (see fn. 13).

In *Sensations*, Helmholtz directly attacked Young's position that beats could become tones. He maintained on theoretical grounds that by definition the ear only hears pendular vibrations of the air, and that beats were strictly speaking not simple pendular motions.[23] Koenig responded by creating "artificial beats," and showing that the ear has the ability to perceive beat tones no matter how they were created. In order to demonstrate this point he stimulated a tuning fork before a rotating disk with holes.[24] No matter what the pitch of the tuning fork, the siren (disk with holes) determined the frequency of the resultant pitch. One did not hear the underlying tuning-fork tone at all, but only the repeating disk pulses that turned into their own beats or beat tones. This was a mechanical way of demonstrating that the ear had the ability to discriminate any kind of periodic motion as a tone.

Koenig took this imitation form of argument one step further. He created a siren disk (with wind bellows) with seven rings of 192 equidistant holes around the circumference. The holes varied periodically from small to large. In one circle, for example, there were twelve maximums, with gradations of smaller holes. Such an arrangement, designed to mimic the maxima of beats in a sound wave, produced the frequency from 192 holes, with a series of beats (or beat tones) from the twelve maxima. In another arrangement, Koenig tried to improve the apparatus by "directly

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[21] Koenig, *Quelques Expériences* 130. In 1882, when Koenig republished his original 1876 article in his book, he hardened his position in a footnote, "I know of no experiment up to the present through which one can prove with some certitude the existence of difference tones and summation tones." Ibid.
[22] Koenig, "On the Simultaneous Sounding of Two Notes," 424.
Koenig, *Quelques Expériences* 98.
[23] See Helmholtz's definitions of beats and simple tones in Hermann Helmholtz, *On the Sensations of Tone as a Physiological Basis for a Theory of Music*, trans. Alexander J. Ellis (New York: Dover Publications, Inc., 1885) 159-73. For a summary of his objections, see Ibid., 533.

imitating" the changes of phase of the individual vibrations, which had not been accounted for in the first disk. Such an arrangement, according to Koenig, produced even more distinct notes.[25]

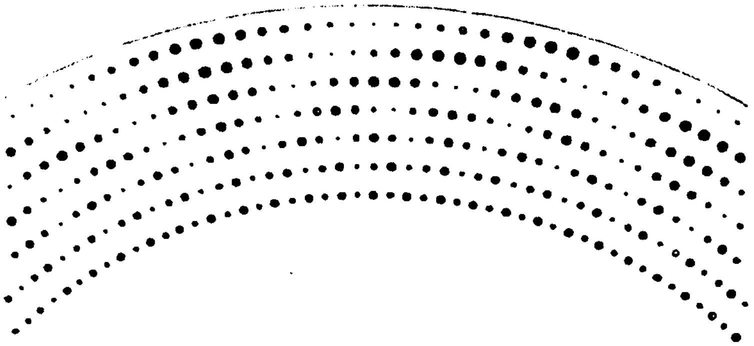

Figure 4.6 Large siren disk for artificially creating tones and beats. Koenig *Catalogue* (1889) 74.

Helmholtz challenged Koenig on experimental grounds, where the debate was now heading. In 1877, by inserting a small addition to the section of *Sensations* that dealt with combination tones, he responded to Koenig's results by doing the same thing Koenig had done to him – he questioned the purity of Koenig's tuning forks. He alleged that Koenig's beats of the upper periods (i.e. 12 beats from the two forks 100 and 512) were actually from upper partials, completely discounting Koenig's claim that his forks were pure. He further added that Koenig should have tried to verify some of these higher partials with resonators, just to demonstrate if they were there or not.[26] Helmholtz's brief comments on the debate, which in the words of Alexander Ellis, were "calculated to give an inadequate impression of the results of Koenig's paper,"[27] produced an astonishing amount of activity on the part of Koenig and other experimenters.

4.4 THE BRITISH RESPONSE TO THE COMBINATION-TONE DISPUTE

Koenig's paper attracted great attention in England. A translation was immediately published in the *Philosophical Magazine* and communicated by his good friend, William Spottiswoode, presi-

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[24] See diagram in Koenig, *Quelques Expériences* 139.
[25] Koenig, "On the Simultaneous Sounding," 523.
Koenig, *Quelques Expériences* 144-45.
[26] Helmholtz, *Sensations* 159.
[27] Ibid.

dent of the Royal Society.[28] In May 1879 Spottiswoode presented his own version of Koenig's results (with demonstrations of his instruments) to the British Musical Association. John Tyndall, Alexander Ellis (translator of *Sensations*), Lord Rayleigh, and the young Oxford physicist, R.H.M. Bosanquet, were all present at this meeting. William Thompson (later Lord Kelvin), who had briefly studied under Victor Regnault in Paris, was also performing experiments at this time based on Koenig's work.[29]

The English scientists realised the potential significance of Koenig's experiments as a major threat to the core fabric of Helmholtz's theories, and subsequently performed their own experiments on combination tones. There was a great spurt of activity around these questions in the period from 1876 to 1883. Bosanquet undertook the most extensive studies in order to verify Koenig's experiments. He presented a series of these experiments to the Musical Association and the Physical Society in the late 1870s and early 1880s. He was particularly interested in testing Helmholtz's claim that some combination tones were "objective." Koenig's results which showed that Helmholtz's combination tones simply did not exist, intrigued him. As a test, Bosanquet designed a new resonator that totally blocked any unwanted sounds from impinging on the ear. He did this by running a tube from the resonating jar into the ear with a special connection. Therefore, if any sounds reached the ear, Bosanquet could say for certain that they were objective, as they had come from the resonator. In the end, his experiments failed to confirm the "objective existence of all forms of beats and beat notes or difference tones."[30]

After much experimenting, however, Bosanquet staked his own ground between Helmholtz and Koenig. He concluded that the first-order beat tones of Koenig and first-order difference

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[28] Koenig, "On the Simultaneous Sounding."

[29] William Thomson, "On Beats of Imperfect Harmonics," *Proceedings of the Royal Society of Edinburgh*, (1877-8).

[30] R. H. M. Bosanquet, "On the Beats of Mistuned Harmonic Consonances," *Proceedings of the Musical Association* 8 (1881-82): 19. For a detailed description of the resonator see R. H. M. Bosanquet, "On a Mode of Producing Continuous Notes from Resonators," *Proceedings of the Musical Association* 6 (1879).

tones of Helmholtz were identical and were indeed *subjective*.[31] He further stated that there were higher-order summation tones and difference tones, and that they too were subjective (produced in the ear).[32] He preserved, however, Helmholtz's idea of summation and difference tones by developing a new theory of how combination tones were created by a process of asymmetrical "transformation" in the ear. This transformation process, based on specific mathematical assumptions about the workings of the inner ear, allowed Bosanquet to discard a series of hypothetical tones (inaudible tones) that Helmholtz had used to fill in gaps for the creation of certain observable combination tones. He believed, therefore, that he was in a better position to explain the existence of the observable combination tones and to discard completely the controversial ones. For those observations which still did not make sense, such as some of the higher-order beat tones heard by Koenig, Bosanquet simply stated, and claimed to verify by experiment, that such tones must have come from undetected and unwanted overtones.[33]

Bosanquet's experiments were not as complete as Koenig's, and his theory was deemed "hazardous,"[34] so the debate continued. There were discussions about the theoretical credibility of Young's "beat tones" – Lord Rayleigh, for example, tried to clarify the mechanical differences between beats and pendular vibrations[35] – but ultimately the debate continued to revolve around the purity of the instruments. During the initial communication by Spottiswoode in May 1879, it was reported by Alexander Ellis that W. Preyer (1841-1897), professor of physiology in the University of Jena, had also done a very careful series of studies on Koenig's results. He concluded that many of Koenig's results were due to harmonics (impurities) in his tuning forks. He claimed that his tuning forks were so sensitive that he had to do his experiments alone at night to prevent unwanted vibration from contaminating the forks. Preyer also concluded (with Bosanquet and

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[31] The word subjective was used loosely in this debate to mean anything that happened in the ear (or mind).
[32] R. H. M. Bosanquet, "On the Beats of Consonances of the Form H : 1," *Philosophical Magazine* 2 (1881): 430.
[33] Ibid., 280.
[34] Helmholtz, *Sensations* 532.
[35] Spottiswoode, "On Beats," 128.

Koenig) that the combination tones (or beat tones) were subjective.[36] It was further reported by Ellis that Koenig's friend in America, professor Mayer had also gone to great lengths to prevent unwanted vibrations in his instruments. He had done his experiments alone at night in an open field several miles out of town, "and then he was disturbed by grasshoppers."[37]

Ultimately, Koenig and Helmholtz formed the two distinctive camps in the dispute. Rayleigh regarded the dispute as "open" as late as 1896. He sided with Helmholtz's attempts to keep a strict definition of simple pendular tones in order to preserve Ohm's law. "Experiment may compel us to abandon this law," he wrote, "but it is well to remember that there is nothing to take its place."[38] Rayleigh was careful, however, not to favour one side too much. "But the observations most difficult of reconciliation with the theory of Helmholtz are those recorded by König, who finds tones, described as beat-tones, not included among the combination-tones: and these observations, coming from so skilful and so well equipped an investigator, must carry great weight."[39]

Another source of trouble for both sides was that many combination tones and beat tones were simply not detectable by resonators, phonautographs or manometric capsules. Competing claims about disputed tones or purity were almost impossible to settle because in these early experiments the results depended almost entirely upon the judgment of the listener. One participant at the early meetings for the Musical Association, Mr. Blaikley, stated that "owing to the great difficulty different observers have of really judging what they do hear, it [the matter of beats] has certainly become confused." He then recounted a story of a visit to Koenig's studio shortly after hearing Spottiswoode's lecture.

> My opinion was rather different to his as regards the extent of purity that existed in the tone of his two large forks. He took a pair of forks, a mistuned octave, and there was a beating note heard. He said to me, "You hear distinctly the octave beating," and I said, "It is the upper fork beating with the second partial of the lower fork." He said, "the second partial does not exist in sufficient strength to be heard." It is just a question of the diffi-

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[36] W. Preyer, *Akustische Untersuchungen* (Jena: 1879). A summary of Preyer's research can be found in the appendix of Helmholtz, *Sensations* 531-32. Alexander Ellis described these experiments to the Musical Association in a discussion following Spottiswoode's presentation. Spottiswoode, "On Beats," 125.

[37] Ibid., 126.

[38] Baron Rayleigh, *The Theory of Sound*, 2 ed. (New York: MacMillan and Co., 1896) 461.

[39] Ibid., 468.

> culty two observers may have, both competent to hear these notes, to observe exactly what does take place.[40]

In order to rise above these kinds of doubts, Koenig's allies buttressed his findings with high rhetoric about his skill as an experimenter. In fact, this appeared to be one of the main reasons why the dispute carried on for so long. In the introduction to his review of the controversy, Alexander Ellis stated that much of the debate had revolved around Koenig's results: "We must distinguish the phenomena from any theoretical explanation of them that may be proposed. The phenomena described by such an acoustician as Koenig, so careful in experiments, so amply provided with the most exact instruments, will, I presume, be generally accepted."[41] One of Koenig's most loyal devotees, S. P. Thompson, told members of the Physical Society of London that Koenig "lives and works in seclusion, surrounded by his instruments, even as our own Faraday lived and worked amongst his electric and magnetic apparatus." Referring to the controversies with which Koenig had become involved, Thompson added:

> It is not surprising that one who lives amongst the instruments of his own creation, and who is familiar with their every detail, should discover amongst their properties things which others whose acquaintance with them is less intimate have either overlooked or only imperfectly discerned. If he has in his researches advanced propositions which contradict, or seem to contradict, the accepted doctrines of the professors of natural philosophy, it is not that he deems himself one whit more able than they to offer mathematical or philosophical explanations of them: it is because, with his unique opportunities of ascertaining the facts by daily observation and usage, he is impelled to state what those facts are, and to propound generalised statements of them, even though those facts and generalised statements differ from those at present commonly received and supposed to be true.[42]

4.5 KOENIG DEFENDS THE PURITY OF HIS INSTRUMENTS

Throughout his career, Koenig responded to any critiques of his work with a full onslaught of new instruments and experiments. He was an extremely sensitive character who was obsessed with correcting any potential weakness in his instruments, methods or results. His writings exhibit

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[40] Bosanquet, "On the Beats of Mistuned," 25.
[41] Helmholtz, *Sensations* 529.
[42] Silvanus P. Thompson, "The Researches of Dr. R. Koenig on the Physical Basis of Musical Sounds," *Nature* 43 (1891): 200.

the tone of someone who has been personally affronted by suggestions that his instruments or methods were not reliable.

It is not a surprise, therefore, that Koenig's next article, submitted to *Annalen der Physik* in September 1880, was an elaborate defence of the purity of his tuning forks.[43] As we saw above (§4.3), Helmholtz had first raised the possibility that Koenig's results derived from undetected upper partials in his experiment. He suggested that Koenig failed to detect these harmonics with resonators.[44] Koenig responded: "The reason for this omission was quite simply that the tuning forks with resonator boxes that I made use of had no harmonics."[45] He then described his experiments that had proven that forks of a certain thickness produced no harmonics.

Debate continued about these unwanted harmonics. Bosanquet argued that Koenig's sound sources were not entirely pure.[46] He also suggested that certain harmonics develop in the air via "transformation."[47] To complicate matters more, Helmholtz proposed that harmonics were sometimes produced in the ear.[48] These harmonics in turn could lead to various combination effects. Koenig, therefore, set out to clarify the question of the source of these harmonics.

In order to prove that the harmonics did not come from his tuning forks, Koenig created a series of experiments to demonstrate that pure tones could excite harmonics in other sources.[49] These experiments implied that, as Helmholtz had suggested, pure tones could stimulate harmonics in the ear.[50] To illustrate how efficiently such a transfer of even the slightest vibrations could work, Koenig recalled that when he had worked with Regnault in 1866, he had discovered that a

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[43] Rudolph Koenig, "Uber den Ursprung der Stösse und Stosstöne bei harmonischen Intervallen," *Annalen der Physik* 12 (1881c).

[44] Helmholtz, *Sensations* 159.

[45] Koenig, *Quelques Expériences* 150.

[46] Bosanquet, "On the Beats of Consonances," 427, 35-36.

[47] Ibid., 280.

[48] The mechanism was the same as for combination tones, a non-linear disturbance, amplitude dependent, from the asymmetry in the inner ear. Helmholtz, *Sensations* 159.

[49] Koenig, *Quelques Expériences* 193-205. "Ueber die Erregung harmonischer Töne durch Schwingungen eines Grundtones," *Annalen der Physik* 11 (1880b).

[50] Studies in the 1930's verified these kinds of harmonics. Newman, Stevens, and Davis, "Factors in the Production of Aural Harmonics." They are know today as "aural harmonics," or harmonics produced in the ear.

tuning fork (Ut2) could excite another tuning fork (Ut2) from a distance of 1590 meters.[51] With this in mind, Koenig did similar experiments between forks and their harmonics, i.e. Ut2 and Ut5, and found indeed that pure tones could excite harmonic tones in other sources.[52] Unlike his previous experiments, he used his precision detection instruments in order to prove that these powerful sympathetic vibrations between fundamental tones and harmonics was not due to harmonics in the first generating tone. He used resonators[53] and a Lissajous comparator[54] to detect the presence of partials. There were none. He used his phonautograph and manometric flames to disprove the hypothesis of Bosanquet that harmonics may be created in the air by a special "transformation."[55] He uncovered no traces of these kinds of sounds. He even developed a clever pendulum device, with two proportionally sized inscription pendulums, that was to mimic the mechanical action of a fundamental vibration stimulating a harmonic motion.[56]

With the purity of his forks demonstrated through these experiments, Koenig agreed with Helmholtz that pure tones could excite harmonics in the ear. At the same time, however, he found that these harmonics did not produce secondary effects, such as beats and beat-tones (something that Helmholtz had implied).[57] They did not produce the kind of beats that Koenig would have expected according to his previous observations.[58]

Another criticism people made about Koenig's beat-tone experiments was that the beat-tones were quite difficult to hear, or the sounds from the tuning forks had a short duration. This made it difficult to demonstrate beat tones before large audiences. In 1881, in the midst of his work on combination tones, Koenig addressed this concern with a new invention for demonstrating

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[51] Koenig, *Quelques Expériences* 194.

[52] Ibid., 194-95.

[53] Koenig used "all known methods of observation" to prove that the vibrations of the fork were "simple pendular vibrations." Ibid., 201. He mentioned using the resonators in an article that came out in 1881. Ibid., 152.

[54] Ibid., 199.

[55] Ibid.

[56] Ibid., 201-05.

[57] Helmholtz, *Sensations* 159.

"strong and persistent" combination tones and interference phenomena.[59] This instrument was composed of two tuned glass tubes, a tall iron frame, and a wheel covered with felt that made contact with the glass tubes. The friction of a clothed wheel as it rubbed against the rods caused the emission of powerful and pure simple tones via longitudinal vibrations. These pure, powerful simple tones were played simultaneously giving strong combination tones (beat tones). As with other teaching instruments of Koenig, this instrument served as a source of information on the

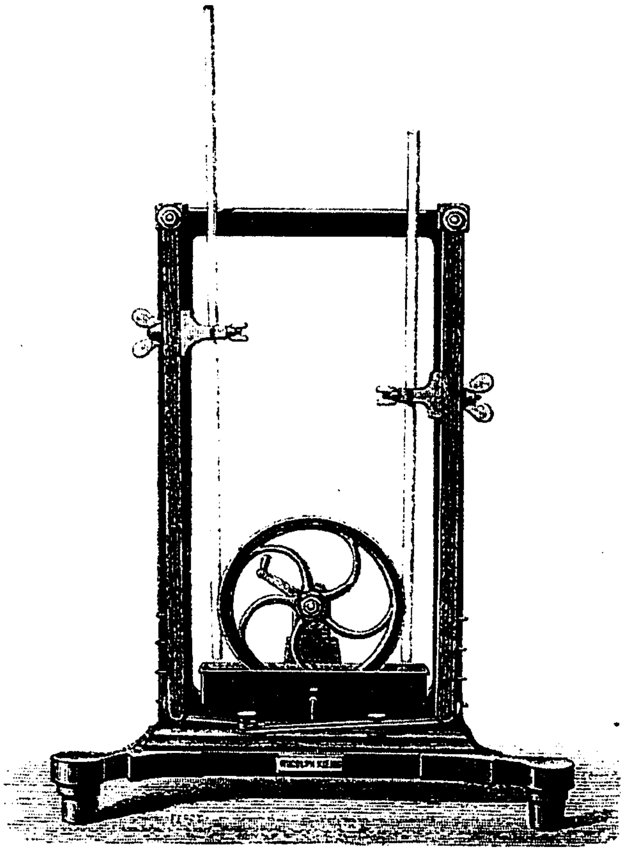

Figure 4.7 Apparatus for producing beats and beat tones from glass rods. Koenig *Catalogue* (1889) 71.

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[58] Koenig had made specific observations on the nature of beats in his first study of 1876, see Koenig, *Quelques Expériences* 99. During his observation with single, external sound producers, he did not observe these customary beat effects attributed to the simultaneous sounding of two tones. Ibid., 153-54.
[59] Ibid., 163.

mechanics behind the combination tones, no matter which side of the debate one took. Pictures of this instrument are found in several textbooks of the time, attesting to its pedagogical appeal.[60]

Frustrated by his inability to stifle criticism related to the purity of his tuning forks, by 1881 Koenig developed a totally new instrument to prove his arguments. In one of his last experiments in 1875, he had used the modified siren disks to artificially create beats and beat-tones.[61] In 1881 he went one step beyond this by creating a device that directly imitated the sound wave, the wave siren.[62] We saw in §2.14 how Koenig had actually invented this form of apparatus in the midst of his timbre research in the late 1860's, but the instrument now took on a radical new use.[63] He cut the edge of a siren disk in the exact shape of a waveform that had been produced by two combined, pure tones. In one of the first examples, he used a waveform that combined 120 simple sinusoidal waves with 64 waves, which together formed a slightly mistuned major seventh (ratio 8:15).[64] The combined waveform ran the circumference of the disk. For comparisons of the simple components, Koenig created two concentric rings of 120 and 64 holes. If these holes sounded at one revolution a second, 8 beats would result (the superior beat frequency being 128 minus 120). Koenig added a series of eight holes in the interior of the disk to represent this beat figure. A wind stream activated the first series of holes producing a tone corresponding to the series of 64. A second jet activated the tone of 120. Koenig then activated the wave component that resulted in the sound of the combined notes, and a slow series of beats. When the disk increased in speed, these beats blended into a beat-tone. Then the series of eight holes were played for com-

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[60] A well-preserved example of this instrument (almost a meter in height) can be found at the *Gabinete de Física Experimental* at the University of Coimbra, Portugal. A smaller version made by a Parisian competitor of Koenig, Lancelot, can be found at the Conservatoire National des Arts et Métiers in Paris. For Koenig's images, see Rudolph Koenig, "Beschreibung eines Stosstöneapparates für Vorlesungsversuche," *Annalen der Physik* 12 (1881d): 164. Koenig, *Catalogue, (1882)* 23.
Koenig, *Quelques Expériences d'Acoustique* 165. Textbook images are found in A. Winkelmann, *Handbuch der Physik: Akustik*, vol. 2 (Leipzig: Johann Ambrosius Barth, 1909) 626. Zahm, *Sound and Music* 329.

[61] Koenig, *Quelques Expériences* 142-46.

[62] Ibid., 157-62.

[63] Ibid., 157.

[64] Ibid., 158.

parison, and it resulted in the same tone. Koenig had recreated a beat-tone from an artificial metal waveform.

Koenig made another version of the siren with eight different waveforms (eight different intervals) cut from bands of copper.[65] The waves wrapped around a rotating, vertical axis with one wind slit for the pressured air. A rotating siren disk (with holes) on the top of the apparatus produced tones for comparison. Koenig called it his "grand wave siren for the sound of beats," and it stood almost 75 cm in height.

There were criticisms raised that the vibrations of the air did not correspond to the curves of the copper waveforms. Some suggested that when the wind-slit was not infinitely small, nor with a perfectly constant wind pressure, that unwanted harmonics appeared.[66] Koenig agreed but said the distortions would be very weak, "because I could not establish them by means of a direct analysis with resonators."[67] To prove further that the resultant beats and beat-tones did not come about from unwanted harmonics, Koenig applied a trick he had discovered by accident. When he twisted the wind-slit so that it faced the copper wave at a slight inclination from the vertical, he found that the simple tone became more strong and shrill, and at a further angle produced the rich timbre of a "reed pipe."[68] If the beats were caused by the harmonics, Koenig argued, when one twisted the wind-slit, the beat-tones or beats would simply strengthen as the harmonics strength-

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[65] Koenig, *Catalogue (1882)* 160. Rudolph Koenig, *Catalogue des Appareils d'Acoustique* (Paris: 1889) 74-75. Koenig, "Ueber die Erregung harmonischer Töne," 347.

[66] Koenig, *Catalogue (1882)* 159-60.

[67] Ibid., 160.

[68] Koenig developed a simple apparatus to demonstrate this point. Ibid., 10. Koenig, *Catalogue (1889)* 29-30. Koenig, *Quelques Expériences* 161, 241. His catalogue description reads, "In blowing against this sinusoid with the slit in the radial position, one obtains a simple tone; by inclining the slit in the direction of the rotation of the disk, the simple sound transforms into a timbre made up of its fundamental accompanied by a series of harmonics of decreasing intensity with a phase difference." An example of this instrument, originally from Amherst College, can be found at the National Museum of American History, Smithsonian Institution, cat. no. 328742. Steven Turner, Roger Sherman and David Pantalony demonstrated this instrument on August 25, 1999. There was a slight change (more raucous) in the overall sound upon rotation of the slit, but this change is difficult to characterise.

ened. But in actuality, he concluded, the intensity of the beat-tones seemed to diminish a little, meaning that the beat-tone effect must have come from the waveform, and not from impurities.[69]

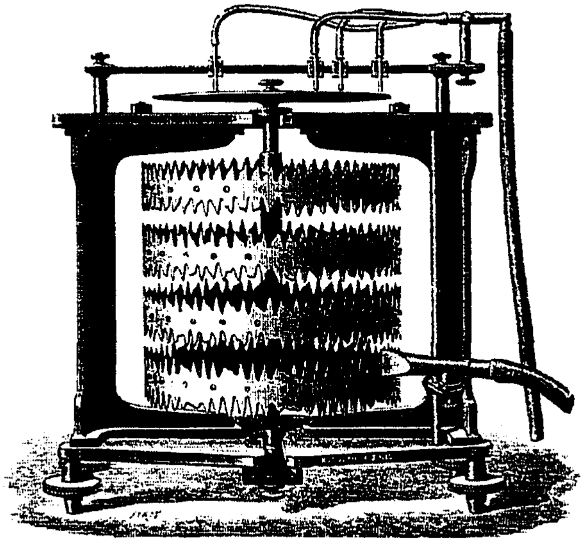

Figure 4.8 Grand wave siren for studying beats. Koenig *Catalogue* (1889) 75.

4.7 PRECISION AND THE CLOCKFORK

Disputes for Koenig were ultimately about instruments and not necessarily about theory. He treated his instruments like works of art. The beauty was not just in their appearance, but in the way they reflected years of disciplined (but pleasurable) labour and the unrelenting thoroughness of his experimental imagination. He therefore took any criticism of them very seriously. During the period of his intensive work on the combination-tone dispute, Koenig's whole life and identity became intertwined with tuning forks. He had spent a number of years purifying his forks, and he had spent even more time creating his masterpiece, the tonometer of 670 forks. He had contributed more than anyone else to transforming the tuning fork into a reliable instrument for scientists. It therefore came as a great surprise in 1877 when Alexander Ellis, who had been doing extensive studies on standard pitch throughout Europe, publicly questioned the reliability of the pitch number for Koenig's standard fork. Koenig responded by inventing an improved method for

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[69] Ibid., 162.

tuning or creating tuning forks with unparalleled precision. Such a development had no small impact on acoustics, music and other areas of physics. For the next fifty years, the tuning fork became the standard carrier of frequency for music, electrical studies and timing apparatus.[70]

In the 1870s Alexander Ellis had undertaken an intensive study on the standardisation of pitch.[71] For most of his early tests, Ellis used a tonometer of reed pipes made by Georg Appunn, an instrument maker in Hanau, Germany. In an article on standard pitch in *Nature* Ellis announced that he used Appunn's tonometer to measure Koenig's standard fork of La3 (435 Hz) which produced a figure of 439 Hz.[72] Koenig responded immediately charging that Ellis had attacked the exactitude of the French tuning fork with "too great a haste," too easily ignoring the work of others – Lissajous, Helmholtz, Despretz and Mayer – who had confirmed its accuracy. He quoted an earlier letter from Helmholtz to Appunn in which Helmholtz had praised the reed tonometer of Appunn, and using this instrument (the same one Ellis used), specifically found the French standard fork to be 435.01 Hz.[73] Koenig turned out to be correct. After further investigation, Ellis discovered that there had been a constant drift in the frequencies of his reed pipes and in 1880 he retracted his claim. "I feel I owe an apology to Herr Koenig, for my having been unfortunately misled by the unknown error of Appunn's instrument to attribute that error to him, and I make this apology most sincerely, for no one deserves more thanks from acousticians than Herr Koenig, both for the excellence of his worksmanship, and the ingenuity of his contrivances."[74]

But the apology came too late. In the midst of his work on combination tones and the role of phase in timbre, Koenig set time aside to make his tuning forks of a precision that was beyond

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[70] See the comments in Wood, *A Textbook of Sound* 121-22.

[71] For a history of the standardisation of pitch in Europe, see Alexander J. Ellis, "On the History of Musical Pitch: A Paper Read before the Society of Arts, 3 March 1880," in *Studies in the History of Musical Pitch: Monographs by Alexander J. Ellis and Arthur Mendel*, ed. Arthur Mendel (Amsterdam: Frits Knuf, 1968). Helmholtz, *Sensations* 493-513.

[72] Alexander J. Ellis, "Koenig's Tuning-Forks and the French Diapason Normal," *Nature* 16 (1877).

[73] Helmholtz's letters had been published by Appunn in an advertisement in his catalogue. Rudolph Koenig, "Koenig's Tuning Forks," *Nature* 16 (1877).

criticism. By 1879, after twenty years of experience making tuning forks, Koenig started a series of experiments that would lead to groundbreaking findings of the properties of tuning forks, the invention of the most precise instrument to date for determining pitch, and the creation of a new international standard tuning fork (the first since Lissajous's in 1859).

In the summer of 1879 Koenig started experimenting with a new instrument for determining pitch called the clock-fork which yielded the most precise determination of pitch to date. In this instrument Koenig attached a tuning fork of *approximately* 128 v.s. to the escapement of a clock that registered 128 vibrations for each second on the clock. One hour on the clock-fork, therefore, corresponded to 460,800 single vibrations. This number was compared to the hour registered on an actual chronometer, and the number of vibrations in a real (chronometer) second could be calculated. If, for example, the tuning fork was exactly 128 v.s., then the clock-fork and the chronometer would agree. If the fork was actually a little higher, for example, 129 v.s., then the time

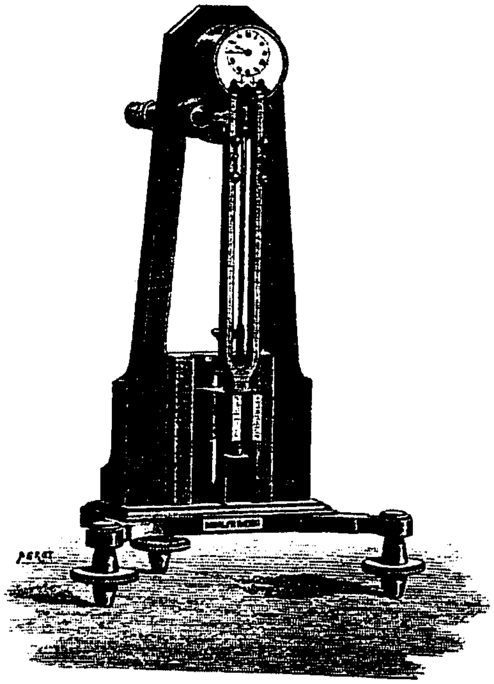

Figure 4.9 Clockfork with clock mechanism, tuning fork and Lissajous objective lens. Koenig *Catalogue* (1889) 19.

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[74] Ellis, "On the History of Musical Pitch," 19.

on the clock-fork would read a tiny bit faster than the chronometer. Koenig attached special micrometer screws to the fork prongs in order to adjust the frequency. In this way, the fork could be adjusted until it was at the exact pitch of 128 v.s. After setting this standard by using comparisons with the chronometer, Koenig attached a Lissajous microscope to one prong and a steel mirror to the other in order to use the calibrated fork as a standard for tuning. In this way he used the famous Lissajous optical method to tune other forks. Koenig stated that this apparatus was not only remarkable for its "extraordinary precision" but also because it could be operated with "little complication or difficult manipulation."[75] It was almost completely automatic and thus free of human error.

Koenig studied his tuning forks, isolating the key variables that affected its pitch, and then analysing every aspect of those variables. Temperature was revealed as one of the key variables in his study. At the start of his business twenty years earlier, Koenig had made a standard fork of 512 v.s. (Ut3) "without indication of temperature."[76] He discovered in the course of further research that this standard was likely a fraction above 512 v.s. at 20 ° C, (heat decreased the rate of vibration, whereas cold increased the rate). Researchers, according to Koenig, almost never worked at the temperature at which the fork was made, so it was necessary to develop a way of knowing with certainty the variation in rate of a tuning fork for each degree of temperature change. He first placed a thermometer between the branches of the tuning fork so that the reservoir reached down to the heel of the fork (where the influence of heat was at a maximum and the movement of the fork at a minimum). He then performed a series of control tests. He calculated the time required for tuning forks to adjust their internal temperature to their surroundings. He discovered, for example, that it took on average of forty-five minutes for a fork to recover its natural vibrations after being held in a warm hand. In another trial it took over four hours for the

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[75] Koenig, *Quelques Expériences* 173.
[76] Ibid., 172.

fork to recover from a slight drop in temperature over night.[77] He studied the effects of prolonged use of the fork (and therefore, its internal rise in temperature) and discovered that he could only run an experiment for approximately eight and a half hours before the internal temperature of the steel changed significantly due to overusing the fork.[78] He even studied the influence of the resonator cases on vibrations of a tuning fork discovered that resonators that were a bit off the intended frequency prolonged the vibrations of the fork (eighty to ninety seconds), and at the same time, altered its frequency.[79] On a related point, he found that resonators which were exactly in tune with the forks, caused the forks to vibrate for only ten seconds at times, making it difficult to do comparisons. He therefore had to find the right balance that would allow the fork to vibrate for a long period so as to compare it to the clock-fork using beats or Lissajous figures, but which did not alter the pitch significantly.

Koenig's thoroughness was also expressed through his efforts to control the conditions of his experiments. The caves of subterranean Paris had the most constant temperature, but turned out to be too cold at 12 ° C.[80] He therefore used a room with high ceilings, shut on all sides, in which the temperature varied slightly "especially during overcast and sombre days, that there had been a lot of during the year 1879 in Paris."[81] Koenig also developed an oven that was manually regulated to adjust temperature. Using this appliance, he was able to extend his tests into higher temperatures, to determine whether the vibrations of the forks changed at different rates for these temperatures. He performed a series of tests on forks of the same tone but with different shapes and thickness.[82]

From all of these studies Koenig gained a remarkable control of the experimental variables and was thus able to determine with greater certainty that for temperatures under 50 ° C a change

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[77] Ibid., 176.
[78] Ibid., 177-78.
[79] Ibid., 180-82.
[80] Ibid., 177.
[81] Ibid.
[82] Ibid., 187.

in temperature of 1 ° C resulted in a change of 0.0143 v.s. for the fork Ut1 (128 v.s.), and 0.0572 per 1 ° C for his Ut3 fork (512 v.s.).[83] In total he conducted 300 to 400 experiments between July and December 1879.[84]

Koenig now had at his disposal a highly precise instrument and combination of techniques for re-evaluating the previous standards. He started with his own Ut3 fork from 1859. He used the method of beats to obtain the exact number of vibrations that the old standard differed from the true Ut3, which had been created using the clock-fork. He found that the old Ut3 was actually 512.3548 v.s. at 20 ° C.[85] Using his conversion figures, Koenig calculated that the old standard would be 512 v.s. at 26.2 ° C. In order to avoid these calculations in the future he added a small weight-calibrated adjustment device to the prong that allowed the fork to be set at 512 v.s. for any temperature.[86] He then verified these results by placing his old standard fork, equipped with Lissajous mirrors, in his oven and watched as the heated fork came into unison with the new standard. This occurred between 6 and 6.5 ° C, roughly the within range of his calculation. Ellis, who had done several experiments (with his tonometer) to determine the pitch number of Koenig's standard fork of 1859, came up with a very similar figure for the old standard.[87] By 1880 Ellis stated that with the clock-fork Koenig had made it possible to measure changes of vibration "absolutely inappreciable by ordinary methods of observation."[88]

The pinnacle of Koenig's achievement was that he was now able to examine the actual French Standard that had been made by Lissajous in 1859.[89] Through a combination of trials he

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[83] Ibid., 189.
[84] Ibid., 182.
[85] Ibid., 189.
[86] Ibid., 189-90.
[87] Ellis, "On the History of Musical Pitch," 61.
[88] Ibid., 60.
[89] The Lissajous standard fork remains in storage at the Musée de la Musique in Paris. The fork is gilded and marked "Secretan, Paris." It is 5 cm from the top of the prongs to the stem of the fork. It rests upside down, in a wooden frame, connected to a pine resonator box. The whole apparatus is 46 cm in height. The base of the frame reads, "Diapason Normal, 870 vibrations par seconde, à la température de 15° C, Arrêté Ministériel, en date du 16 Février, 1859. Sons Excellence, Monsieur Achille Fould, Ministre d'Etat." There are two piano keys on either side of the two prongs with felt hammers. One reads, "Etouffoir," (dampener) the other reads "Marteau," (hammer).

developed a fork that was exactly 870 v.s. at 15 °C (what the standard was supposed to be). He then went to the Conservatory of Music and deposited this fork beside Lissajous's fork for two days to equalise their temperatures. Using the method of beats he found that Lissajous's fork was actually 870.9 v.s. (or 435.45 Hz) at 15° C.[90] But he could not determine the number more precisely because the fork vibrated for only twenty seconds making optical comparisons difficult.

Koenig's work on the tuning fork had a considerable impact on acoustics, music and physics. The clock-fork appeared in his catalogues of 1882 and 1889 at a cost of 2000 francs.[91] To emphasise its prominence, he put a picture of it on the cover of his catalogue in 1889. His clock-fork brought the standard of the physicist's scale, Ut3 (256 Hz) and the French standard for musicians, La3 (435 Hz) to many institutions throughout the world. The premium standard forks were gilded to prevent rust and came with a brass resonator and stand.[92] Some of them came equipped with a small dial on one of the prongs to be used to adjust the pitch for varying temperature, between 5 and 35° C.[93] Koenig delivered clock-forks and standards to institutions in Italy, Russia, Austria, Canada, the United States and Germany.[94]

Although Koenig had created the means to resolve technical issues surrounding standards, by 1888 there was still a heated debate about what standard(s) to adopt. There were many standards and traditions even within single countries. Koenig proposed the adoption of two standards, one for physics (Ut3, 512 v.s.) and one for music (La3, 870 v.s.). Both standards, he argued, were

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[90] Koenig, *Quelques Expériences* 190-91.

[91] The clock-fork apparatus measured 65 cm in height. Koenig, *Catalogue, (1882)* 6.
Koenig, *Catalogue (1889)* 19. For more on the uses of this instrument, see W.J. Loudon and J.C. McLennan, *A Laboratory Course in Experimental Physics* (New York, London: MacMillam and Co., 1895) 118-20. Dayton Clarence Miller, *The Science of Musical Sounds* (New York: MacMillan, 1916) 38-42. Winkelmann, *Handbuch der Physik: Akustik* 190.

[92] The Museo di Fisica at the University of Rome has a set of gilded Koenig standard forks with the royal stamp on them. There are two forks marked "RK, La3 (870 v.s.) at 20 °C." One is for 15 ° C. They rest on a cast iron stand with a brass resonator. Italy used Koenig's standard forks to establish a standard pitch by order of King Umberto I, October 30, 1887.

[93] The Museo di Fisica at the University of Rome has three such Koenig forks with brass resonators on a cast iron tripod stand: Ut3 (512 v.s.), La3 (870 v.s.) and Si3 (921.7 v.s.) each with aluminum dials on one of the prongs graduated from 5 to 35 °C. These forks can be found in Koenig's catalogue, Koenig, *Catalogue (1889)* 19-20.

close enough to each other that adopting them simultaneously would not cause any undue confusion.[95] Although not a big player at the conferences on standards,[96] Koenig became influential in this debate by transmitting his methods and standards throughout the world. In Italy, the King officially adopted Koenig's standard.[97] In the United States D.C. Miller at Case School provided a "tuning" service to companies and institutions around the country. In effect, Miller's operation "tuned" America well into the twentieth century. Among others, he certified forks for Steinway and Sons and the scientific instrument maker, William Gaertner and Company.[98] He used Koenig's forks and a copy of Koenig's clock-fork by Max Kohl of Germany.[99]

Koenig's new forks also had a large impact on the practice of science, especially as electrical and timing standards. Between 1882 and 1884 Albert A. Michelson (1852-1931) used a Koenig tuning fork to determine the speed of a revolving mirror through a comparison with a standard clock, as part of his experiments to measure the velocity of light. Although these experiments did not relate directly to acoustics, Michelson, an avid musician, had a keen interest in Koenig's instruments and saw the potential of his new precision forks as a standard frequency.[100]

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[94] See November 7, 1888. Rudolph Koenig, "Koenig Letters (1878-1901)," in *University of Toronto Archives, Loudon Papers, B72-0031/004.*

[95] See November 7, 1888. Ibid.

[96] In a letter to Loudon, Koenig ridiculed the International Congress of Standards at Vienna in 1885: "I could not stop myself from finding it quite amusing and perfectly ridiculous the explosion of enthusiasm and warm congratulations on the importance of their work, those who were at the end of the session gratifying each other." Ibid.

[97] Information and instruments related to the standardisation of pitch in Italy can be found at the Museo di Fisica at the University of Rome.

[98] The D.C. Miller papers, Case Western Reserve Archives. One such certificate from July 1, 1927 reads: "Certificate of Accuracy of a Tuning Fork. Submitted by Steinway and Sons, of New York.... Frequency of the Fork. – This fork has been accurately adjusted in the Physical Laboratory of Case School of Applied Science to its nominal frequency, the absolute frequency being determined directly from the Riefler Standard Clock, No. 89, by the method of optical comparison with a Koenig Clock-Fork. (See Miller: The Science of Musical Sounds, Pages 38-42.) The calibration was carried out in the constant temperature clock-room. The exact temperature of the fork was observed at each measurement, and the observations have all been reduced to the standard temperature coefficient, - 0.00011, (Annalen der Physik, 9, 408 (1880). The final determinations show: FREQUENCY OF FORK NO. 3, C=261.620 at 20 ° C (68 °F)."

[99] This clock-fork can be found on display at the Physics Department at Case Western Reserve University. It is nearly identical to Koenig's model. The frame is 70 cm in height, the middle fork is 37 cm long. The thermometer is missing.

[100] Dayton Clarence Miller, *Anecdotal History of the Science of Sound.* (New York: MacMillan Company, 1935) 75.

4.7 TIMBRE AND THE REALITY OF WAVEFORMS

Alexander Graham Bell's invention of the telephone in 1876 sparked a dispute on the nature of timbre that would get tied into the combination-tone debate and have a large influence on the rest of Koenig's career. After the introduction of the telephone, Helmholtz's colleague, Emil du Bois-Reymond, used the new invention as a way of illustrating the nature of timbre.[101] He claimed that the partial tones of a complex sound travelled through the wires as electrical vibrations and maintained their amplitude and frequency. There was a slight phase displacement, but the timbre remained the same. The Königsberg physiologist, Ludimar Hermann, set out immediately to test this theory with an experimental current-producing telephone. Based on the arrangement of the coils, and taking account of the laws of electro-dynamic induction, Hermann hypothesised that *there were* amplitude changes of the partial tones, but he found that the quality of sound remained the same. He concluded that these results were incompatible with Helmholtz's theory of timbre (where amplitude changes should change timbre). Helmholtz responded with a lecture in 1878 showing that Hermann had neglected to take into account the properties of the entire circuit he was using; he further concluded that the differences of phase were negligible.[102] Koenig replied with his own article in 1879. Reflecting on the debate between Helmholtz and Hermann, Koenig thought it was "important to offer an experimental method that permitted exact verification" of the supposed phase changes[103] He constructed a telephone that operated with tuning forks in order to transmit simple tones of different frequencies. He compared the phase of the input frequency with the outcoming frequency using the Lissajous method and found there to be a sizeable displacement of phase (1/4).[104]

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[101] Leo Koenigsberger, *Hermann von Helmholtz*, trans. Frances A. Welby (New York: Dover Publications, Inc., 1965; reprint, 1906) 313.

[102] Hermann Helmholtz, "Telephones et timbre," *Journal de Physique* 8 (1879). For a brief review of this initial dispute, see Koenigsberger, *Hermann von Helmholtz* 313-14.

[103] Rudolph Koenig, "Reserches sur la différence de phase qui existe entre les vibrations de deux téléphones associés," *Journal de Physique* s. 1; t. 8 (1879): 175.

[104] Ibid. Koenig later used a variation of this instrument to demonstrate that a fundamental tone could excite an harmonic tone via the telephone. Koenig, *Catalogue (1882)* 19. *Catalogue (1889)* 59.

The telephone controversy confirmed Koenig's instinct about the role of phase in timbre. As described in §2.7, Helmholtz had used his synthesiser to test for the influence of phase on timbre and concluded that it did not play a role. He adhered to his analytic conception of sound, whereby the number and strength of harmonics determined the timbre of a compound sound. He did, however, note "an apparent exception." He noticed that when the fundamental of the synthesiser was played with the next note (the octave) but slightly out of tune, "an attentive ear will observe very weak beats which appear like small changes in the strength of the tone and its quality."[105] He concluded that these beats were associated with changes in phase. Furthermore, he stated, the "apparent" changes were merely due to combination-tone effects where "slight variations of quality are referable to changes in the strength of one of the simple tones."[106] When doing his own experiments, Koenig heard these slight differences of quality, but interpreted them quite differently from Helmholtz: "But if timbre depends precisely on the existence of harmonics and their relative intensity, and if this relative intensity is modified by the difference of phase, it is clear that the influence of the latter is not only apparent, but very real."[107]

The questions about timbre touched on a number of issues that marked Koenig's career and the birth of this new science: the role of instruments and craft knowledge in influencing this debate; the tension between theoretical and empirically (naturally) based conceptions of nature; the manner in which pictorial representation determined what was deemed "real"; the importance of demonstrations for proving a case; and the shifting and murky boundaries between physics and physiology/psychology in the latter part of the nineteenth century. As we will see below, the dispute also related on a fundamental level to the nature of combination tones. Koenig was trying to replace Helmholtz's new acoustics with a coherent alternative based on his pictorial perspective

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Quelques Expériences 201. An example of this instrument can be found in Florence, see Paolo Brenni, *Gli Strumenti di Fisica dell'Istituto Tecnico Toscano, Elettricita e Magnetismo* (Firenze: La Lettere, 2000) 256-58.

[105] Helmholtz, *Sensations* 127.

[106] Ibid.

[107] Koenig, *Quelques Expériences* 224.

and rigorous experiment. In his own history of acoustics, Koenig remarked: "In the sense of timbre being understood as an assemblage of coexistent sounds, the study of phenomena that are products of the joining of two or more sounds [beats and beat tones] becomes inextricably linked to the study of timbre itself."[108]

Koenig's training as a violinmaker was important in this dispute. His craft knowledge of musical instruments gave him a different perspective on the nature of complex tones and timbre. In his first full-length discussion of phase and timbre in 1881, Koenig made a distinction between harmonics and partial tones. Harmonics, he wrote, represented the ideal mathematical series of tones related to the fundamental; partial tones, on the other hand, were the actual sounds that approached, more or less, the theoretical values. These slight enharmonic deviations, Koenig argued, were quite apparent to anyone who listened carefully to organ pipes and vibrating strings and plates. Imperfections in stringed instruments such as violins, produced partials tones far from pure, or ideal.[109] In his article he reproduced one of his earliest graphical inscriptions of a vibrating string producing a fundamental and its octave. By studying the inscriptions, Koenig found a continually changing waveform. The first partial (octave) was not exactly an octave, thereby creating a slight difference in phase, and therefore continual changes in the waveform. These slight changes, according to Koenig, were detected as slight changes in timbre. Homogeneity of the vio-

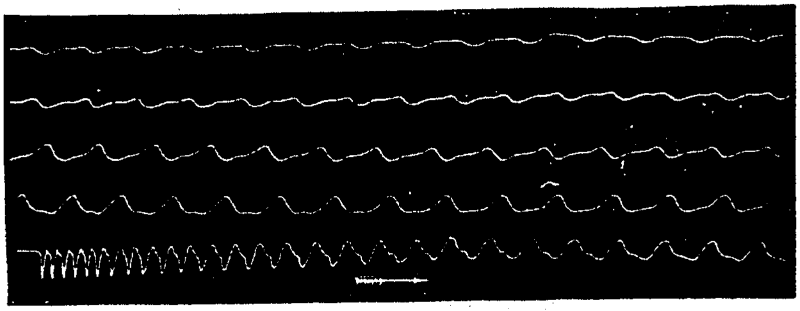

Figure 4.9 Phonautograph tracing of a string producing a slightly mistuned octave. Koenig *Quelques* (1882b) 16 and 221.

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[108] Rudolph Koenig, "Quelques notes," in *University of Toronto Archives, Loudon Papers B72-0031/017(05)* (1901).

lin string had been a source of concern to him as a former violinmaker (§3.2). He now made use of this knowledge in challenging Helmholtz.

His work on the influence of phase, he argued, showed that Helmholtz's understanding of sound was limited. "If this influence exists," he stated in his article on timbre in 1881, "the hypothesis that had existed before the work of Helmholtz on this subject, where timbre depended on the form of vibrations, should be conserved."[110]Koenig's argument in favour of the primacy of the waveform constituted a direct challenge to Helmholtz's analytic conception of sound. Helmholtz's physiology, for instance, depended on a linear, one-to-one relationship between simple tones in the outside world and simple-tone receivers in the ear. Accepting Koenig's experiments would have demanded a complete reconceptualisation of this piano model of the inner ear. Helmholtz's biographer understood the stakes of this dispute when he commented: "By establishing...that the difference of phase does not come into the question, Helmholtz confirmed his previous assumption that our sensation of different qualities of tone is reduced to the fact that other nerve-fibres, corresponding with the partials, are simultaneously excited along with the fibres that respond to the fundamental tone. This simple explanation would not suffice, if the difference in phase of the deeper harmonics had to be considered."[111]

As with the other disputes, the focus was on instruments. Koenig argued that the Helmholtz synthesiser represented an ideal yet limited conception of sound. Furthermore, it produced a compound sound of "doubtful clarity."[112] Built into Helmholtz's series of tuning forks and resonators was the assumption that all sounds were perfectly harmonic, based on the fundamental tone. Koenig believed that the synthesiser did not properly represent the natural timbre with its continually changing intensities and phases. And even though Helmholtz had devised a few in-

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[109] Koenig, *Quelques Expériences* 218-22.
[110] Ibid., 222.
[111] Koenigsberger, *Hermann von Helmholtz* 180.
[112] Koenig, *Quelques Expériences* 223.

genious means for testing the phase, Koenig argued that these experimental tricks were not easily carried out in practice.[113]

Koenig saw the changing waves and the different waveforms produced by phase changes as constituting a "real" difference in timbre. Just as with beats and beat tones, he resorted to his wave-siren technique in order to recreate artificially the "natural" timbre from actual waveforms. He first constructed waveforms for complex tones which consisted of a series of harmonics of equal intensity. Using his graphical inscriptions and photography to reduce some of the curves, he drew the resultant compound waveforms under four different phase conditions, with shifts of 0, ¼, ½, and ¾. He then traced and cut these figures on the circumference of a cylindrical band of thin brass. Like the combination tone siren, these cylindrical bands wrapped around a central rotating axle. Wind slits, connected to a large wind bellows, were positioned beside each curve.[114] By studying the waveforms compounded from the first eight harmonics, and then waveforms consisting of the odd harmonics, he consistently discovered that waveforms with a phase shift of ¼ were much stronger and more strident in tone. Waveforms based on the shift of ¾ were soft in tone, while the other patterns representing shifts of ½ and 0 were of an intermediate quality.[115]

To imitate even more faithfully the conditions found in nature and musical instruments, Koenig created metal waveforms from harmonics of decreasing intensity (in nature, the harmonics farther away from the prime tone generally decrease in intensity).[116] He made six curves derived from the combination of the first eight harmonics with decreasing intensity, and two curves derived from the combination of the odd harmonics (1,3,5,7). He was therefore able to compare two different timbres based on the partials, and different timbres based on the same partials but with different waveforms. The results were similar to his first observations.[117] He also built three curves meant to imitate the vowels, OU, O, and A. These waveforms derived from Auerbach's

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[113] Ibid., 224-25.
[114] Ibid., 226.
[115] Ibid., 227.
[116] Ibid., 228.

analytic studies of vowels and the relative intensities of their first eight harmonics.[118] In general, Koenig verified his earlier results showing that the phase shift of ¼ produced the greatest difference in timbre. He added, however, that these curves did not succeed in reproducing the vowels. Only the "A" curve gave something close to an "A."[119]

By 1882 Koenig had created a standard form of this apparatus for the market.[120] There were six curves – four deriving from the first twelve harmonics of decreasing intensity, and two from the odd harmonics of the same series. The standard wave siren cost 350 francs.[121] Like other Koenig instruments its mere presence in texts, lantern slides or articles was also a powerful means of illustrating the points to be made, providing a way to conceptualise visually the contentious role of phase in timbre.[122]

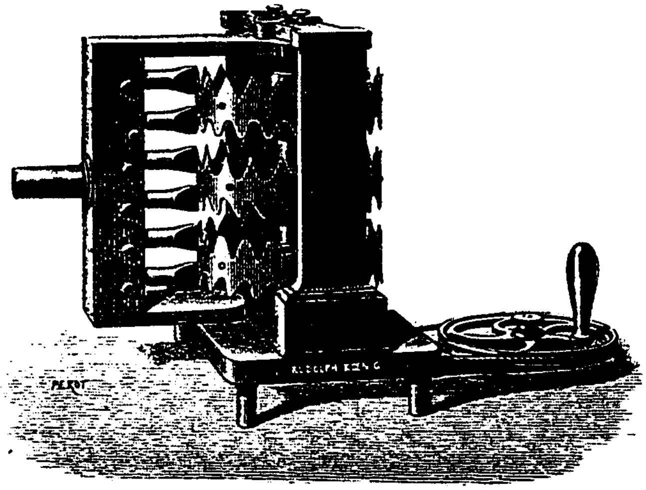

Figure 4.10 Wave siren for studying timbre. Koenig *Catalogue* (1889) 28.

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[117] Ibid., 229.
[118] Félix Auerbach, "Untersuchungen über die Natur des Vocalklange," *Annalen der Physik* 8 (1878).
[119] Koenig, *Quelques Expériences* 234.
[120] Koenig, *Catalogue (1882)* 9. *Catalogue (1889)* 28-29.
[121] An example of this instrument can be found on display at the Conservatoire National des Arts et Métiers, Paris. Other examples are on display at Museo di Fisica at the University of Rome and at the University of Moscow. They are approximately 40 cm in height. The rotation of the axle is surprisingly smooth and quiet. McGill University once had this instrument, but it is now missing (see Figure 1.7).
[122] Thompson, "The Researches of Dr. R. Koenig," 251. Zahm, *Sound and Music* 374. Other texts carried pictures of the beat-wave siren, Miller, *The Science of Musical Sounds* 245. Winkelmann, *Handbuch der Physik: Akustik* 267.

Like the beat-wave siren, the phase-wave siren was open to criticisms concerning its ability to reproduce airwaves that faithfully derived from the waveform of the copper disk. Koenig believed that such problems were negligible, but he worked to build a siren with many new features. His "grand wave siren" was his most elaborate and exotic instrument.[123] It was his second most expensive instrument at 6000 francs, putting it out of the reach of most laboratories. He was particularly proud of this instrument and placed it on the cover of his book in 1882. Unfortunately, there are no known examples of this instrument in museum collections today.

The grand wave siren was 1.9 meters in height. It consisted of sixteen disks cut with simple sinusoidal waveforms instead of complex curves. The first disk was a fundamental tone, the other fifteen were pure harmonics of that tone. Each disk had its own wind slit. A long lever connected to the slits allowed one to change the phase of each slit at will. Sixteen buttons allowed one to

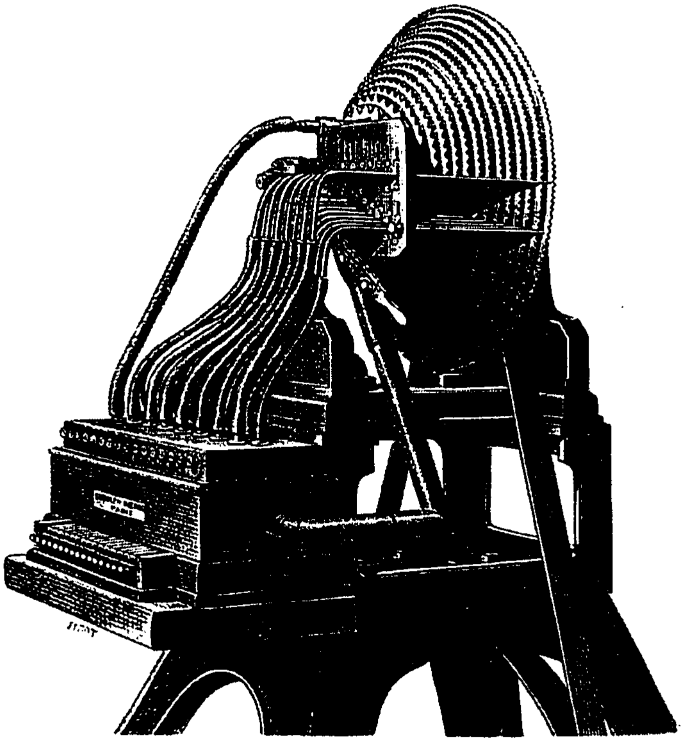

Fig. 18 (h = 1m,90) (N° 59).

Figure 4.11 Grand wave siren for studying timbre. Koenig *Catalogue* (1889) 27.

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[123] Koenig, *Catalogue* (1882) 9. *Catalogue* (1889) 27. *Quelques Expériences* 236.

open or shut the flow of pressure air in the slits. One could also regulate the pressure of air to imitate varying intensity. With this instrument Koenig was able to confirm his earlier research.[124] It had the advantage of having the versatility to explore many combinations of harmonics in different situations. Koenig's main goal had been to explore the role of timbre, but he stated that some preliminary research on vowels had shown promise.[125]

The wave sirens represented Koenig's complete departure from Helmholtz's analytic theory of sound. Koenig had done more than anyone else to transmit the analytic perspective through his tuning forks, sirens, resonators, synthesisers and analysers. But, when he designed a whole family of instruments that challenged this conception, he faced a tough battle. Unlike the combination-tone debate, people in the physics community did not vigorously defend, or even test, his position. Even in Britain, there was not much enthusiasm for Koenig's experiments on phase. In fact, when S. P. Thompson gave his lecture on Koenig's work in 1891 for the Physical Society of London, Koenig's position regarding the role of phase in timbre raised some criticism. After Bosanquet wrote inquiring about Koenig's experiments, Thompson replied: "Please bear in mind that on Friday I spoke purely as the exponent of Koenig's views, not necessarily of my own: otherwise I should have said something in criticism of the whole method of wave-sirens, and should have suppressed sundry other things that Koenig wished to be said. I wish you had been in front of the wave-sirens, as they can not be heard from behind with any success."[126] Lord Rayleigh cited Koenig's work, without taking sides, but after cautioning his audience that such a view demanded a "departure from Ohm's law."[127] One can argue that Koenig's own analytic instruments had helped solidify Ohm's theory of sound, and through their sheer numbers and presence these instruments were acting as stabilising features for the reforms introduced by Helmholtz. People like Bosanquet had spent much time honing the analytic approach in the laboratory, making it

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[124] Ibid., 236-43.

[125] Ibid., 243.

[126] Jane Smeal Thompson and Helen G. Thompson, *Silvanus Phillips Thompson: His Life and Letters* (New York: E.P. Dutton and Company, 1920) 159.

difficult to accept a method (wave sirens) so contrary to their laboratory habits and consequently their theoretical perspectives.

On the other hand, scientists in the physiological community were much more open to Koenig's message. As we will see below, physiologists used graphical equipment more frequently than their colleagues did in physics. They were therefore more accepting of a holistic, pictorial approach to acoustics. In the 1880s and 1890s, physiologists began to see the limitations to Helmholtz's rigid physiological conceptions. Physiologists such as Hermann believed that Helmholtz's theories of vowels, for example, needed modification.

4.8 DEMONSTRATING THE TRUTH

Koenig's faith in proving his case before other scientists was a deep expression of his confidence in experiment; demonstrations told the true story better than anything else. He invested enormous effort in these demonstrations and attached great importance to their outcome. In the nineteenth century, as in all the years since the foundation of the Royal Society of London, demonstrations were a common vehicle for proving a case, not just for teaching.

One of Koenig's more important demonstrations came in October of 1881, when scientists from around Europe had gathered in Paris for an electrical congress. He used his studio to show all the visiting scientists his new series of experiments. At the time, he was corresponding with James Loudon in Toronto about organising a demonstration/lecture series in Toronto and Montreal for the summer of 1882 (§1.2) and in suggesting a possible course of events for their series, he informed Loudon that he had just hosted "numerous visits by foreign scientists" and shown them his latest experiments.[128]

> I have the conviction that the exposition of several of the more important phenomena of acoustics, such as they are, and not as one imagined them to be according to preconceived theories, will be quite interesting, and could result in a very fine book after these lectures. I recently had the occasion to demonstrate, before the most important German

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[127] Rayleigh, *The Theory of Sound* 469.
[128] See November 25, 1881. Koenig, "Koenig Letters (1878-1901)."

> scientists, and before Helmholtz himself, the absolute truth of all the facts that I described in my different articles.[129]

In the spring of 1882, as plans were taking shape for the Toronto and Montreal lectures, Koenig repeated the story of his famous visitors to underline the satisfaction he felt in his current work.

> I assume that you have received my book by this time and that you would have noticed the great importance of my work that completely overturns the proposition of Mr. Helmholtz on the non-influence of the difference of phase of harmonics on timbre. I think that the demonstration of facts related in this article, that I had the great pleasure of making to Monsieur Helmholtz in the presence of Mr. Kirchoff, Du Bois Reymond, Clausius, Mach, Kundt, Quincke, Hittorf and others during the visit of these gentlemen at Paris for the electrical exposition, cannot be missed in our sessions.[130]

Although the Toronto crowd would be mostly a non-scientific audience, and therefore not able to understand the subtleties of the dispute, Koenig continued to press Loudon to include a full description and demonstration of his latest experiments in their lectures. He made meticulous plans for these parts of the lecture to be a success. For his work on timbre he brought his smaller wave siren (No. 57 in the 1882 catalogue).[131] He did not bring the grand wave siren (No. 56 in the 1882 catalogue), because it was too heavy and expensive to transport.[132] For demonstrating the beat phenomena, "since it is properly in the beats of harmonics that one finds the key for the great influence of phase of the harmonics on timbre,"[133] he used a number of Loudon's instruments, such as high-pitched tuning forks,[134] and the disks with holes that could be used with these forks.[135] He was worried, however, that he did not have the proper equipment to demonstrate beat phenomena with low notes, "whose absence in our lectures will be to me too obvious."[136] Since he was going to Philadelphia to recover his instruments from the centennial exhibition (§1.2), he suggested bringing some of them up to Canada. This was no small task. The lowest notes, for ex-

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[129] See November 25, 1881. Ibid.
[130] See March 21, 1882. Ibid.
[131] No. 57 in the catalogue of 1882. This was most likely the wave-siren that eventually came to McGill, (see Figure 1.7).
[132] See March 21, 1882. Koenig, "Koenig Letters (1878-1901)."
[133] See May 21, 1882. Ibid.
[134] Nos. 191 and 196 from the catalogue of 1882.
[135] Nos. 197, 199a, 202 a or b from the catalogue of 1882.

ample, consisted of five forks of the lowest range of frequencies with sliding brass weights to adjust the frequencies, and three adjustable brass resonators. Some of the forks in the stands measured almost a meter in height and the whole set weighed over 130 kilos. The University of Pennsylvania still had the entire, unsold collection of these forks and others that Koenig had used for his paper of 1875, and brought to the centennial exhibition of 1876.[137]

The demonstrations were not just about proving a contentious issue of science, they were often about selling an instrument, or group of instruments. Indeed, it was hard to distinguish Koenig the businessman from Koenig the researcher. He wanted to sell his ideas and instruments at the same time. Just before he left Paris in the summer of 1882, he made sure to ask one more time that Loudon include in the lecture series his experiments on beats and beat tones, and their relation to timbre.[138] In an off-handed but obvious attempt to promote a sale, he included a post script in a letter from the same time informing Loudon: "the collection of large tuning forks and resonators with the stands and supports, at Philadelphia, described in my book p. 88 and 89 of [sections] I to VII, costs 20,000 francs."[139] He left Le Havre on August 5 aboard the Steamship "France" for New York, spent a few days in Philadelphia packing and shipping the series of low forks and resonators, then he went on to Montreal to a meeting of the American Association for the Advancement of Science to deliver a lecture on timbre. In September, he arrived in Toronto for the lecture series with Loudon. Loudon ended up buying almost half of this special collection, comprising twelve of the lowest forks from Ut1 to Ut4 with six adjustable resonators for approximately 8,000 francs.[140]

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[136] See March 21, 1882. Koenig, "Koenig Letters (1878-1901)."

[137] For description of these instruments, see Koenig, *Quelques Expériences* 88-89.

[138] See May 21 and June 30 1882. Koenig, "Koenig Letters (1878-1901)." With classroom demonstrations constantly on his mind, Koenig developed a giant manometric organ pipe (2.5 m in length) with which one could study the vibrations of air at every point along the length of the pipe. Koenig did not take this instrument to Toronto because of transport expense. Koenig, *Catalogue (1882)* 12. *Quelques Expériences* 206-17.

[139] See May 21, 1882. Koenig, "Koenig Letters (1878-1901)."

[140] Loudon purchased I and II of Koenig's forks from the paper Koenig, *Quelques Expériences* 88-89.. They are also found in Koenig, *Catalogue (1882)* 22-23. See October 17, 1882. Koenig, "Koenig Letters

After an extremely busy period in the early and mid-1880s (§1.3), Koenig was able to get back to questions of timbre and his challenge to Helmholtz. He had been quite pleased with his synthetic experiments on timbre, but was now working on the more elusive examples of timbre – reed instruments, trumpets and the vowels. He was frustrated that he could not satisfactorily reproduce (synthesise) the distinctive sounds of these instruments and the human voice. His solution was a combination of his ideas on beat-tone and the influence of phase on timbre.

In both disputes, Koenig had seen the primacy of waveforms in determining what was heard. Beats and beat tones were simply waveforms that were somehow perceived by the ear. Changes in phase likewise created changes in the waveform that were perceived as changes in timbre. Koenig envisioned different situations whereby timbre was produced. One of his most powerful examples was the continually changing waveform caused by imperfect harmonics. Such a situation combined the idea of a mistuned consonance (leading to beats and beat-tones) and changing phase relationships. Koenig believed that these waveforms, produced by natural instruments and voices, were responsible for the more elusive timbre of brass musical instruments and vowels. He therefore set out to imitate and synthesise these waveforms in order to produce such complex sounds.

In August 1888 Koenig wrote to Loudon that he wanted to test whether the ear could indeed distinguish differences among these complex, multiform waveforms.[141] First, he made six disks for his wave siren that resembled specific combinations of harmonious and inharmonic partials to create complex waveforms of continually changing shape. His experiments, he believed, were a success. He concluded that the "waveforms of a sound do not have to be absolutely uniform to produce musical timbre."[142]

(1878-1901)." These forks were enormously expensive. In comparison, Koenig sold his grand tonometer of Philadelphia (670 forks) to Prof. Mitchie for 8000 francs at the same time.

[141] See August 31, 1888. Ibid.

[142] Ibid.

It was now important for him to "show that timbres of this nature [non-uniform] are often truly produced by vibrating bodies."[143] He had already found such complex waveforms with stringed instruments, but he now wanted to find such non-uniformities in other instruments and vibrating bodies. In light of criticisms that not all seemingly periodic behaviour (such as beats) produce sounds, he set out to prove that any maximum isochronous intensity could "give birth to a sound." After noticing that some of his steel cylinders, when hit in different places produced two sounds, Koenig created modified steel cylinders that could emit two sounds, and if they were near unison, beats were heard.[144] Under certain circumstances, he even heard beat-tones. Seeing that all of these tones came from one source, and therefore, as Koenig thought, from one motion (just like a violin string), he interpreted this finding as evidence that any vibrating body could produce these complex vibrations and that the ear could distinguish these motions as a single perceptual event. As we will see later in the chapter, this was a revealing anticipation of Gestalt psychology.

The latter experiments on vibrations revealed Koenig's commitment to resurrecting the pre-Helmholtzian theories. In a statement that recalled his lineage to Vuillaume's workshop and the early school of Parisian experimental acoustics, he told Loudon that his latest round of observations on the vibrating cylinders had been partly inspired by some of Savart's previous work on the vibrations of systems. "It is a subject that interests me very much, and that I hope to pursue further."[145]

In the next year, 1889, with his experiments on these questions complete, Koenig prepared to go to the congress of naturalists at Heidelberg to present all of his demonstrations and make his case to the newer generation of German scientists (§1.3). Helmholtz was the president of the society and he spoke at length (on another topic), leaving less time for the next speaker, Koenig.

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[143] Ibid.

[144] The Canadian National Museum of Science and Technology in Ottawa has the only known example of this instrument. It most likely came from Toronto. It is marked with the RK monogram with three different notes on three of its sides: 12, Sol6, 6144 v.s., 4, Ut5, 1024 v.s., and 8, Ut6, 4096 v.s.

Nevertheless, "in going very fast," Koenig wrote to Loudon, "I succeeded in giving all the needed explanations and most important experiments on the co-existence of two sounds, the influence of the difference of phase, and the role of inharmonic sound in timbre."

Helmholtz responded, even though Koenig sensed that he did so out of obligation, "because I doubted that he himself thought that what he had to say was very strong." Koenig recalled Helmholtz's responses in a letter to Loudon later that month. Helmholtz's first rebuttal concerned the notion that Koenig's beats and beat-tones were not classified as sounds, and that his theory showed how important it was to separate the two main components. "It appeared difficult for him to admit," wrote Koenig, "that beats can become sounds because the theory that he had given of combination tones had been found confirmed in other branches of science, as in the theory of tides, where two equally different forces, the sun and the moon act at the same time on the water."[146] In other words, Helmholtz saw combination tones as objective phenomena coming from two distinct sources, not from one single vibratory motion or waveform. On the experiment with a wave-siren, Helmholtz noted that it was "important to observe that it [the wind slit] requires very much exactness in adjustment, and the most difference of timbre in the two positions of the wind slit, appeared to him very weak."[147] Finally, Helmholtz commented on one of Koenig's cherished arguments, the role of inharmonic partials in the production of timbre. Koenig had used the example of the non-uniform, continually changing, vibrating string. Helmholtz, not to be outdone in the world of music, responded with his own knowledge of strings. He admitted, Koenig wrote, that

> one can maybe find something of this [inharmonic sounds] with the lowest cords of the piano, but they do not give in reality much musical timbre. Then he again gave the description of an experiment that he had done himself with a cord, that being laden with a little weight, had its timbre changed, experiments that had absolutely nothing to do with my talk, and finished in excusing himself from having to speak, but having been directly attacked in his position, he could not do otherwise. He thanked me again in the name of

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[145] See August 31, 1888. Koenig, "Koenig Letters (1878-1901)."
[146] See October 11, 1889. Ibid.
[147] See October 11, 1889. Ibid.

> the section, like he had already done before his observations, and we passed on to other things.[148]

4.9 RESOLUTION

It was the physiologists who seemed more open to Koenig's findings at the Heidelberg conference. This was partly owing to his increasing willingness to tackle vowel research again. For example, in the early 1890s he developed another grand wave-siren that he believed could better study the complexities of vowel sounds.[149] Physiologists also worked in a very different laboratory context. Graphical and optical studies were more entrenched in the physiological laboratory, so his "pictorial" and holistic approach was not as foreign to this community. Ironically, he had shied away from giving any physiological explanations of his findings, but these same findings strengthened doubts others were having about Helmholtz's earlier explanations.

Ludimar Hermann became both an ally and critic of Koenig's work on combination tones, timbre and vowels.[150] On combination tones, he agreed with Koenig's caution regarding these hypothetical entities and found in his own experiments that it was impossible to verify the existence of the supposed difference and summation tones Helmholtz had proposed from theory.[151] Hermann's main interest, however, was the physiology of speech and hearing, particularly vowel studies. He used an ingenious modification of the Edison phonograph to graphically reproduce vowel sounds,[152] and found evidence that caused him to seriously question Helmholtz's theory of vowels. Helmholtz had proposed the fixed-pitch theory based on the idea that the vocal cords produced a number of mathematically related harmonics, in which one fixed region was rein-

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[148] See October 11, 1889. Ibid.

[149] Rudolph Koenig, "Die Wellensirene," *Annalen der Physik* 57 (1896a). Also see P.J. Rousselot, *Principes de Phonétique Expérimentale*, vol. 1 (Paris, Leipzig: H. Welter, 1897) 172-74, 218.

[150] Ludimar Hermann, "Phonophotographische Untersuchungen," *Pflüger's Archiv für Physiologie* 45 (1889). "Phonophotographische Untersuchungen," *Pflüger's Archiv für Physiologie* 47 (1890). "Phonophotographische Untersuchungen," *Pflüger's Archiv für Physiologie* 53 (1893). "Phonophotographische Untersuchungen," *Pflüger's Archiv für Physiologie* 58 (1894). "Ueber die Prüfung von vocalcurven Mittels der König'schen Wellensirene," *Pflüger's Archiv für Physiologie* 48 (1891a). "Zur Theorie der Combinationstöne," *Pflüger's Archiv für Physiologie* 49 (1891b). For summaries of these experiments, see Rayleigh, *The Theory of Sound* 469-78. Rousselot, *Principes de Phonétique* 175-232. Edward Wheeler Scripture, *The Elements of Experimental Phonetics* (New York: Scribner's, 1902) 411-24.

[151] Rayleigh, *The Theory of Sound* 459.

forced by the resonating cavity in the mouth. Hermann found in his studies that often this fixed region was not at all related harmonically to the other tones present. In fact, he found that most of the time it was totally independent of the fundamental tone. He called this region of inharmonic reinforcement, the "formant." Hermann, therefore, believed that Helmholtz theory of vowels had been idealised and was not based on actual observations of the throat. Like Koenig, Hermann had challenged the Ohmian framework of Helmholtz.

Whereas Koenig had sensed the same problem with Helmholtz theories on the timbre of vowels, he had chosen to answer this question through his work on phase and beat-tones. Hermann, however, judged the wave-siren as flawed and he also believed that phase did not have anything to do with timbre. Both came to their conclusions using visual methods. Hermann performed a meticulous series of studies with his graphical device and then tied these in with his findings on the sounds produced at source in the vocal cords. Today, psychologists use Hermann's word "formant" to describe a similar theory of vowel production.[153]

Remarkably, Koenig's earlier results for the characteristic pitch of vowels held their ground amidst continued experiments with different apparatus.[154] Investigators at Cornell even confirmed his results using the manometric device with brighter gas and photography of the flame signals.[155] But by 1920 the flame method and other techniques such as Hermann's phonophotograph were being replaced by electronic instruments.

Koenig's critique of Helmholtz and his work on vowels may have had a direct influence on the early Gestalt movement. Wolfgang Köhler (1887-1967), who was the first to look at vowel

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[152] Scripture, *The Elements of Experimental Phonetics* 39.

[153] For more on the history of this development see Robert T. Beyer, *Sounds of Our Times: Two Hundred Years of Acoustics* (New York: Springer-Verlag, 1998) 213-15. Boring, *Sensation and Perception in the History of Experimental Psychology* 367-75. Miller, *The Science of Musical Sounds* 215-43.
David J. Murray and Farahmand Bahar, "Gestalt Theory and Evolutionary Psychology," in *Psychology: Theoretical-Historical Perspectives*, ed. R. W. Rieber and K. Salzinger (Washington D.C.: American Psycholigical Association, 1998). For more recent accounts on the physics of the human voice, see Berg and Stork, *The Physics of Music* 169-75..

[154] Boring, *Sensation and Perception* 367-75.

[155] Ernest Merritt, "On a Method of Photographing the Manometric Flame with Applications to the Study of Vowel A.," *Physical Review* 1 (1894).

production from a Gestalt (single perception) point of view, produced very similar numbers to Koenig in his 1916 experiments on vowels.[156] In addition, each figure was separated by an octave, similar to Koenig's figures. More importantly, Köhler came to view the timbre of vowels as something that humans perceived as a single unity, not in an analytic fashion. In this way Koenig anticipated a Gestalt view of vowels by almost forty years.

Regarding timbre in general, a partial resolution emerged in the 1960s. The position that phase did not have a role in timbre held its ground, with some minor and interesting deviations. Koenig did indeed hear something, and a Dutch acoustician, Reiner Plomp, partially vindicated his view using modern psychological methods and explanations based on twentieth-century neural processing.[157] Plomp found first that mistuned consonances (i.e. two tones just slightly out of tune) produced an irregular, continually changing, waveform that correlated with a perceived change in timbre. Since the changing, waveform was actually a series of beats making their way through the wavetrain (just as Koenig had found in his graphical study of the violin string) Plomp called these "quality beats." Plomp suggested, as Koenig had, that the ear somehow had the ability to discriminate these changing waveforms. He suggested that neural processing played a role in this ability.[158] In general the Ohm/Helmholtz's law of hearing remains intact, but it may break down in certain conditions.

4.10 ULTRASONICS AND THE "REALM OF FANTASY"

The physiological community played a major role in Koenig's last controversial project. Just before his death Koenig took his tuning forks into the uncharted domain of ultrasonics. Previously,

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[156] Boring, *Sensation and Perception* 367-75. Murray and Bahar, "Gestalt Theory and Evolutionary Psychology," 257-72.

[157] Plomp, "Beats." R. Plomp and H.J.M. Steeneken, "Effect of Phase on the Timbre of Complex Tones," *Journal of the Acoustical Society of America* 46 (1969).

[158] Unfortunately, Plomp's results were not conclusive. He used a very small number of subjects (10) with a large margin of error. Some present day texts on the physics of music use Plomp's findings uncritically to state that phase does have a very slight influence on tone quality, see Berg and Stork, *The Physics of Music* 160.

Roederer, *Introduction to the Physics and Psychophysics of Music* 37-40. They also describe the effects of "phase distortion," or the phase displacement due to electronic equipment. Berg and Stork, *The Physics of Music* 204, 14.

he had been reluctant to study tones that were "in the realm of fantasy,"[159] but recent inquiries into the psychology and physiology of higher tones by Carl Stumpf (1848-1946), Max Friedrich Meyer (1873-1967) and Franz Emil Melde (1832-1901) stimulated him to take another look at this area.[160] These researchers had discovered that Appunn's forks, which were supposed to go up to 50,000 Hz, were in fact wrongly calibrated.[161] Preyer had used these forks in his early acoustical research, and his work had been cited uncritically by Helmholtz and Zahm.[162] In fact, Zahm tried his best to dismiss any doubts about Appunn's forks:

> Many persons have been able to hear the note yielded by this fork [49,152 Hz]; but a question may arise whether it really gives a note of the high pitch claimed for it. Without here entering into an explanation of the manner in which the pitch of such forks is determined, I may observe that Herr Appunn, in a letter to me about this and other forks of very high pitch which he furnished me, states that he can guarantee that the frequencies of the forks correspond absolutely with the numbers stamped on them. No one can doubt the skill of Herr Appunn as a mechanician, and the delicacy of his ear for very acute sounds is, according to the testimony of all who are acquainted with him, something quite astonishing. It would probably be impossible for one with a less delicate ear to tune such a fork, even if he were familiar with the method of tuning employed in such cases. We are consequently, by the very necessities of the case, compelled to accept Herr Appunn's estimate as that of an expert and that he is an expert in his specialty no one can gainsay.[163]

For most of his career, Georg Appunn (1816-1885), and later his son Anton Appunn (1839-1900), had been Koenig's only competition in Germany for making tuning forks. Helmholtz cited his forks several times in *Sensations*.[164] Appunn Sr. had collaborated with Preyer in the 1870s in experiments that did not fully agree with Koenig's findings on beat-tones.[165] So Koenig believed

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[159] Koenig, *Catalogue (1889)* 23. "Ueber die höchsten hörbaren und unhörbaren Töne," *Annalen der Physik* 69 (1899): 628-29. Koenig complained to August Zahm that working with high pitches was very unpleasant as the sounds rang in his ears for days, and even weeks, afterwards. Zahm, *Sound and Music* 84.

[160] For overviews of auditory threshold studies, see Boring, *Sensation and Perception* 332-339. Audrey B. Davis and Uta C. Merzbach, *Early Auditory Studies: Activities in the Psychology Laboratories of American Universities* (Washington D.C.: Smithsonian Institution, 1975) 12-14. Feldmann, H. "Die Galton-Pfeife und die Entdeckung der Altersschwerhörigkeit." *Laryngo-Rhino-Otologie* 74 (1995).

[161] These forks were made by Georg Appunn (1816-1885) of Hanau, Germany.

[162] Helmholtz cites these forks without question in *Sensations* 18, 151. Zahm also cites these forks in *Sound and Music* 83-84.

[163] Ibid.

[164] Helmholtz, *Sensations* 18, 151, 27-28, 67.

[165] This debate related to Appunn and Preyer's suggestion that summation tones were actually differential tones of the second order. See Ibid, 532.
Koenig, *Quelques Expériences* 127-28.

he had good reason to doubt the integrity of Appunn's tuning forks. After reading Melde's papers, Koenig described to James Loudon how Appunn's forks were found to be "absolutely untruthful, as I had thought for a long time."[166] But he was also unnerved by a suggestion that some of his own higher forks (Ut8 and Ut9 - 8192 and 16,384 Hz) were not of the proper frequency. Koenig demonstrated to Mayer, who was visiting Quai d'Anjou in the summer of 1894, the exactness of his forks up to Fa9, "which was for both of us the limit of our perceptibility!" He then added: "Prof. Zahm, who, like many others, was taken by the charlatanism of Appunn and Preyer, as his book shows, will be a little astonished when he realises what he must now think of their affirmations."[167]

In 1899 Koenig responded to the suggestion that his forks were also off the mark by producing a comprehensive study of the behaviour of inaudible tones up to 90,000 Hz. In his earlier work on combination tones (1874) he had produced forks up to 21,845 Hz. Those forks had been as thick as they were long (15 mm), and were almost impossible to keep vibrating. He tried making the forks thinner, but this meant they were softer and therefore could not produce a strong tone. After hearing about Preyer's experiments in 1876, Koenig set to work to develop higher frequency forks, but having no way to verify them properly, he did not include them in his catalogue of 1882.[168] The findings of Stumpf, Meyer and Melde inspired him to develop a more objective method for verifying the highest forks. Among other test with plates, cylindrical steel bars and whistles, Koenig used cork-dust figures that made the sound waves visible in a tube (Kundt's invention). Through this method, he was able to measure objectively the frequency of inaudible tones. He also extended (and confirmed) his studies on beats and beat–tones into ultrasonic frequencies.[169]

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[166] See July 26, 1894. Koenig, "Koenig Letters (1878-1901)."
[167] See July 26, 1894. Ibid.
[168] Koenig, "Ueber die höchsten hörbaren und unhörbaren Töne," 627-29.
[169] Ibid.

Throughout his career, Koenig made use of a mixture of thorough experiment, mechanical innovation, demonstrations and visual techniques to prove or disprove disputed claims. His last round of experiments combined all three aspects of this approach, applied to phenomena far beyond the limits of human observation. J.C. McLennan was in Paris for a week in August 1898 and spent each afternoon at Koenig's studio witnessing the latest demonstrations and experiments. Koenig was quite sick by this time and was living entirely on milk, but he had the energy to carry out a host of demonstrations. In one of the experiments he demonstrated a set of small forks whose "individual vibrations cannot be heard but the beat tones can."[170] The next year, 1899, McLennan visited again and Koenig showed him his completed experiments with high tones. He had now reached 90,000 Hz. As proof he gave the photographs of the Kundt figures to McLennan to pass on to Loudon in Toronto.[171] These figures presently rest in the archives of the University

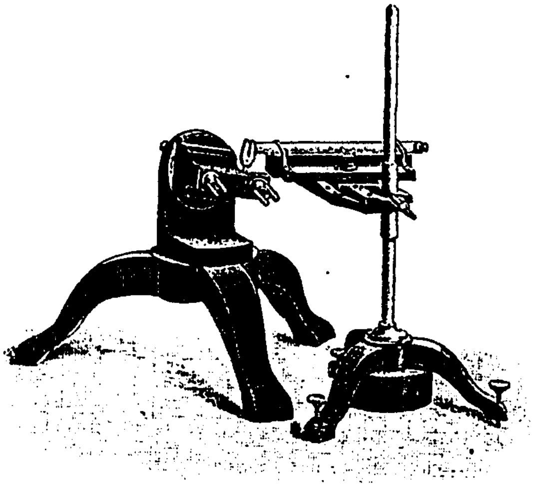

Figure 4.12 Small fork with glass Kundt tube for measuring high frequencies. Koenig (1899) 657

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[170] J.C. McLennan, "Letter to James Loudon, Sept. 4. 1898," in *University of Toronto Archives, Loudon Papers, B72-0031/004.*

[171] See September 14, 1899. Koenig, "Koenig Letters (1878-1901)."

of Toronto; they are the witnesses to Koenig's final experiments in a realm well beyond the threshold of human hearing.

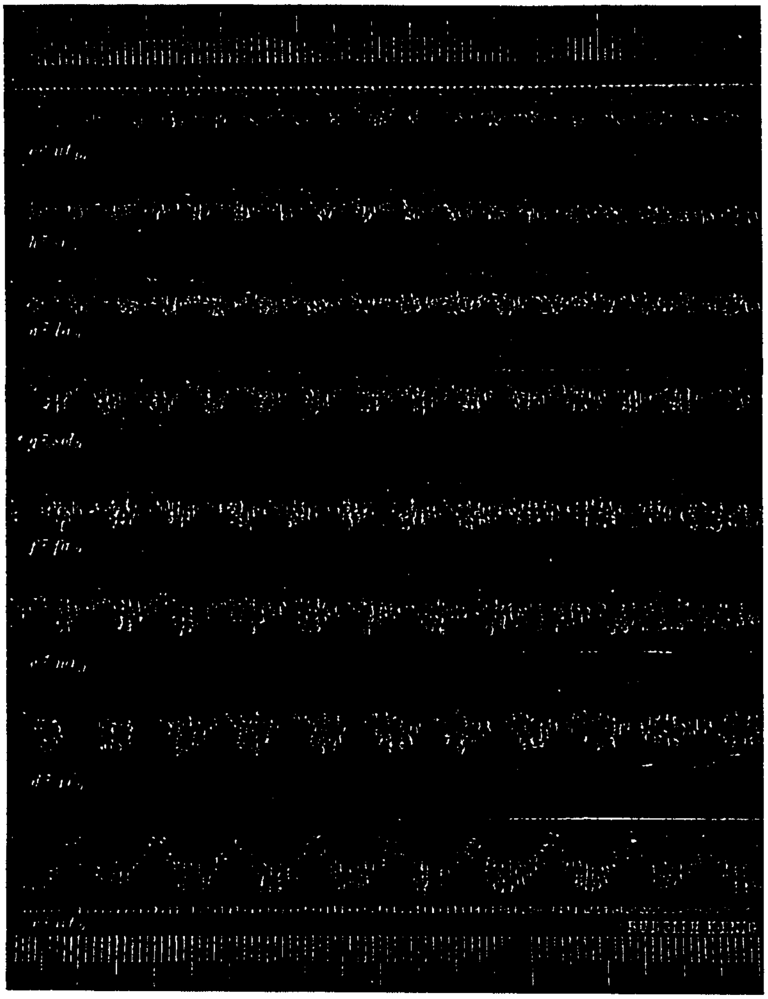

Figure 4.13 Kundt figures for high frequencies. Koenig (1899) 647

CONCLUSIONS

One theme that underlined all of these disputes was the need to reduce human error or dependence on the ear. In the study of vowels and ultrasonics Koenig developed instruments that visually displayed the elusive phenomena. He even developed methods for quantifying these figures. In his work on the standardisation of pitch, he developed an instrument, the clockfork, that completely automated the counting of the vibrations of a tuning fork. One no longer had to discriminate pitch with a good ear, or by using beats, but instead could rely upon a clock mechanism.

Koenig failed to accomplish the same in his two main disputes with Helmholtz. He tried to objectify beat tones and timbre by displaying graphical representations of them, even artificially creating them from waveforms, but as Rayleigh noted, the experiments still depended on the judgement of the listener. This is what happened at Heidelberg in 1889. Koenig demonstrated what he heard to be a difference in timbre; Helmholtz said he heard no difference. Where could the argument go from there?

These disputes revealed fundamental tensions in psychophysics in the latter part of the nineteenth century. Researchers could not always agree on their observations, thus creating much uncertainty. Related problems with the introspectionist methodology (concerns about the credibility of the reports) resulted in an intense focus on precision apparatus and the need to reduce what was called the "personal equation" in the psychology laboratory.[1] In a sense, the brass instruments of the early psychology laboratories masked an underlying insecurity about the subjective source of the data. In the present case, the context of uncertainty about observations translated into an intense focus on purity and precision in instruments. This was how scientists such as Koenig faced the murky boundaries between physics and psychology. In twentieth-century psycho-acoustics, the researcher called upon groups of subjects and statistics to infer what the typical

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[1] Ruth Benshop and Douwa Draaisma, "In Pursuit of Precision: The Calibration of Minds and Machines in Late Nineteenth-Century Psychology," *Annals of Science* 57, no. 1 (2000).

subject probably heard. This is what Plomp tried to do in the 1960s when he revisited the combination-tone and timbre disputes.

One sees in the disputes over combination tones and timbre Koenig's firm belief in the ear's ability to discriminate complex waveforms as a single perceptual event. This was a revealing anticipation of the Gestalt movement of the early twentieth century. Koenig's rejection of Helmholtz's analytic model demonstrated the tensions that gave rise to Gestalt thinking in the psychological and physiological communities of the 1890s. Helmholtz employed a reductionist approach (reducing problems of the mind to problems of physics) that firmly established the links between physiology and psychology. People such as Koenig thought this type of theorising went too far and might have distorted what was really going on. He adopted a more holistic approach to sound phenomena and a more cautious approach to the nervous system.

Graphical and optical instruments played a major role in producing these tensions. They seemed to give people like Koenig and Hermann the freedom to question Helmholtz's analytic model. The visual instruments conditioned and reinforced different conceptions and approaches to the study of sound. Koenig appeared to be an extreme example of someone who interpreted his pictures as a mirror of nature. His instruments shaped his conception of sound. In turn, this conception directly influenced the kind of instruments he made.

This situation is similar to what the philosopher Ian Hacking terms a "self-vindicating" relationship in the laboratory.[2] Theory and instruments reinforce each other strengthening a point of view, and ultimately creating a form of stability in the sciences. In the present case, Koenig was tapping into the older traditions in acoustics that viewed sound as a vibrating string. Distinctive sounds, were simply distinctive vibrating forms. The new graphical instruments powerfully reinforced this older notion, helping to propagate an alternative to the analytic model. Hermann may not have not have been as interested, or even aware of, the older theories of vibrations and wave-

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forms, but the graphical techniques, passed on from Koenig carried this distinctive approach to sound that led him to question the Ohmian model of sound

Helmholtz's instruments - the siren, the piano, resonators and tuning forks – fit his mathematical and physiological conception very tightly and ended up reinforcing, through practice, the analytic notion of sound. The whole system left little room for the problems Koenig and others were experiencing. Ironically, Koenig was the person who spread these instruments.

The two groups of instruments also reflected Helmholtz's and Koenig's attitude towards skill in the laboratory. Helmholtz was more comfortable relying on his listening skills using simpler instruments that were closer to the phenomena.[3] Koenig, on the other hand, appeared to be conditioned by the demands of his clients – the new teaching laboratories throughout Europe and North America – whereby he made instruments that catered to the needs of less skilled experimenters.

Other disciplines in the nineteenth century went through a similar shift toward graphical, automatic instruments. Meteorology, for example, had a long tradition in self-recording instruments.[4] As far back as the 1660s Christopher Wren and Robert Hooke developed a form of self-registering "weather clock" for observing changes in temperature, humidity, wind and pressure. But by the nineteenth century, these kinds of instruments were becoming quite common. George Dolland displayed a sophisticated self-registering meteorological instrument at the London Exhibition in 1851. By 1860 the movement to automate observations had a broad instrumental foundation. These self-recording instruments, regardless of discipline or theoretical commitments, exhibited the attitude to automate, lessen the need for skill, and remove subjectivity.

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[2] Ian Hacking, "The Self-Vindication of the Laboratory Sciences," in *Science as Practice and Culture*, ed. Andrew Pickering (Chicago: The University of Chicago Press, 1991).

[3] Frederic Holmes has written about the relationship between skill and simplicity of instruments in Lavoisier's work. Frederic L. Holmes, "The Evolution of Lavoisier's Chemical Apparatus," in *Instruments and Experimentation in the History of Chemistry*, ed. Frederic L. Holmes and Trevor Levere (Cambridge, Massachusetts: MIT press, 2000).

[4] W.E. Knowles Middleton, *Visibility in Meteorology: The Theory and Practice of the Measurement of Fisual Range*, 2 ed. (Toronto: University of Toronto Press, 1941).
Robert P. Multhauf, *The Introduction of Self-Registering Meteorological Instruments* (Washington D.C.: Smithsonian Institution, 1961).

The Canadian composer, R. Murray Schafer, who is also known as a pioneer "sound ecologist" sees the early graphical studies as the origin of the modern separation between sounds and their sources. "While the science of acoustics has advanced greatly since the nineteenth century, the listening abilities of average mortals have not shown corresponding improvement. In fact, they may have deteriorated in inverse proportion to the pictorialization of sound. Today, many specialists engaged in sonic studies – acousticians, psychologists, audiologists, etc – have no proficiency with sound in any dimension other than the visual."[5]

This raises another unique feature of the early acoustics – the fact that most of its adherents did have an expert ear, and were, like Helmholtz and Koenig music lovers. This gave the field a certain unity, or definition around a culturally determined set of questions. It is amazing, therefore, that Koenig and Helmholtz took such distinctive paths in the study of sound. Helmholtz proposed and defended a bold theory that had remarkable explanatory power and has just as remarkably remained the main framework for studying sound and music; Koenig proposed new methods and instruments that have just as profoundly shaped the way we conceive of, and interact with sound. The tensions created by the coexistence of these two currents of theory and practice formed part of the foundation of modern acoustics.

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[5] R. Murray Schafer, *The Tuning of the World* (Toronto: McClelland and Stewart, 1977) 128.

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