Thing and Form: Seeing Sound, or What's in a Pendulum?

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> The bodily eye . . . cannot see the condensations and rarefactions of the waves of sound. We construct them in thought, and we believe as firmly in their existence as in that of the air itself.
>
> —John Tyndall, 1870[1]

> Humans do not merely assemble different apparatuses for satisfying particular knowledge projects; they themselves are part of the ongoing reconfiguring of the world.
>
> —Karen Barad, 2007[2]

At the height of his fame, the first thing the acoustician Ernst Chladni felt obliged to point out to readers of *Die Akustik* (1802) was the foundational role of the pendulum. Nothing was so obvious or uncontroversial, it seems. By 1602 Galileo had discovered its isochronism—a perfect balance between equal, alternate motions at constant speed—and extrapolated from this the principle of vibratory motion, including, in microcosm, "harmonic motion" that gave rise to the

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1. John Tyndall, *On the Scientific Use of the Imagination* (London: Longmans, Green, 1870), 8.
2. Karen Barad, *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning* (Durham, NC: Duke University Press, 2007), 171.

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perception of what would come to be called simple tones.[3] The story is well known. According to his first biographer, writing in 1654, Galileo observed a lamplighter in Pisa Cathedral who inadvertently pushed a roof-suspended chandelier into swinging motion; upon timing this motion against his own pulse, he noted that even as each swing diminished in length (amplitude), its speed (period) remained constant.[4] The suspicion that Galileo may first have observed this principle of isochrony via *sound*, in the swinging motion of weights attached to vibrating strings in his father's musical experiments (following Vincenzo's realization that the ratio 3:2 applies to *lengths* but not to *tensions* of a string for tuning perfect fifths), remains unproven. But it offers historians of acoustics a case of what Niklas Luhmann called "double contingency," with musical vibration positioned both before and after the common advent of pendular isochrony on which it relies, namely as "a fact [that] is contingent when seen as selection from other possibilities which remain in some sense possibilities despite a selection."[5] Once the paradigm of isochrony was established, few acoustic theorists could do without it. With Mersenne's treatise on vibrating strings (*Harmonie universelle,* 1636),[6] it came to anchor a way of thinking so deeply embedded in models of sound propagation that by 1802

3. The first publication to use this term, where "simple" air vibrations are modeled on the motion of the "simple pendulum," was Alexander J. Ellis, "XXIII. On the Physical Constitution and Relations of Musical Chords," *Proceedings of the Royal Society* 13 (1863–64): 392–404, at 392. See Sigalia Dostrovsky, "Early Vibration Theory: Physics and Music in the Seventeenth Century," *Archive for History of Exact Sciences* 14 (1975): 169–218.

4. Stefano Gattei, ed. and trans., *On the Life of Galileo: Viviani's Historical Account and Other Early Biographies*, ed. and trans. Stefano Gattei (Princeton: Princeton University Press, 2019), 9. Written in 1654, Viviani's *Racconto istorico della vita del Sig.r Galileo Galilei* was first published posthumously, in 1717.

5. Niklas Luhmann, "Generalized Media and the Problem of Contingency," in *Explorations in General Theory in Social Science: Essays in Honor of Talcott Parsons*, ed. J. Loubser, R. C. Baum, A. Effrat, and V. M. Lidz (New York: Free Press, 1976), 507–32, at 509. On the musical origin of a set of laws of motion, see Stillman Drake's claim that "no such revolutionary change in the very nature of science itself would have occurred to Galileo had the musical measurements of his father not first interested him in the motions of pendulums." Stillman Drake, "Music and Philosophy in Early Modern Science," in *Music and Science in the Age of Galileo*, ed. Victor Coelho (Dordrecht: Kluwer, 1992), 3–16, at 11. Viviani's biographical account broadly supports this reading: "As a child, he had also practised music (under the guidance of the great Vincenzo[])] . . . and had his mind imprinted with the equality of times that governs music: accordingly, pondering that motion, it was easy for him to see it as isochronous." Gattei, *On the Life of Galileo*, 64n18.

6. Marin Mersenne, *Harmonie universelle, contenant la théorie et la pratique de la musique*, 2 vols. (Paris: Cramoisy, 1636), vol. 2, book 1, *Livre premier des consonances*, Proposition III, 9, https://gallica.bnf.fr/ark:/12148/bpt6k5471093v/f532.item: "Since all the returns of the string continue the same sound, and since the two-thousandth return of the string is no flatter or sharper than the first or the second, it follows that all these returns joined together produced only the unison" ("Mais puis que tous les retours de la chorde continuent seulement un mesme son, & que le deuxmilliesme retour de la chorde n'est pas plus grave ou plus aigu que le premier ou le second, il s'ensuit que ces retours estant joints ensemble ne peuvent faire que l'Unisson"). Unless otherwise indicated, translations are mine.

Chladni barely thought to justify it.[7] Sonic vibrations travel through liquids and solids faster than through air, he explains, so limiting sound to the study of gasses alone would be incomplete: "One must make it part of the theory of motion [in general] and join it to the theory of pendulums."[8]

The horizon he pointed to—wider than he knew—was a distinction between physical object and immaterial shape, thing and form.[9] This sidestepped the philosophically provocative question of what sound *is* by separating modes of propagation from putative ontology. Yet asserting pendular shapes or patterns of propagation in place of that absent ontology (whether figures as atoms, force, or energy) raised the need for models or visualizations of those pendular motions—that is, an image of waveforms, even if they could often appeal only to a broader "mind's eye" for their authority. Picturing sound was not just a matter of establishing an objective set of techniques for visualizing vibration mechanically, void of human agency. Nor was it a magical unveiling by number, in the sense of Leonard Euler's claim to "render visible the real origin of musical notes . . . the secret [mathematical] power of genuine harmony."[10] Rather, it became a matter of faith in mathematical principles—I argue—and asserted the agency of the viewer as a constituent part of the very ontology being viewed, resulting in an irreducible

7. Mersenne was the first translator of Galileo's works into French. He sent three letters to Galileo (all unanswered) and corresponded at length with Descartes about Galileo's work on pendulums, correcting the latter's observation that the length of the string made no difference to its velocity (Proposition XIX), with an experiment noting how, in amplitudes of two feet and one inch, two otherwise identical pendulums lost one oscillation after thirty oscillations. See Mersenne's translation *Les nouvelles pensées de Galilée* (Paris: Guenon, 1639). The historiographic presentation of the Mersenne-Galileo relationship as one of supportive friendship is misleading; for example, Pierre Boutroux, "Le Père Mersenne et Galilée," *Scientia* 31 (1922): 279–90. See also John Lewis, "Mersenne as Translator and Interpreter of the Works of Galileo," *Modern Language Notes* 127, no. 4 (2012): 754–82.

8. Ernst Chladni, *Treatise on Acoustics: The First Comprehensive English Translation of E. F. F. Chladni's "Traité d'acoustique,"* trans. Robert T. Beyer (Cham: Springer, 2015), 1. See also the mathematician Sir William Thomson's statement from 1867 that "amongst the most important classes of motions which we have to consider in Natural Philosophy, there is one, namely *Harmonic Motion*, which is of such immense use, not only in ordinary kinetics, but in the theories of sound, light, heat, etc., that we make no apology for entering here into some little detail regarding it." Sir William Thomson and Peter Guthrie Tait, *Treatise on Natural Philosophy*, 2 vols. (Oxford: Clarendon Press, 1867), 1:35–36.

9. While theories of "things" have acquired multiple associations, from Martin Heidegger to Bill Brown, I refer here to Aristotle's separation of matter/thing and form (hylomorphism), whose intellectual frame encompasses the breadth of the nineteenth-century discourse on sound as matter-less shape, notably by analysing perception as the reception of form without matter (*De Anima* 2.12, 424a).

10. Leonard Euler, *Letters of Euler on Different Subjects in Physics and Philosophy Addressed to a German Princess*, trans. Henry Hunter, 2 vols. (London: Murray and Highley et al.,1802), 1:24–29 (Letter 7), at 25.

contingency for sound waves, a co-production that appears to blur the boundaries between outside world and perceiving mind.

This opens the door to a broader conception of "seeing" sound during the nineteenth century. For a visually attuned historian like Michel Foucault, all objects of natural history engender modalities of seeing and need to be visualized in order to lend a discourse credibility and coherence, "the possibility of *seeing* what one will be able to *say*."[11] Nineteenth-century investigations into sound, like those into heat and light, offer a comparable discursive object of natural science in this sense, where theatrical public demonstrations at London's Royal Institution or Paris's Panthéon functioned as a necessary component of the empirical pact, both in persuading audiences via collective displays of visual proof, and in unlocking new ways of understanding vibratory motion across all branches of the natural sciences. "Empiricism" was now the battle cry, music critic Richard Pohl told readers of the *Neue Zeitschrift* in 1852, and it extended to ocular as well as to aural proofs of sound.[12] A clever soul will see here a cause, there an effect, but cannot link the two—he explains—for "the eternal enchantress 'living force' has once again veiled herself in a thousand shrouds, concealed herself in a thousand forms, before she becomes visible and recognizable to us. But she *is* there—only seek the *key* to her workshop."[13] Sound's transience meant that this key was forever disappearing, however. Like fleeting acts of hearing, a temporality of *seeing* encompassed the constant motion that Michael Faraday discovered in seemingly static dust plate particles alongside the constant fading of retinal impressions.[14] This situation foregrounded an irreducibly material dependency between observer and object, marking the shared properties of experimental imaging techniques that can "shape the kind of scientific knowledge they enable," as Chitra Ramalingam puts it.[15] In the context of the agon between idealism and materialism underpinning this period, it is here, in

11. Michel Foucault, *The Order of Things: An Archaeology of the Human Sciences* (London: Routledge, 2002), 141. On Foucault as a visualist historian, see Rebecca A. Longtin, "Mapping Transformations: The Visual Language of Foucault's Archaeological Method," *Epoché: A Journal for the History of Philosophy* 23 (2018): 219–38, and John Rajchman, "Foucault's Art of Seeing," *October* 44 (1988): 88–117.

12. Richard Pohl, *Akustische Briefe für Musiker und Musikfreunde: Eine populäre Darstellung der Akustik als Wissenschaft in Beziehung zur Tonkunst* (Leipzig: Hinze, 1853), 4. These letters were first serialized in *Neue Zeitschrift für Musik* 37–38 (1852–53). See also Peter Pesic, "Thomas Young's Musical Optics: Translating Sound into Light," *Osiris* 28, no. 1 (2013): 15–39.

13. Pohl, *Akustische Briefe*, 28: "hier hat sich also die ewige Zauberin 'lebendige Kraft' wieder ein Mal in tausend Schleier gehüllt, in tausend Gestalten verborgen, ehe sie uns sichtbar und erkennebar wird. Aber sie *ist* da—suche nur den *Schlüssel* zur Werkstatt."

14. Michael Faraday, "On a Peculiar Class of Acoustical Figures; and on Certain Forms Assumed by Groups of Particles upon Vibrating Elastic Surfaces," *Philosophical Transactions of the Royal Society of London* 121 (1831): 299–340.

15. Chitra Ramalingam, "Dust Plate, Retina, Photograph: Imaging on Experimental Surfaces in Early Nineteenth-Century Physics," *Science in Context* 28, no. 3 (2015): 317–55, at 320.

a distinction between thing and form, that the structures of knowledge holding apart these intellectual perspectives on sound can begin to coalesce. This is not to artificially bridge what remained different worldviews. It suffices to draw attention to their shared inscrutability within nineteenth-century metaphysics and the crucible on which any coalescence was to be founded: the impulse to visualize sound.

Accordingly, this article investigates a desire among empiricists for ocular proof of sound waves via the pendulum. It traces a genealogy of devices for visualizing sonic vibrations as a means of knowing what sound is, and places these within an (Aristotelean) distinction between matter and form, seeking thereby to interpret from afar a wider collision of empiricism and imagination among experimentalists and philosophers. Many experimentalists sought to relate acoustics, causality, and sense perception via epistemic tools—I touch primarily on Charles Wheatstone, John Herschel, Hermann von Helmholtz, John Tyndall, Jules Lissajous, and Édouard-Léon Scott de Martinville—but by the 1850s this only raised the question of the observer's agency in imagining the behavior of invisible sound, thereby "reconfiguring the world" in Karen Barad's words. I pursue Helmholtz's doubts about this, namely whether a visual representation of wave propagation expressed an ontology—what was actually in the air—or whether this was always a "mathematical fiction," an impenetrable scheme of representation behind which no observer could see. And finally, I take seriously his later argument that it is not the experimentalist but "the artist who has beheld the real,"[16] leading to the possibility that *musical* evocations of waveforms, by composers as diverse as Franz Liszt and Amy Beach, share at least an equal epistemic validity with visualizations afforded by the numerous tools devised for representing sound waves.

In Defense of "Philosophical Toys"

On February 19, 1848, London's weekly *Literary Gazette* (1817–63) carried a startling announcement under the heading "Sound Visible!":

> In this age of wonders, what will the world think when we assure it that a method has been discovered and matured by which *sound will be made visible to the human eye,* its various forms and waves demonstrated to sight, and the power to discriminate between the tones of one musical instrument and another be as complete as to observe the action of water when disturbed by any material cause. The experiments, we believe, are likely

16. Hermann von Helmholtz, "The Facts in Perception" (1878), in *Science and Culture: Popular and Philosophical Essays,* ed. and trans. David Cahan (Chicago: Chicago University Press, 1995), 342–80, at 355.

> to be ere long repeated in the Royal Society. The exhibition of effects on fine sand has probably led to this astonishing issue.[17]

This anonymous claim sparked immediate curiosity. Ostensibly, it pointed to a breakthrough beyond Chladni's sound figures in "fine sand," and was breathlessly reprinted in a cluster of British and American journals between February and May of the same year.[18] From a comparative perspective, the visualization of sound was not inconceivable. As early as 1825 the Weber brothers' monumental study of wave motion in fluids, dedicated to Chladni ("the founder of experimental acoustics"),[19] had devised a glass-paneled instrument called a "wave trough" (*Wellenrinne*) to reveal the movement of compound waves by using fluids of different colors and different specific weights layered horizontally on top of one another (see fig. 1a). Wave motion visible on the surface of a liquid was also present in its depths, they argued. The submerged waves could not be seen, but a "pulsating movement" ("schwingende Bewegung") could where "the particles of the liquid lying perpendicularly, or almost perpendicularly, below [those of the surface wave] appear to enter the *corresponding points* of their oscillation paths *simultaneously*."[20] These simultaneous paths, in short, are what were separated out by layering differently colored and weighted liquids in a wave trough: "In this way one can see different horizontal layers, each of which is traversed by waves, which cannot be seen if the entire channel is filled only with water, although even then similar waves move inside the water."[21] Lithographs were created to show a cross section of one full and two half waves of mercury, shown in figure 1b, as transcribed from eye to hand; the Webers then telescoped these layered motions into one plane to produce a theoretical model of their interaction as an invisible (submerged) compound wave (fig. 1c). Given this precedent, it seems the corresponding visualization of sound waves in air became plausible. After all, the *Gazette*'s announcement of "sound visible" had likened pitch discernment directly to observing "the action of water." No comparable demonstration at

17. "Sound Visible!," *Literary Gazette, and Journal of the Belles Lettres, Arts, Sciences, &c.*, February 19, 1848, 135.

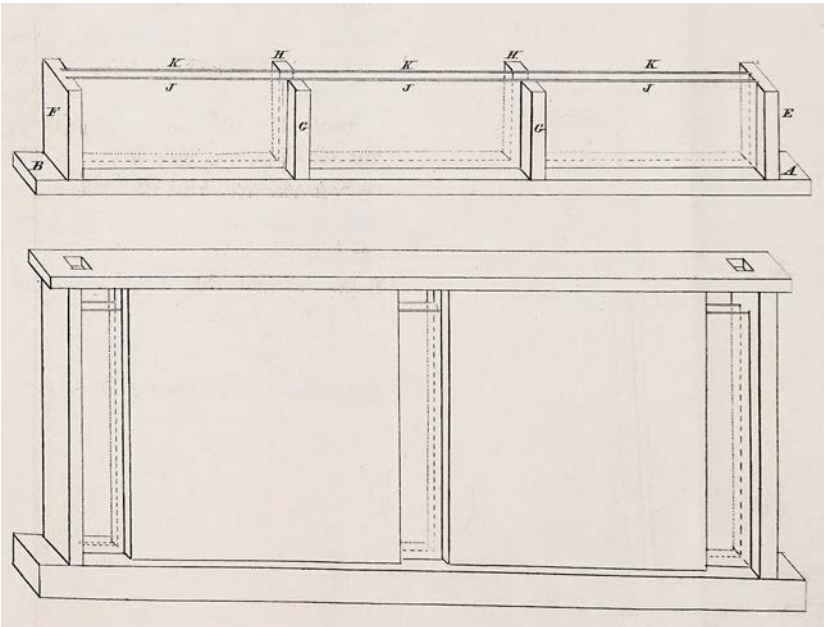
18. The paragraph was reprinted in the *Patents Journal and Inventors' Magazine*, February 26, 1848, 329, and *The Lancet*, March 4, 1848, 273, in Great Britain; and in *Scientific American*, April 8, 1848, 230, and the *Golden Rule*, May 27, 1848, 346, in North America.

19. Ernst Heinrich Weber and Wilhelm Weber, *Wellenlehre auf Experimente gegründet* (Leipzig: Gerhard Fleischer, 1825), front matter: "de[r] Begründer einer auf Versuchen beruhrenden Akustik."

20. Weber and Weber, *Wellenlehre*, 127: "die senkrecht, oder fast senkrecht unter einander liegenden Theilchen der Flüssigkeit scheinen dem Anblicke nach *gleichzeitig* in die *sich entsprechenden* Puncte ihrer Schwingungsbahnen einzutreten."

21. Weber and Weber, *Wellenlehre*, 107: "Man sieht auf diese Weise verschiedene horizontale Schichten, von den jede von Wellen durchlaufen wird, die man, wenn die ganze Rinne nur von Wasser erfüllt wird, nicht sehen kann, obgleich auch dann ähnliche Wellen sich im Innern des Wassers fortbewegen."

FIGURE 1A. The Webers' two designs for a wave trough, each made of spruce, with the smaller comprising six glass panels (K, J), to display wave motion under controlled conditions. Pairs of panels are to be filled "with water, mercury, milk, brandy etc. to any height." Ernst Heinrich Weber and Wilhelm Weber, *Wellenlehre auf Experimente gegründet* (Leipzig: Gerhard Fleischer, 1825), figs. 12–13, 105. By permission of the Master and Fellows of Trinity College, Cambridge.



Edinburgh's Royal Society or London's Royal Institute followed, however. Nor were follow-up discussions published in the *Gazette*, then in the final years of its editorship by Scotsman William Jerdan, who was not known for tolerating hoaxes.

While hoax cannot be ruled out, the claim concerning sound visualization almost certainly relates to the Scottish physicist and mathematician William Swan (1818–94), whose recommendation for election to the Royal Society of Edinburgh occurred just one day before the *Gazette*'s announcement, on February 18, 1848.[22] A year earlier, Swan had published a paper on measuring the refraction of light through

22. Swan was proposed by the mathematician Reverend Professor Phillip Kelland, and his membership was approved by the council on March 3. See the nomination form at the Royal Society of Edinburgh Archives ACC10000/47.

FIGURE 1B. The Webers' vertical cross section of wave motion in mercury, showing one full and two half waves, the arrows indicating lines and direction of pressure in and between each wave form. Weber and Weber, *Wellenlehre*, fig. 28. By permission of the Master and Fellows of Trinity College, Cambridge.

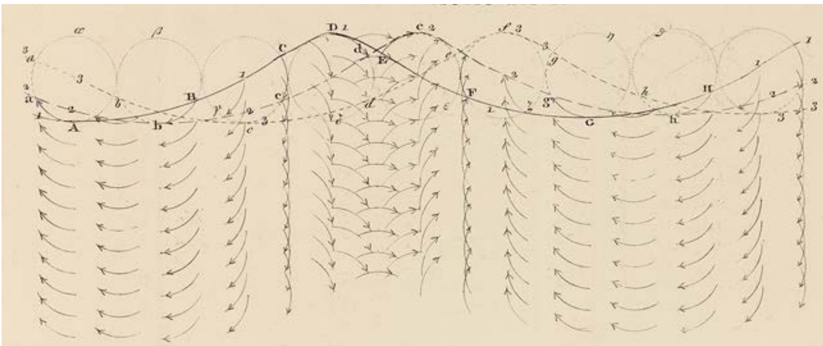
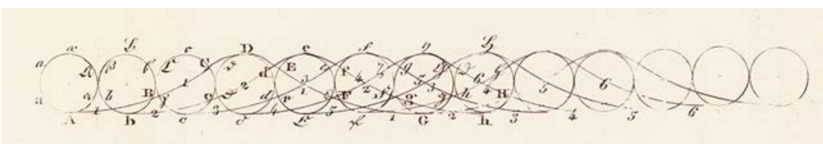


FIGURE 1C. The layered motions shown in figure 1b telescoped into a single plane, showing the circular path of an individual particle, from ABCDEF to abcdef, and divided into six parts. Weber and Weber, *Wellenlehre*, fig. 29. By permission of the Master and Fellows of Trinity College, Cambridge.



crystal,[23] and he worked thereafter to adapt a recently developed Y-shaped pendulum technique (where one pendulum balances two competing swing impulses in a single inscription apparatus) to the purposes of acoustic writing. To this he added the key ingredient that the motion be driven by a sounding tuning fork. The resulting vibrations were simultaneously audible *and* rendered visible. First sand, then electrical sparks "wrote" the curves of his tuning forks in a series of demonstrations leaving a visual trace either on paper or on the retina. A description of these innovations is to be found in an 1879 article by physicist Joachim Hagen:

23. William Swan, "Experiments on the Ordinary Refraction of Iceland Spar," *Transactions of the Royal Society of Edinburgh* 16 (1847): 375–78.

> One of [Swan's] methods consisted in letting sand flow out of a fine opening at the lower end of the pendulum bob. In the Lectures he also let the graphics be executed by electric sparks by using wires of soft iron for suspension, fitted the lower end of the pendulum body with a metal tip and one pole of a Ruhmkorff induction apparatus connected to one of the two suspension points of the pendulum, while the other pole was connected to a tinfoil plate that was lying on a table immediately below the aforementioned metal point.[24]

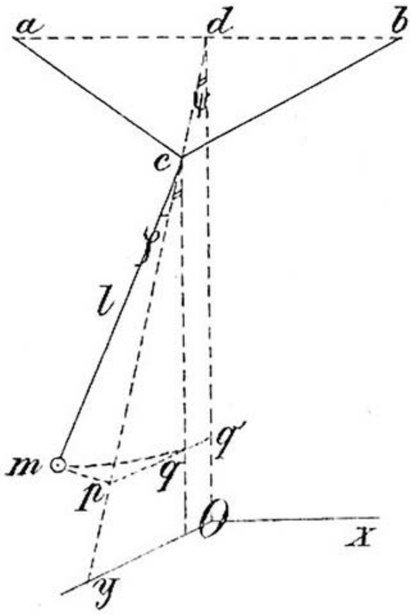
Taken at face value, writing sound in fire in this way was probably the novelty that prompted the *Gazette*'s premature scoop in 1848. "As far as I know," Hagen concludes, "William Swan . . . was the first to use [a pendulum body swinging in two perpendicular vertical planes] for the graphic tracing of tuning fork curves."[25] His retrospective illustration of Swan's apparatus is reproduced as figure 2. While none of Swan's own publications refer to these early experiments, his 1849 article "On the Gradual Production of Luminous Impressions on the Eye, and Other Phenomena of Vision" describes the attempt to measure the time taken for visual impressions of sparks to register fully on the retina.[26] His objective of improving retinal recall led him to conclude that extending the duration of an electric spark by 1/100th of a second would increase its apparent brightness by a measure of 10,000, with continuous sparking increasing it 100,000-fold. This, along with references in his private correspondence to "defective observations" in John Herschel's 1823 work

24. Joachim Hagen, "Ueber die Verwendung des Pendels zur graphischen Darstellung der Stimmgabelcurven," *Zeitschrift für Mathematik und Physik* 24 (1879): 285–303, at 286: "Eine seiner Methoden bestand darin, dass er am untern Ende des Pendelkörpers aus einer feinen Oeffnung Sand ausströmen liess. In den Vorlesungen liess er die Zeichnungen auch durch elektrische Funken ausführen, indem er Drähte von weichem Eisen zur Aufhängung benutzte, den Pendelkörper an seinem untern Ende mit einer Metallspitze versah und den einen Pol eines Ruhmkorff'schen Inductionsapparates mit einem der beiden Aufhängepunkte des Pendels verband, während der andere Pol mit einem Staniolplättchen in Verbindung stand, das auf einem Tische unmittelbar unter der erwähnten Metallspitze lag."

25. Hagen, "Ueber die Verwendung des Pendels," 286: "Soviel mir bekannt ist, [wurde den Pendelkörper in zwei zu einander senkrechten Vertikalenebenen schwingen] zuerst von Herrn William Swan . . . zur graphischen Darstellung der Stimmgabelcurven benutzt." A list of nineteenth-century instrument makers (not including Swan) who built pendulum-tracing devices is given in Arturo Gallozzi and Rodolfo Maria Stollo, "Between Mechanics and Harmony: The Drawing of Lissajous Curves," *Foundations of Science* 29, no. 1 (2024): 205–24, at 216.

26. William Swan, "On the Gradual Production of Luminous Impressions on the Eye, and Other Phenomena of Vision," *Transactions of the Royal Society of Edinburgh* 16 (1849): 581–603, at 602. This built on Charles Wheatstone's attempt to measure the velocity of sparks in a rotating mirror, where the hidden evolution of a spark's shape was revealed in its reflected images in different snapshots. Charles Wheatstone, "An Account of Some Experiments to Measure the Velocity of Electricity and the Duration of Electric Light," *Philosophical Transactions of the Royal Society of London* 124 (1834): 583–91.

FIGURE 2. A retrospective illustration of the mechanism behind William Swan's Y-shaped pendulum of 1848. Joachim Hagen, "Ueber die Verwendung des Pendels zur graphischen Darstellung der Stimmgabelcurven," *Zeitschrift für Mathematik und Physik* 24 (1879): 285–303, table 4, fig. 1. Credit: Niedersächsische Staats- und Universitätsbibliothek Göttingen.



on "the spectrum of flames" and the need for a "graphic comparison of my results with those of others," makes it at least plausible that he may at one time have struggled to follow the optical path of a sparking pendulum bob driven by auditory vibrations.[27]

Placing this experiment in the context of others reveals what was particular about it. During the 1830s and 1840s, connections between acoustic figures and the transmission of electricity, including vigilant observation of sparks, led to "an implicit and shared phenomenology of experimentation" between these apparently disparate fields.[28] This focus on defining the temporality of perception was new within the

27. Swan to J. D. Forbes, May 10, 1856, Archives of the University of St. Andrews, J. D. Forbes collection. He was referring to John Herschel's article "On the Absorption of Light by Coloured Media, and on the Colours of the Prismatic Spectrum Exhibited by Certain Flames," *Transactions of the Royal Society of Edinburgh* 9 (1823): 445–60.

28. Ramalingam, "Dust Plate, Retina, Photograph," 320.

history of acoustics. Before it, the English polymath Thomas Young (1773–1829) and the French mathematician Jean-Marie Duhamel (1797–1872) had unveiled what are usually understood as the earliest devices for graphically inscribing the vibrations of a sounding fork.[29] Young's "vibrograph" (1807) and Duhamel's "vibroscope" (1853) were essentially adapted lathes (the most common machines found in Parisian workshops, with the majority driven by hand or foot), so neither included a pendulum mechanism. The vibroscope, shown in figure 3, comprised a horizontal cylinder, wrapped in smoke-blackened paper, to be rotated on its axis by a crank handle.[30] Perpendicular to this, Duhamel brought a modified tuning fork into direct contact with the paper, via a light brass stylus affixed with wax to one of its prongs. When the cylinder rotated without the fork vibrating, the stylus carved a helix into the smoke black; when the fork was bowed into vibrating motion, the helix became sinuous, with each sinusoid corresponding to a complete vibration.[31] As a writing system, this was understood to do for the eye what the acoustic siren had done for the ear, namely provide a means of measuring vibrations within a given unit of time. There was no claim to visualize sound itself, suggesting that the vibroscope's status remained that of a simple counting device. Absent the tuning fork, it joined other, non-pendular techniques for visualizing acoustic vibrations that had existed for decades as philosophical amusements.

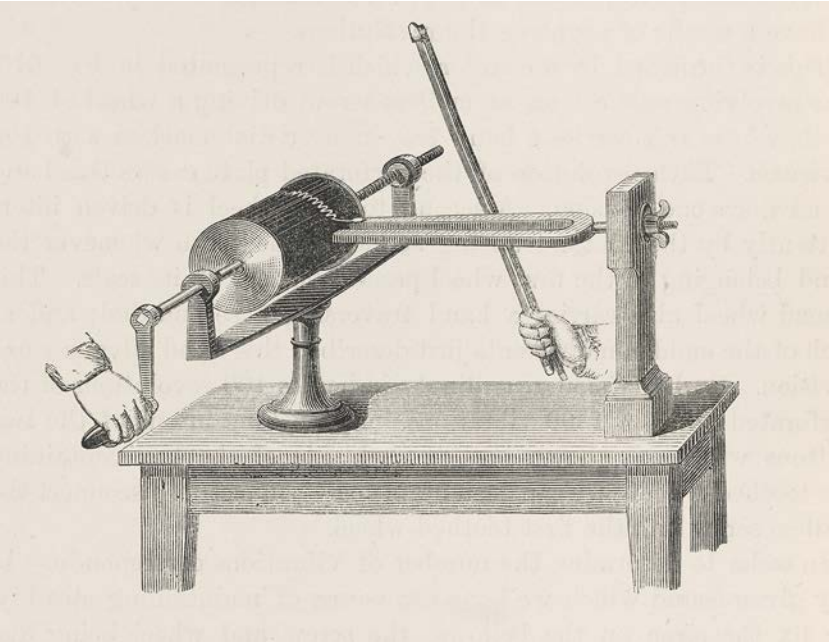
Most prominently, Charles Wheatstone's "kaleidophone" (1827) had dazzled London audiences with its illustration of symmetrical patterns, placing him at the "forefront of bringing new forms of sonorous analysis to popular audiences in 1820s London," as Edward Gillin

29. The canon is given in Jules Lissajous, "Mémoire sur l'étude optique des mouvements vibratoires," *Annales de chimie et de physique* 51 (1857): 147–231, at 148. Duhamel's role was most credited in Paul-Quentin Desains, *Leçons de physique*, 2 vols. (Paris: Dezobry, E. Magdeleine, 1857–60), 2:29–30. Young's role has been pieced together by recent historians. See Andrew Robinson, *The Last Man Who Knew Everything* (Cambridge: Open Book, 2006), 165–78, and Peter Pesic, "Young's Musical Optics," *Osiris* 28, no. 1 (2013): 15–39. An anomaly in the origins story is Franz Pisko, who credits Wilhelm Weber as the inventor of "Phonautographie," or graphic inscription of tuning fork vibrations, in 1830, without providing details. Franz Josef Pisko, *Die neueren Apparate der Akustik* (Vienna: Carl Gerold's Sohn, 1865), 56. By 1870, permanence was an explicitly valued feature: "By plunging the paper in ether, the trace will be fixed, so that the paper may be laid aside, and the vibrations counted at leisure." A. Privat-Deschanel, *Elementary Treatise on Natural Philosophy* (1870), trans. J. D. Everett, 4 vols., 10th ed. (New York: Appleton, 1891), 4:905.

30. See David Pantalony, *Altered Sensations: Rudolph Koenig's Acoustical Workshop in Nineteenth-Century Paris* (Dordrecht: Springer, 2009), 39. References in secondary literature claiming that the vibroscope emerged in 1843 are not supported and appear to be the result of a typographical error introduced in 1983 and subsequently copied. See Richard James Burgess, *The History of Music Production* (Oxford: Oxford University Press, 2013), 3, and Gerard L'Estrange Turner, *Nineteenth-Century Scientific Instruments* (London: Sotheby Publications, University of California Press, 1983), 138.

31. See the contemporary description given in Desains, *Leçons de physique*, 2:29–30.

FIGURE 3. Jean-Marie Duhamel's vibroscope (1853), depicting the inscription of tuning fork vibrations onto smoke-blackened paper, here with oversize tuning fork and crank handle. Augustin Privat-Deschanel, *Elementary Treatise on Natural Philosophy*, trans. J. D. Everett, 10th ed. (London: Blackie & Son, 1891), 904. Credit: Cambridge University Library.

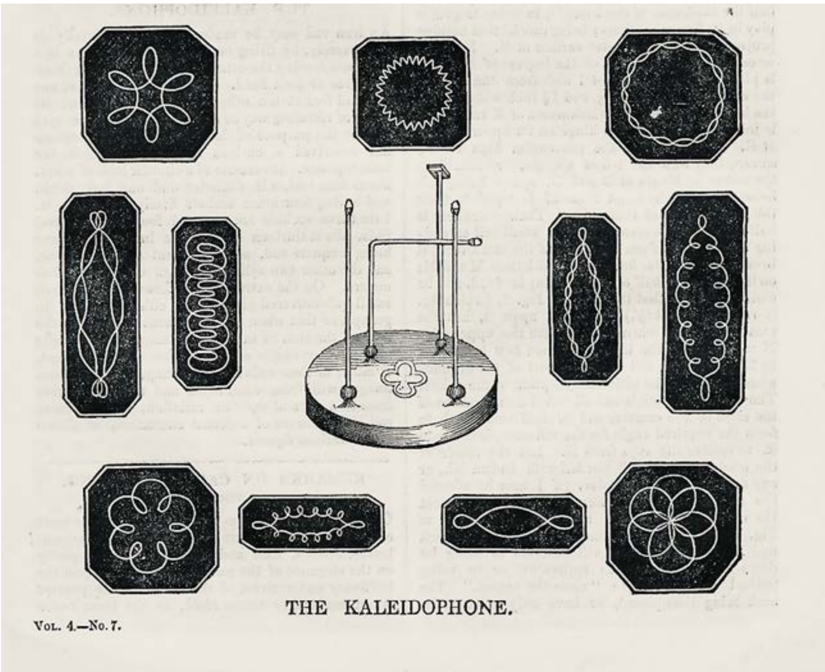


notes.[32] This early apparatus consisted of three steel rods affixed onto a solid wooden board. Each rod's tip held a different device: a silvered glass bead to reflect light, a moving mirror plate, and a four-sided prism, respectively. In concert, these reflected the oscillation of the rods when each was set into motion by a bow stroke or hammer strike. A fourth rod, placed horizontally, had a second silvered bead for the reflection of compound wave patterns. As the frontispiece of an issue of the *Magazine of Science* from 1842 shows (fig. 4), these collectively reflected a faint beam resulting in changing symmetrical shapes, becoming ever smaller, that Wheatstone likened to an ornamental "engine-turning."[33] But he

32. Edward J. Gillin, *Sound Authorities: Scientific and Musical Knowledge in Nineteenth-Century Britain* (Chicago: University of Chicago Press, 2021), 40.

33. Charles Wheatstone, "Description of the Kaleidophone, or Phonic Kaleidoscope: A New Philosophical Toy, for the Illustration of Several Interesting and Amusing Acoustical

FIGURE 4. Charles Wheatstone's kaleidophone (1827), advertised on the frontispiece of the *Magazine of Science* on May 14, 1842, showing the apparatus (center) encircled by examples of the variety of its resulting vibrational patterns. Credit: Cambridge University Library.



distanced himself from any deeper claims at the outset by declaring his invention a mere "philosophical toy," a result of "the application of the principles of science to ornamental and amusing purposes."[34] Entertainment formed a necessary part of the popularizing agenda for public science, so his dismissal of any hypothetical significance for his work is understandable, but it also points to professional reticence over the very question of visualizing sound.

and Optical Phenomena" (1827), in *The Scientific Papers of Sir Charles Wheatstone* (1879; Cambridge: Cambridge University Press, 2011), 27.

34. Wheatstone, "Description of the Kaleidophone," 21. On the question of philosophical toys, see the chapters by Myles W. Jackson, "Charles Wheatstone: Musical Instrument Making, Natural Philosophy, and Acoustics in Early Nineteenth-Century London," and Melissa Dickson, "Charles Wheatstone's Enchanted Lyre and the Spectacle of Sound," in *Sound Knowledge: Music and Science in London, 1789–1851*, ed. James Q. Davies and Ellen Lockhart (Chicago: Chicago University Press, 2016), 101–24, 125–44.

Ordered progressively rather than chronologically, the claims accompanying these devices proceed from the trivial (Wheatstone's toy offering "another proof, that . . . the most beautiful order and symmetry prevail through all"),[35] to the quantitative (Young and Duhamel's tool for optically measuring sinusoids), and finally to the fantastical, a pendulum-driven, sounding visualization of auditory vibrations, or "sound visible" (Swan). What led to the amplification of a "philosophical toy" into a scientific "wonder" (the *Gazette*'s overly bold claim for pendulum sparks) was, it seems, the alliance of a sounding fork with the pendulum (Wheatstone's kaleidophone was silent; Duhamel's vibroscope had no visible pendulum). The fork offered sentient proof of sound, the pendulum its modern, physical anchor in the world. Expressed differently, sounding forks could be heard but vibrated too fast to be seen; pendulums moved too slowly to sound but regulated the principle of harmonic motion in acoustics. Swan's device interwove these affordances, which set it apart.

Not all were persuaded. And predictably, the *Gazette*'s promise of sound "made visible" met with rebuttals. One dry-eyed reply, from a Welsh doctor writing in London's *Medical Times*, effectively forecast the lines of a future debate. After the expected Berkeleyan correction[36]—that sound has no existence independently of a perceiving mind, so all that could be demonstrated would be the vibrations that *produce* the sensation of sound—J. W. Moses restricts the nature of what may be made visual to "a *cause* of sound," contradistinguishing this from "sound itself," as though to unveil sound in itself would commit a kind of secular profanity, an attempt to see behind nature's curtain.[37] What could be revealed, by contrast, were causal tracings of vibration, for these were mechanical and dealt in Newtonian laws:

> It is easy to conceive that delicate impulses and vibrations may be made manifest to the sight by an equally delicate mechanical contrivance, and that the different tones of various instruments may be discriminated by such apparatus. But still this is not rendering "sound visible," nor is it demonstrating the effects of sound . . . [which] are feelings which surely cannot be made visible by any mechanical contrivance.[38]

35. Wheatstone, "Description of the Kaleidophone," 21.

36. George Berkeley's arguments over immateriality are foundational for modern idealism and explicitly included sound. In his *Three Dialogues between Hylas and Philonous* (1713), the former (named after "hyle"/ὕλη, the Greek word for matter) is driven to concede, "I had better admit that sounds also have no real existence outside the mind." George Berkeley, *Three Dialogues between Hylas and Philonous*, in the version by Jonathan Bennett presented at www.earlymoderntexts.com/assets/pdfs/berkeley1713part1.pdf, 9.

37. J. W. Moses, "Sound Visible," *Medical Times*, March 14, 1848, 467.

38. Moses, "Sound Visible," 467.

One cannot but have sympathy with these distinctions, and in 1848 others chimed in.[39] Experimental science might reveal the physical mechanism of sound but not its affective power. This had been presented as a contradiction fully a century earlier. To quote Berkeley, "If sound is a sensation, how can it exist in the air, if by 'the air' you mean a senseless substance existing outside the mind?"[40] By mid-century, the *sensations* of heard sound were untranscribable, thus "sound itself" remained inscrutable. Swan's pendulum only made the hidden *causes* of sound visible. But—critically—these causes were now assumed within the air.

If we step outside the lab and into the concert hall, the tension between sonic cause and effect/affect becomes dramatized. European concert listeners of all stripes could see *where* sound was produced—the sinews of singers' trained bodies, vibrating soundboards, virtuosic fingers manipulating objects engineered for resonance—but not *what* it was. The frisson of offstage effects for theater audiences only heightened this uncertainty; it depended on an acousmatic principle whereby the effects of sound could continue to be felt despite its point of origin remaining hidden—a denial of visual contact that stoked a desire to identify the cause.[41] In the staged narratives of opera, acousmatic devices typically invoked the imaginary: witness the invisible spirits in the Wolf's Glen Scene of Weber's *Der Freischütz* (1821) that give voice to Max's psychological trauma. But visual separation from a sonic source could also operate as a metaphor for blindness, as an inability to see/understand. Consider the massed chorus of the Trojan public at the end of act 1 of Berlioz's *Les Troyens* (1863), which moves between various locations behind the stage to convey a spatial sense of people approaching, then eventually joins Cassandra onstage before moving offstage again. This dramaturgical strategy thematizes her isolation in warning against the wooden horse, but also a collective blindness to the danger that she desperately reflects back onto the approaching horse: "Lead him to the abyss by closing his eyes" ("Le conduire à l'abîme en lui fermant les yeux!"). In all cases, playing with sound's concealed causes has the effect of stoking intrigue. The underlying principle remains that of the acousmatics listening to Pythagoras's spectral voice behind a curtain. In the words of Pierre Schaeffer, "Pythagoras' curtain doesn't suffice to divert our curiosity, which is

39. See, for example, "Sound Visible," *Golden Rule*, May 27, 1848, 346: "the effects of sound may be made visible, and have been before now many a time, but sound itself can never be made visible."

40. Berkeley, *Three Dialogues*, 8.

41. On the history of acousmatic sound, see Brian Kane, *Sound Unseen: Acousmatic Sound in Theory and Practice* (New York: Oxford University Press, 2014), 45–72.

instinctively, almost unstoppably occupied by what lies behind."[42] Separating causal agency from ontology makes intuitive sense, in other words, because it satisfies this curiosity, which helps explain why the idea of conflating sound-causing objects with sound "itself" was largely alien to nineteenth-century acousticians.

Sound, Shape, and "Absolute Space"

As a result, sound was consistently pictured in the air, as emanating from its causal objects—as signal or substance connecting ear and vibrating body. It had been considered as such at least since Aristotle's *De Anima*, where it exemplifies the philosopher's broader categorical separation of matter from form: "The air itself, which is easily dispersed, is not productive of sound, but its movement, whenever it is prevented from dispersing, is sound. . . . [S]ound is a certain movement of air."[43] This is often cited as the first statement in Western philosophy to place sound in the air. Less appreciated perhaps is the non-material sense in which Aristotle posits the air's movement, and its implications for nineteenth-century debates over the materiality of waveforms. In short, he argues that sound moves but the air remains still (unlike when the wind blows), making sound a kind of matter-less form;[44] it is precisely the stillness of the air's matter, both within the ear and between listener and struck object, that for Aristotle permits sounds to move along it. This non-physical process articulates his separation of matter from form, as noted above, leading Myles Burnyeat to call sound "a quasi movement" because "Aristotelian physics does not recognize the movement of a wave or a vibration properly so called. . . . Sound, therefore, is a travelling of form alone . . . without material processes."[45] In Aristotle's complementary logic, sense impressions such as sound, heat, or color were received via a stamping process of visualized, matter-less shapes: "A sense is what is capable of receiving sensible forms without matter, as wax receives the

42. Pierre Schaeffer, *Traité des objets musicaux* (Paris: Seuil, 1966), 184. Translation from Mladan Dolar, *A Voice and Nothing More* (Cambridge, MA: MIT Press, 2006), 66.

43. Aristotle, *De Anima*, trans. Hugh Lawson-Tancred (London: Penguin, 1986), 2.8, 420a9–11 and 420b11.

44. Aristotle's closest analogy, Burnyeat suggests, is that of smell, whose movement in air Aristotle likens to the passage of ice freezing over water in a linear path. The water's form changes progressively as freezing takes place, but its substance remains. Myles Burnyeat, "How Much Happens When Aristotle Sees Red and Hears Middle C? Remarks on *De Anima 2.7–8*," in *Essays on Aristotle's "De Anima,"* ed. Martha C. Nussbaum and Amélie Oksenberg Rorty (Oxford: Oxford University Press, 1993), 421–34, at 430.

45. Burnyeat, "How Much Happens When Aristotle Sees Red," 430.

marking of the ring without the iron or gold; it takes on the golden or brazen marking, but not insofar as it is gold or insofar as it is bronze."[46] Echoes of phonographic cylinders aside, here the wax/sense impression is emblematic of what might be called the negative matter of form—the removed metal stamp; that is, it visualizes an understanding of sound perception by placing a non-physical form at the discourse's genesis.

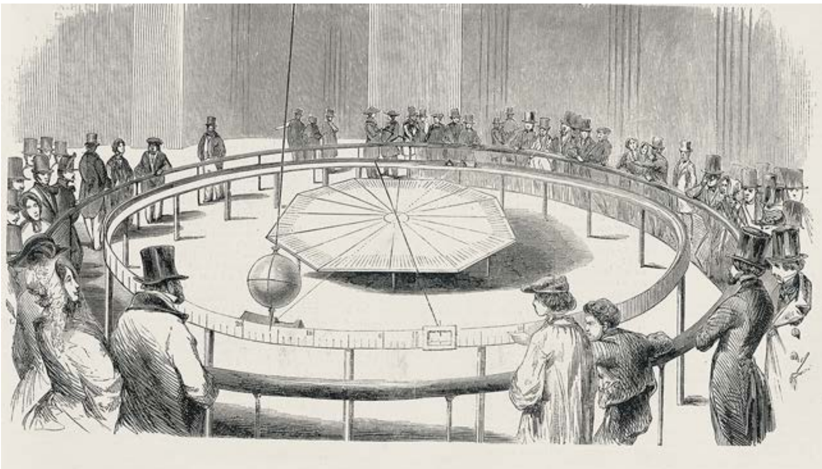
Amid the vast historiography of *De Anima*, the legacy of this unseeable behavior has allowed uncertainty to linger into the present. *Pace* Aristotle, at least one recent philosopher argues that sound should be identified not with invisible vibrations but with their origin, namely vibrations in the sound-producing object: "We should think of sounds as existing within the object that 'makes' them," argues Robert Pasnau. The only reason such a view never took hold, he continues, is an epistemic need for mystery within metaphysics after Aristotle: "Surely sound is more than [simple motion], or so [our ancestors] thought. So they took the sound out of the object, where it belongs, and put sound into the invisible air. There its nature could remain a comfortable mystery, a primitive quality of the medium, caused by motion, but somehow something more than motion."[47] As refreshing as this reclassification is, the specter of post-Aristotelian conspirators smuggling ambiguity into musical sound presents a tautology, for abstract sound was already an inherently polyvalent sign, irreducible to mathematically simple motion, as a numerical sign, and ungeneralizable in the private relational ontology it forms for individual listeners. Moreover, locating sound within the physical substance of the object itself risks returning it to an early modern episteme of (Locke's) secondary qualities. Pasnau's true insight, then, is to register just how conceptually unstable invisible properties of matter remained, underscoring recent calls within the philosophy of science to acknowledge that "the primary ontological units [of matter] are not 'things' but phenomena," as Barad argues, "dynamic topological reconfigurings/entanglements/rationalities/(re)articulations of the world."[48] These acts also foreground the roles of language and discursive practices in asserting a reality for natural objects like sound waves, the perception of which is dependent on merged agencies of visualizing apparatus and the contingencies of human cognition.

46. Aristotle, *De Anima* 2.12, 424a. Translation from Burnyeat, "How Much Happens When Aristotle Sees Red," 431.

47. Robert Pasnau, "What Is Sound?," *Philosophical Quarterly* 49, no. 196 (1999): 309–24, at 316, 323.

48. Barad, *Meeting the Universe Halfway*, 141.

FIGURE 5. Léon Foucault's first public demonstration of a pendulum in 1851, suspended sixty-seven meters from the ceiling of the Panthéon in Paris, whose imperceptibly slow motion around the circle depicted the rotation of the earth. *L'Illustration: Journal universel*, April 5, 1851, 213. Credit: Gallica, Bibliothèque nationale de France.



In the early nineteenth century, the idea that sound propagates as a matter-less shape, in Aristotle's sense, was taken up explicitly by British astronomer John Herschel as the basis for his treatise on sound for the *Encyclopedia Metropolitana* of 1830, which essentially applied the postulate of "a travelling form . . . without material process" to modern experimental physics. It would become one of the most influential English texts on acoustics of the century.[49] The basic principle is that a violin's pattern of aerial oscillations is not a material object. It does not belong to the vibrating wood, or to the performer's body, or to the bow arc or finger trajectory. "It belongs to space—to absolute space," as the physicist Léon Foucault would say of his pendulum, which first visualized the earth's rotation in January 1851 in the basement of his mother's house, and a month later at the Panthéon in Paris (see fig. 5).[50] Foucault had wanted

49. Its authority was succeeded only by Lord Rayleigh's *Theory of Sound* (1877), which opens, "since the well-known Article on Sound . . . by Sir John Herschel . . . no complete work has been published in which the subject is treated mathematically." John William Strutt, *The Theory of Sound*, 2 vols. (London: Macmillan, 1877), 1:v.

50. Léon Foucault, *Journal des débats*, March 12, 1851, quoted in Amir D. Aczel, *Pendulum: Léon Foucault and the Triumph of Science* (New York: Atria Books, 2003), 157. Foucault first built a two-meter pendulum capable of swinging in all directions and observed its apparent clockwise rotation; suspecting this had in fact visualized the earth's rotation, he then built

to explore the effect of the ether on the earth's movement. Inspired by Chladni's own observation that a tuning fork or metal bar held in a lathe would vibrate in the same plane regardless of whether the lathe was spinning or not, he constructed a metal pendulum, freely suspended from the ceiling, that appeared to rotate clockwise as it swung in a fixed plane. In fact, it was the rotation of the earth that was made visible—an untouchable, invisible, matter-less motion.

As John Tresch notes, though, the experiment proved little. Very few doubted the earth's rotation, so the success of the effect of a sixty-seven-meter wire pendulum suspended over the grandest of French stages was due not to the flurry of mathematical proofs it inspired but "to its powerful effect on its audiences. Here, for the first time, was a full-bodied, immediate experience of a central article of scientific faith."[51] The public demonstration of a phenomenon defined by movement in space, rather than the movement of matter, illustrates just what acoustics lacked, namely a positive demonstration of the propagatory motion of sound.

Within ten years of Foucault's demonstration, Herschel would assert the pendulum as one of only two universal standard lengths for measuring natural phenomena. A pendulum placed at the extremity of the polar axis whose period was precisely one second provided an infallible measure of time, he argued, just as the linear dimensions of the earth provided an equivalent measure of space.[52] By the time of his 1830 treatise on sound, Herschel had already served his first term (of three) as president of the Royal Astronomical Society and was arguably the most senior astronomer in Great Britain. When scrutinizing the velocity of sound in air, he pointed out that, unlike physical matter in motion, sound's velocity is independent of "the nature, extent and intensity of the primitive disturbance"; that is to say, the isochrony of harmonic vibrations means that sound's velocity in air under constant conditions is uniform, at 1089.6 feet per second at freezing temperature, regardless of whether it is initiated by a gun shot or a whisper.[53] (Otherwise, the

a sixty-seven-meter pendulum of brass-coated lead swung relative to a fixed octagon at the Paris Observatory in February 1851. For a discursive account of its unveiling, see John Tresch, *The Romantic Machine* (Chicago: University of Chicago Press, 2012), 296–305.

51. Tresch, *Romantic Machine*, 302.

52. John Herschel, *An Essay, Entitled the Yard, the Pendulum and the Metre* (London: Longman et al., 1863), 9. In 1859 he had already applied this natural unit of time to musical pitch where a new mathematical scheme for universal pitch would have taken a pendular period of one second as the natural basis for measuring the C above middle C at 512Hz, namely as the ninth octave above 60Hz. See Edward Gillin and Fanny Gribenski, "The Politics of Musical Standardization in Nineteenth-Century France and Britain," *Past and Present* 251, no. 1 (2021): 153–87, esp. 176ff.

53. John Herschel, *Treatises on Physical Astronomy, Light and Sound Contributed to the Encyclopaedia Metropolitana* (London: Richard Griffin, 1829–43), 760. Herschel tabulated all experiments to calculate the velocity of sound undertaken between 1660 and 1823,

notes of a "rapid piece of music" played by a band would become uncoordinated for listeners at a distance, he adds.) In view of this decoupling of sound's velocity from its initiating force, an instinctive comparison for Herschel was with the speed of the earth's rotation: "It may, therefore, be stated in round numbers, that Sound, in dry air and . . . at 62° Fahrenheit . . . runs over 9000 feet in eight seconds, 12¾ British standard miles in a minute, or 765 miles in an hour, which is *about three-fourths of the diurnal velocity of the Earth's equator*."[54] Twenty-one years before Foucault's demonstration in Paris, that is, sound's propagation had intuitively brought to mind the challenge of abstracting a virtual shape from an object (the largest object touchable by human hands). This is hardly surprising, given the significance of the pendulum in metrology for determining the shape of the earth and the force of gravity,[55] but it meant that in the mind of astronomers like Herschel, sound propagation and the untouchable "absolute space" of planetary rotation become rehearsals for one another in the way matter-less forms could be understood.[56]

To help articulate this process of abstraction, Herschel settled upon the behavior of a single molecule experiencing an auditory stimulus. It illustrates the independence of speed from shape of propagation—he explains—as stages of quantifiable rest and movement:

> Thus, we see that the molecule distant by x from the origin of the coordinates [where the initial disturbance / sound source occurred] will remain at rest for a certain time $t = \frac{x-a}{a}$, will then begin to move, and continue moving, during a time equal to $\frac{x+a}{a} - \frac{x-a}{a} = \frac{2a}{a}$, or till $t = \frac{x+a}{a}$, and will then return to a state of permanent rest.[57]

In Herschel's mathematical demonstration, the longitudinal motion cancels its own value perfectly, i.e., $\frac{x-a}{a} = \frac{x+a}{a}$, without defining the

recorded their method of measurement, and adjusted for a temperature of 0°C; he then selected those that fell within a range of less than seven feet (per second) and calculated the mean average of them (751).

54. Herschel, *Treatises on Physical Astronomy*, 751 (my emphasis).

55. For an account of the state surveys launched by the British Admiralty and the Royal Society using the pendulum, see David Philip Miller, "The Revival of the Physical Sciences in Britain, 1815–1840," *Osiris* 2 (1986): 107–34.

56. A century on, the self-same pairing would underpin Heidegger's concept of *earth*—the literalized "ground"/soil for an artwork's immateriality—where his illustration of a Greek temple enclosing the presence of a god becomes explicable by gaps in the stone: "The temple's firm towering makes visible the invisible space of air." Hence, what this concept of *earth* does—he continues—is precisely to reveal immaterialities, and "is not to be associated with the idea of a mass of matter deposited somewhere, or with the merely astronomical idea of a planet." Martin Heidegger, "The Origin of the Work of Art" (1935–36), in Martin Heidegger, *Basic Writings*, ed. David Farrell Krell (New York: Harper & Row, 1977), 169.

57. Herschel, *Treatises on Physical Astronomy*, 759.

perceived linear path of sound. On this basis, he effectively distinguished sonic matter from sonic immateriality by distinguishing *things* from *forms,* particles in motion from the theoretical equation governing the assumed path of that motion.[58] The waves rippling along the surface of water or the sinuosity that runs along the stretched cord are not moving masses that advance in the direction along which they seem to run, but

> outlines, or figures, which at each instant of time include all the particles of the water or the cord which, it is true, *are* moving, but whose motion is in fact *transverse* to the direction in which the waves advance. . . . The waves in a field of standing corn, as a gust of wind passes over it, afford a familiar example of the relation between the motion of the wave, and that of the particles of the waving body comprised within its limits.[59]

An analogy of physically moving particles betrays the fact that this was not quite the Aristotelian paradigm of forms traveling "without material process," however. The ensuing desire to scrutinize acoustic waves *as* a "material process" presents something of a crash site for this theory of sound's non-physical identity in its relation to matter.[60]

To take just one example from within Herschel's circle, in 1849 a public quarrel broke out in the *Philosophical Magazine* between two Cambridge researchers over whether sound travels at a constant speed despite its waves of compression. If so, this questioned whether either "plane" waves (directional) or "spherical" waves (concentric) could be mathematically true as shaped forms. In particular it resulted in a standoff over whether the constant velocity of sound was in conflict with the law of constancy of mass, which states that the mass of a system must

58. See also Mark Burford, "Hanslick's Idealist Materialism," *19th-Century Music* 30 (2006): 166–81.

59. Herschel, *Treatises on Physical Astronomy*, 755.

60. Elisions between physical and non-physical identities was a problem shared across scientific fields. In a parallel case, Michael Faraday initially regarded lines of magnetic force as geometric abstractions whose materiality was merely possible, but by 1852 he had switched to confirming them as true physical objects in the world: "the idea of the *physical mode* of transmission of the force." Michael Faraday, "Experimental Researches in Electricity—Twenty-Eighth Series," *Philosophical Transactions of the Royal Society* 142 (1852): 25–56, at 56. The basic habit of thought driving this was analogy, as James Clerk Maxwell summarises in 1855: "In order to obtain physical ideas without adopting a physical theory we must make ourselves familiar with the existence of physical analogies." James Clerk Maxwell, "On Faraday's Lines of Force," in *The Scientific Papers of James Clerk Maxwell* (1890; Cambridge: Cambridge University Press, 2011), 155–229, at 156. See also F. Finley and M. C. Pocovi, "Lines of Force: Faraday's and Students' Views," *Science and Education* 11 (2002): 459–74.

remain constant over time.[61] James Challis (1803–82), the Plumian Professor of Astronomy and Experimental Philosophy, countered George Gabriel Stokes, newly appointed Lucasian Professor of Mathematics and preeminent natural philosopher, over whether sound propagating either as a directional pressure wave or as a spherical ripple (after throwing a stone into water) could be true. Both appeared to result in contradictions of matter: directional waves shift from a point of maximum velocity to one of no velocity, resulting in "one of these points . . . overtak[ing] the other," a physical impossibility; for spherical waves "the *same* portion of matter has a different value . . . at one time from that which it has at another time," but the same portion of matter should have the same value at all times according to the law of constancy of mass. "I have no doubt whatever," Challis concludes, "that I have pointed out *real* contradictions resulting from the suppositions of plane-waves and spherical waves, of the utmost importance in hydrodynamics, since they prove that the true theoretical value of the velocity of sound cannot be deduced from those suppositions."[62] In short, a linear model of propagation (think train carriages shunting each other in sequence) confuses the path of propagation with the longitudinal (forwards-backwards) motion of its excited particles. The debate rumbled on in two further exchanges before concluding in June with a statement from the Astronomer Royal, George Biddell Airy (1801–92), on this "*apparent* difficulty."[63] Herschel's differential equation needed to be applied to individual particles of air rather than to the theoretical path of motion: "The interval of time from the extreme backward motion of a particle to the extreme forward motion is less than half the whole period of vibration [and] this inequality is greater as we consider the movement of particles whose original position is more and more advanced."[64] After noting the "very violent" compression and expansion of particles, Airy stressed the need to separate the theoretical path of

61. This had been associated with Antoine Lavoisier's statement that "nothing is created . . . in any operation, there is an equal quantity of matter before and after the operation" ("rien ne se crée . . . dans toute opération, il y a une égale quantité de matière avant et après l'opération"), in *Traité élémentaire de chimie* (Paris: Cuchet, 1789), 140–41. But scholars have accorded it both wider currency during the eighteenth century, and ancient origins. See, respectively, Robert Whitaker, "An Historical Note on the Conservation of Mass," *Journal of Chemical Education* 52, no. 10 (1975): 658, and David Sedley, "Epicureanism: The Principles of Conservation," in *The Hellenistic Philosophers*, ed. A. A. Long and D. Sedley, 2 vols. (Cambridge: Cambridge University Press, 1987), 1:25–27.

62. Reverend J. Challis, "On the Theoretical Value of the Velocity of Sound, in Reply to Mr Stokes," *London and Edinburgh Philosophical Magazine and Journal of Science* 34 (1849): 284–86.

63. G. B. Airy, "The Astronomer Royal on a Difficulty in the Problem of Sound," *London and Edinburgh Philosophical Magazine and Journal of Science* 34 (1849): 401–5, at 401 (my emphasis).

64. Airy, "Astronomer Royal," 403.

velocity from the actual movement of particles: "Physically considered, the expression of this fact is, that the continuity of the particles is interrupted,"[65] a discontinuity that gives rise—he imagined—to various interference noises: "a *hiss*, a *buzz*, or a *whisper*."[66] Here, in short, Aristotle's non-physical forms come into direct conflict with mid-century particle physics concerning how air particles were to carry the shape of a pressure wave without contradicting their own mass. Airy's conclusion was unequivocal: "If the assumption is made 'that the waves are to preserve the same character through infinite space and infinite time,' *the wave is impossible*."[67] This episode has been associated within the prehistory of a theory of shock waves, but for present purposes it also shows that the motion of individual particles was in no way linear within waveforms, resulting in a constantly changing "shape."[68]

The idea of shaped *matter* had long been accepted, and it received an intellectual foundation in modern materialism.[69] But shaped *non-matter* required something of a leap of faith. It was unobservable and counterintuitive—and for scientific materialists, downright counterfactual. It contravened an older, Cartesian theory of substance, where a substance is immediately perceivable and must be conceivable as something "in itself" that persists "even if we imagine the context of other things in which it is actually placed as destroyed," as Amos Funkenstein once summarized.[70] Allowing for organized shapes in space, such as the earth's rotation or Herschel's moving forms, the concept of shaped *non-matter* teased apart perceptible reality from an imagined existence (or, a scientific "realism") for sound waves. As a leap of faith, it meant acousticians had to trust in realities of motion that could never be seen—or visualized only symbolically.

Implicitly, this harked back to an older, theological mode of belief, one accepting of the existence of multiple co-extant physical worlds

65. Airy, "Astronomer Royal," 404.

66. Airy, "Astronomer Royal," 405.

67. Airy, "Astronomer Royal," 404 (my emphasis).

68. See Manuel D. Salas, "The Curious Events Leading to the Theory of Shockwaves," *Shock Waves* 16, no. 6 (2007): 477–87.

69. By the late 1830s, even lay texts such as Whitelaw's *Conversation Lexicon* declared that "materialism differs according as it considers matter merely, or matter *in an organized shape*, as the original existence" (my emphasis). The book aimed at providing arguments for after-dinner conversation, and during the 1830s this distinction hinted at the larger question of design in nature, forming a key problem that Charles Darwin would address when explaining, for instance, how "an organ so perfect as the eye could have been formed by natural selection" given its inimitably contrived functions, uniquely suited to our needs for vision. "Materialism," in *The Popular Encyclopedia, or Conversations Lexicon*, ed. Alexander Whitelaw, 7 vols. (Glasgow: Blackie & Son, 1846), 4:723; Charles Darwin, *Evolutionary Writings*, ed. James A. Secord (Oxford: Oxford University Press, 2010), 186.

70. Amos Funkenstein, *Theology and the Scientific Imagination*, 2nd ed. (Princeton: Princeton University Press, 2018), 185.

under one God, whose matter—as postulated since the early modern period—obeyed different laws of motion to what could be observed on earth. Newton had accepted this as a tentative possibility:

> Since Space is divisible *in infinitum*, and Matter is not necessarily in all places, it may be also allow'd that God is able to create Particles of Matter of several Sizes and Figures, and in several Proportions to Space, and perhaps of different Densities and Forces, and thereby to vary the Laws of Nature, and make Worlds of several sorts in several Parts of the Universe.[71]

Whereas Robert Boyle asserted it as a probable reality:

> Now if we grant . . . that God has made other worlds besides this of ours, it will be highly probable, that he has there displayed his manifold wisdom in productions very differing from those wherein we here admire it. . . . [T]here may be a vast difference betwixt the subsequent *Phenomena* and productions observable in one of *those* Systems. . . . And the laws of this *propagation* of motion among bodies may not be the same with those . . . in our world.[72]

This acceptance of multiple physical realities, seen and unseen, brings to mind Herschel's deduction that the exact uniformity of observable particles of matter—like a line of spinning jennies or soldiers in uniform—must have the essential characteristics of a "*manufactured article*," that is, as repeated identical objects created by a single agent.[73] But it also established the platform for avowing not only what cannot be observed in the propagation of sound, but for making a cognitive insertion into matter that was putatively real.

By the mid-century, then, a willingness to believe in sound's non-physical forms of propagation implicated a quasi-theological discourse whose strands entwine within a culture of experimentation that sought to visualize vibration as waveforms. The juxtaposition of faith and science that this implies is perhaps unsurprising given the centuries-old habit of comparing sound and souls as "immaterial substances." Canonical descriptions of the soul as "immaterial substance" were echoed by certain nineteenth-century theologians.[74] The leading figure to apply this

71. Isaac Newton, *Opticks, or A Treatise of the Reflections, Refractions, Inflections and Colours of Light* (1704; reprint, New York: Dover, 1954), §3.1, 403–4.

72. Robert Boyle, *On the High Veneration Man's Intellect Owes to God* (London: Richard Davis, 1685), 35–36, 38, 40.

73. John Herschel, *Preliminary Discourse on the Study of Natural Philosophy* (London: Longman et al., 1831), 38.

74. See, for instance, Thomas Hitchcock, "Soul and Substance," *North American Review* 124, no. 256 (1877): 404–16, and Isaac Thomas Hecker, "The Reality of the Soul as a Self-Subsisting Separable Substance," *Catholic World* 29 (1879): 344–58.

description to *sound*, as "a finely attenuated substance," was a Methodist priest, Alexander Wilford Hall, a writer and editor of several science journals, who used its paradoxical logic to discredit the very distinction between matter and non-matter.[75] The heaviest metal can be converted into gas many times lighter than our atmosphere and reconverted into a solid, he argues. This teaches us that the same "gaseous substance, under the manipulation of still higher wisdom and greater chemical resources might be made to reach a second state of attenuation or sublimation, almost if not quite justifying our conception of an 'immaterial substance,'"—that is to say, via a second conversion not much greater than "its first change from metal to gas."[76] Hall's apparent casuistry, in bending aspects of particle physics to a defense of the soul, also bears witness to a desire to philosophize away distinctions between matter and non-matter. This only becomes plausible via debates over sound's matterless forms, I suggest, and the ways of thinking they enabled.

Here a comparison with earlier, more eminent idealists like Hegel reveals a longer-established habit of referencing sound to efface opposites. For Hegel, the paradox of matter and (non-material) spirit was attractive as an abstract concept. He saw their unification in classical sculpture as nothing short of a "miracle" that "gives to [immaterial] spirit itself . . . a corporeal shape appropriate to the very nature of spirit and its individuality, and it brings both . . . before our vision as one and the same indivisible whole."[77] Sound achieves its own unity, but no such miracle. Audible speech gives external expression to spirit, we learn, but its objectivity is not concretely material because it communicates spirit "only as sound, as the movement and vibration of a whole body and the abstract element, i.e. air." Air is assumed abstract here, in contrast to matter in three-dimensional space like wood or clay.[78] This is why Hegel declared sound to comprise immaterial form and matter, which he viewed as infinitely divisible properties held by time: "Individuality includes matter and form; sound is this total form which announces itself in time."[79] Such paradoxes could exist comfortably in the cradle of abstract philosophy, but for mathematical physicists like Airy and Challis ambiguity over the notion of sound's "total form," comprising particles (matter) and patterns of motion (form), raised definable contradictions that were less comfortable, even intolerable, as we have seen.

75. Alexander Wilford Hall, *The Problem of Human Life: Embracing the "Evolution of Sound" and "Evolution Evolved"* (New York: Hall, 1880), 76.

76. Hall, *Problem of Human Life*, 33.

77. Georg Wilhelm Friedrich Hegel, *Aesthetics: Lectures on Fine Arts*, trans. T. M. Knox, 2 vols. (Oxford: Clarendon Press, 1975), 2:702, 711.

78. Hegel, *Aesthetics*, 2:701–2.

79. Hegel, *Philosophy of Nature*, pt. 2 of the *Encyclopaedia of the Philosophical Sciences*, trans. A. V. Miller (1839; Oxford: Clarendon Press, 1970), 138.

In sum, with Foucault's demonstration of the earth's unseen rotation, pendular motion had revealed a persuasive visualization of shaped non-matter, shoring up Aristotle's ancient belief that immaterial shape could be ascribed to sound propagation. This included the very basis of harmonic vibration (since Galileo), yet mid-century studies in particle physics undermined belief in the supposedly immaterial forms of vibration: "the wave is impossible." All of this obfuscated attempts to visualize sonic vibration as an ontology via the apparatuses of Wheatstone, Swan or Duhamel, each of whose inscriptions were typically assumed to be little more than countable symbols.

Helmholtz, Imagination, and Music's Waves

As the discourse on visualization reached the late 1850s, the quantity of apparatuses for visualizing waveforms proliferated across France, Great Britain, and the German states, leading to the publication of several summaries of what had now become "a special branch of wave studies and acoustics."[80] Questions of realism bubbled below the surface. No less an authority than Helmholtz remained open-minded about what exactly it was that pendular motion described: "What makes us hit upon pendular vibrations, and none other, as the simplest element of all motions producing sound?" he asked in *Sensations of Tone.* "We can conceive a whole to be split into parts in very different and arbitrary ways."[81] A frequency of 12 vibrations per second can be created from 7 + 5 just as easily as from 8 + 4, he explains. This wobble was largely rhetorical, but it prompted others to ponder the same.[82] Helmholtz's concern was a suspected overreliance by mathematicians on Fourier analysis to decompose compound waves into their constituent simple waves based on the premise of pendular vibration: "Is this . . . not merely a *mathematical fiction*, permissible for calculating, but not necessarily having any corresponding actual meaning in things themselves?"[83] His answer was that

80. Franz Melde, *Die Lehre von den Schwingungscurven* (Leipzig: Barth, 1864), iii: "ein spezieller Zweig der Wellenlehre und Akustik." See also Pisko, *Die neueren Apparate der Akustik*, chs. 3–4, and Hagen, "Ueber die Verwendung des Pendels."

81. Hermann von Helmholtz, *On the Sensations of Tone as a Physiological Basis for the Theory of Music*, trans. Alexander Ellis, 2nd Eng. ed. (1885; reprint, New York: Dover, 1954), 35.

82. See, for instance, Alfred M. Mayer, "Researches in Acoustics," *American Journal of Science and Arts* 3, no. 44 (1874): 81–109, at 85.

83. Helmholtz, *On the Sensations of Tone*, 35 (my emphasis). Helmholtz popularized Georg Ohm's law, namely where the inner ear separates compound waves into their constituent simple waves, just as Fourier analysis decomposes complex waves into a sum of their simple sine and cosine waves. On the Helmholtz-Ohm relationship, see Melle Jan

the coincidence between the achievements of mathematical analysis and the putative workings of the inner ear was simply too great to ignore, making it "probable" that pendular motion could be assumed as the true shape of simple vibrations in air, even though all audible waves were compound.[84]

That visible waves in water formed an intuitive comparison suggests that the origin of the metaphor sound "waves" was indebted to this illustrative tendency, while contemporary terms for sound propagation were more varied, including "vibration," "undulation," "pulse," and "continuum."[85] Helmholtz confirms the water paradigm in a public lecture of 1857: "The propagation of sound through the atmosphere . . . belongs to the so-called wave motions. . . . The name is derived from the analogy of waves on the surface of water, and these will best illustrate the peculiarity of this description of motion."[86] This, too, entailed assumptions about immaterial form, and reveals invisibility as the locus of disbelief;[87] that is, for Helmholtz the question of realism continued to hinge on the incredulity of what cannot be seen. Approaching peak incredulity, he asks, "Do these partial constituents of a musical tone, such as the mathematical theory distinguishes and the ear perceives, *really* exist in the mass of air external to the ear?"[88] He was concerned by the uncritical assumption that sinusoidal waves were physically real and underlay all compound waves. If seeing is believing, the ease with which the eye takes in multiple waves interacting on the surface of water, distinguishes wave shape, and intuitively determines the different starting point and relation between two wave systems only highlights the ear's relative poverty. "The ear is therefore in nearly the same condition as the eye would be if it looked at one point of the surface of the water, through a long narrow tube, which would permit of seeing its rising and falling, and were then required to undertake an analysis of the compound waves."[89] This flip—swapping the ear for the eye—comically visualizes the "mathematical fiction" hidden within the workings of the inner ear. Its tone of ridicule highlights the lack of trust in existing apparatuses for visualizing compound waves, requiring simple faith in the assumed

Kromhout, "The Unmusical Ear: Georg Simon Ohm and the Mathematical Analysis of Sound," *Isis* 111, no. 3 (2020): 471–92.

84. Helmholtz, *On the Sensations of Tone*, 35.

85. See Peter Rowlands, *Waves versus Corpuscles: The Revolution That Never Was* (Liverpool: Liverpool University Physics Department, 1992), v.

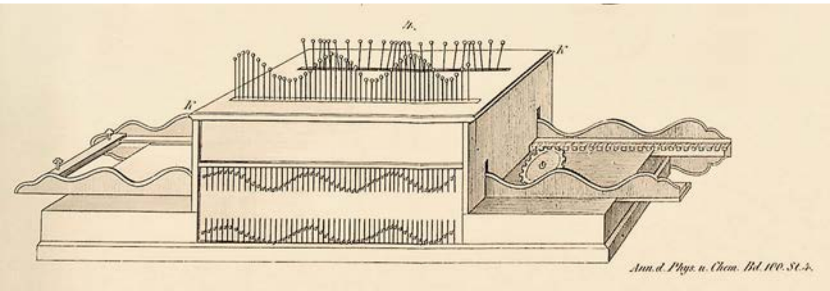
86. Helmholtz, "On the Physiological Causes of Harmony," in *Science and Culture*, 46–75, at 52.

87. "That which really advances as a wave is . . . not the particles of water themselves, but only a superficial form, which continues to be built up by fresh particles of water." Helmholtz, "On the Physiological Causes of Harmony," 52.

88. Helmholtz, *On the Sensations of Tone*, 35 (my emphasis).

89. Helmholtz, *On the Sensations of Tone*, 29.

FIGURE 6. Oscar Schulze's "acoustic wave apparatus" (1855), showing four rows of steel pins with white beads at the tips, each of which displays a different type of wave form. The side rows (front) illustrate component sine waves, the front top row displays its resulting transverse compound wave, while the back top row displays the equivalent longitudinal wave. Oscar Schulze, "Akustischer-Wellen-Apparat," *Annalen der Physik* 100 (1857), 208, table 7, fig. 4. By permission of the Betty & Gordon Moore Library, University of Cambridge.



motion or shape of sound itself: what Helmholtz called "things themselves."

Perhaps the last inventor to assert that sound waves could be straightforwardly visualized as a putative ontology was Oscar Schulze, a German organ builder based in Paulinzella, near Erfurt. His acoustic wave apparatus (*Akustischer-Wellen-Apparat*) received the silver medal at Paris's 1855 Exposition Universelle for its ability to illustrate longitudinal, transverse, standing, interference and compound waves at the same time, allowing for immediate visual comparison of their shapes. In Schulze's mind, its primary purpose was verisimilitude: "an apparatus for making sound waves perceptible."[90] But it is indicative of just how blurred the status of different forms of representation had become that while asserting truest likeness it offered arguably the most symbolic visualization, for it relied on a set of pre-cut sinusoidal shapes—mathematical preconceptions made physical. As figure 6 shows, it contains four rows of steel needles with white pearl-like heads, whose movement was controlled by wooden "wave strips" (*Wellenleisten*) or "wave screws" (*Wellenschrauben*),

90. Schulze to John Tyndall, February 4, 1857, Paulinzella, in *Correspondence of John Tyndall*, ed. Roland Jackson, Bernard Lightman, and Michael S. Reidy, 15 vols. (Pittsburgh: University of Pittsburgh Press, 2016–25), 6:79: "einen Apparat zur Versinnlichung der Schall-Wellen."

intended to capture the oscillations of sonic vibration. The wooden wave strips were pre-cut into various shapes, from simple sinusoids to compound waves. By moving one or more strips (bolted together) along tracks, using a toothed wheel and crank handle, the needles were pushed up and down in a shape corresponding to the wave strips and their resulting combination.[91]

What did Schulze's viewers see? On the apparatus the two side rows and the front row atop the box broke down compound transverse waves into (i) an imagined underlying simple wave, (ii) its interference wave, and (iii) the resulting compound wave. The fourth row (top, back) illustrated the same compound presented as longitudinal vibrations. In private correspondence, Schulze puffed up its full illustrative capabilities as follows:

1. The formation and propagation of simple waves
2. The interference of two simple waves
3. The interference of two compound waves
4. The interference of a simple wave set against its reflection
5. The interference of a compound wave with its reflection (including standing compound waves with fixed and moving nodes to illustrate aliquot tones).[92]

Critically, the original wave shapes remained preformed by the strip or screw position, rather than recording the movement of a vibrating fork, or sound in real time. In decomposing compound waves, the apparatus presents the auditory equivalent of Weber's wave trough, but with predetermined forms that assumed precisely the "mathematical fictions" that would trouble Helmholtz in 1857.

It was against this background that, two decades later, Helmholtz returned to the topic of perceiving invisible objects while preparing a public talk entitled simply "What Is Real?" The hour-long lecture he delivered on August 3, 1878, his last as rector at the Friedrich Wilhelm University in Berlin,[93] had a changed title ("The Facts in Perception") but posed the same neo-Kantian question: How does conscious perception of stimuli from the world relate to objects in the world as they truly exist? His famous conclusion was that sense stimuli were signs whose lawlike behavior in human perception lends them the character of the real,

91. Wave "screws" achieved the same by different means, where the cross section of each metal disc is turned so that the y-axis of the required sinusoid is plotted against the x-axis, or radii of the circle. Their advantage was continuous motion, while the strips had a finite length.

92. List paraphrased from Schulze to Tyndall, February 11, 1857, Paulinzella, in *Correspondence of John Tyndall*, 6:86–87.

93. See David Cahan, *Helmholtz: A Life in Science* (Chicago: University of Chicago Press, 2018), 545.

and that this repeats itself in similar ways creating "an intuitive image of the typical behaviors of the objects" that most interest an observer.[94] Less discussed is his ancillary claim, that this consistency of perception is best detected by artists, who—he implies—encounter "real" objects in the truest way. "That the artist has beheld the real may be concluded from the fact that when he brings before us an example cleansed of accidental disturbances it again fills us with the conviction of truth. He is, however, superior to us [experimentalists] in that he knew how to sift out everything accidental and confusing of the doing of the world."[95] By implication, this sifting skill is exhibited in artworks and validated by communal appreciation. This in turn informs scientific research, he concludes. Common to both artists and experimentalists was the goal of discovering "new lawfulness" in the perception of objects, meaning that a refined perceptual acuity of waves or the refraction of light ascribed to composers or painters already constitutes both an artistic and a scientific endeavor. Hence, "The true researcher must have something of the artist's insight . . . [in order] to give to their work a stable form and convincing similitude."[96]

To test Helmholtz's claim, and to place it in the context of his aquatic illustration of sound waves, we might turn to a composer such as Franz Liszt, who in 1838 explicitly sought a "convincing similitude" of wave motion in the rippling waters of Lake Wallenstadt in Switzerland. While Liszt never engaged with the scientific enterprise or its literature,[97] there can be little doubt that his programmatic piano work "Au lac de Wallenstadt" imitates water (one of two to do so in the first volume of his *Années de pèlerinage,* alongside "Au bord d'une source"). His first long-term partner, Marie d'Agoult, offers biographical testimony: "The shores of Wallenstadt detained us for a long time. Franz wrote for me there a melancholy harmony, imitative of the sighing of the waves and the rhythm of the oars, which I have never been able to hear without

94. Helmholtz, "Facts in Perception," 355.

95. Helmholtz, "Facts in Perception," 355. Sifting through perceptual data might equally be viewed as a quality of attention. On this, see Benjamin Steege, *Helmholtz and the Modern Listener* (Cambridge: Cambridge University Press, 2012), ch. 3, and Alexandra Hui, *The Psychophysical Ear: Musical Experiments, Experimental Sounds, 1840–1910* (Cambridge, MA: MIT Press, 2012), ch. 4.

96. Helmholtz, "Facts in Perception," 365. See also Myles Jackson's openness to multifarious histories of the relation between nineteenth-century musicians and scientists: "Given their epistemological natures, many different types of histories can be written describing their historically contingent relationship." Myles Jackson, *Harmonious Triads: Physicists, Musicians, and Instrument Makers in Nineteenth-Century Germany* (Cambridge, MA: MIT Press, 2008), 2.

97. While his Budapest library contains several music conversation lexicons that touch on wave forms (Hermann Mendel, 1870; Julius Schuberth, 1871), it contains no texts on acoustics. See Mária Eckhardt, *Liszt Ferenc Hagyatéka* [Franz Liszt's estate], 2 vols. (Liszt Zeneművészeti Föiskola: Budapest, 1986–93), vol. 1, *Könyvek* [Books].

weeping."[98] And his attentiveness to wave shape is apparent from private statements such as "I have always been very fond of lakes, and can easily become intimate with their waves and their physiognomy."[99] Even accounting for the methodological traps of the intentional fallacy and life-works paradigm, such sentiments confirm that Liszt's personal attachment to waterscapes involved meditation on wave motion.

An analyst might find in these sources something of the proverbial smoking gun and go in search of Liszt's musical mimesis of water. On the face of it, such an approach seems logical. The music of "Au lac de Wallenstadt," in ABA form, undoubtedly borrows the topos of the barcarolle, more typically in $\frac{6}{8}$, with its lilting rhythmic regularity and untroubled tonic/dominant alternation. But at least two factors differentiate Liszt's music from genre-defining barcarolles such as Chopin's *Souvenir de Paganini* (1829) or Mendelssohn's G minor *Venetianisches Gondellied*, op. 19, no. 6 (1829–30), pointing to areas of particularity or insight that "sift out" what is undifferentiated. First, the accompanimental figure avoids the genre's straight eighth notes: for all but eight measures it juxtaposes triplet and duple sixteenth notes, to be played "egualmente," presenting a constant 3:2 rhythmic ratio that not only defines the first interval of the right-hand theme (perfect fifth) but instills an imbalance within the metrical regularity of the left-hand motion (see ex. 1a).[100] Second, the theme itself is arch-shaped, periodic, and iambic; that is, as rhythmically unsurprising as possible. As example 1b shows, when the A section recurs *un poco piú animato* (m. 62), Liszt displaces the rhythm by a sixteenth note, creating an audible dislocation between hands—two intersecting wave patterns in the (now full) rising arpeggio—before realigning on the downbeat (m. 65). An accented repetition (mm. 70–72) confirms this strategy. The displacement is not a calculated ratio—a "temporal dissonance" as found in player-piano studies by Nancarrow—but a gestural depiction of lines crossing the ear, guided by the mind's eye. If the artist has indeed "beheld the real," it is not the banal observation that Liszt mimics water that offers insight, but rather the character of the features depicted and the means by which they are

98. Marie d'Agoult, *Mémoires, 1833–54*, ed. Daniel Ollivier (Paris: Calmann-Lévy, 1927), 45: "Les bords du lac de Wallenstadt nous retinrent longtemps. Franz y composa, pour moi, une mélancolique harmonie, imitative du soupir des flots et de la cadence des avirons, que je n'ai jamais pu entendre sans pleurer."

99. Liszt to Carolyne von Sayn-Wittgenstein, July 4, 1853, Zurich, in *Franz Liszt Selected Letters*, ed. and trans. Adrian Williams (Oxford: Clarendon Press, 1998), 343.

100. See Robert L. Wells's study of the way in which distinct metrical layers interact in Liszt's works, "A Generalized Intervallic Approach to Metric Conflict in Liszt," *Music Theory Online* 23, no. 4 (2017), https://mtosmt.org/issues/mto.17.23.4/mto.17.23.4.wells.html. Examples 1a and 1b are transcribed from the *Neue Liszt-Ausgabe*, ser. 1, vol. 6, *Années de pèlerinage: Première année—Suisse*, ed. Mező Imre and Sulyok Imre (Budapest: Editio Musica, 1977).

EXAMPLE 1A. Franz Liszt, "Au lac de Wallenstadt," *Années de pèlerinage, première année* (1837–38), mm. 1–20.

presented. The rhythmic displacement, like misaligned compound pendulums, reveals that there were always two wave systems in the music, but the lower ("submerged") one becomes perceptible only when in conflict with the upper (cf. the Webers' "wave trough").

EXAMPLE 1B. Franz Liszt, "Au lac de Wallenstadt," *Années de pèlerinage, première année* (1837–38), mm. 61–78.

If Liszt's imaginative absorption in waterscape leads to an artistic "conviction of truth" (Helmholtz's term), what are we to make of this kind of knowing? The extent to which Liszt's avowed intimacy with "waves and their physiognomy" is recorded in music remains contingent on analytic method, but it was received by contemporaries as nothing less than a reconciliation of human perception with nature. In the first review of Liszt's *Première année* collection, Louis Köhler explains that "the human mind learns to recognize nature; it sees therein no arbitrary force, but an entity guided by an invisible power; this invisible power, as it is animated in the ever-working and weaving laws of nature, remains as something completely unknowable to us."[101] We mistake ourselves for gods, he warns, when we assume that the forms we perceive in nature are the only way of perceiving those forms. Yet Liszt's observation of nature yields higher insight, he continues, as though capturing the midpoint of verisimilitude and simulation:

> If one now wants to inwardly behold and relive this mysterious spirit [of nature] in *the* way it lives and vibrates on the mountains and in the valleys, in the clouds and waters of beautiful Switzerland, as it was reproduced in enchanted sounds through the sublime spirit of a truly ideal artist, just listen to [Liszt's] resounding tone pictures . . . for there sings and resounds again that which has filled so many an enchanted traveler's heart. . . . One breathes the fresh mountain air and the plant scents of the valleys, one glides over the lakes and sees the glaciers' reflection in them.[102]

Echoes of this artistic realism continue within Liszt's reception history,[103] collectively setting up a contrast to putatively objective representations of waves via mechanical pendulums, and raising the question of whether Liszt's musical depiction has any less claim to realism than those apparatuses that would give rise to the call for "sound visible" in 1848 or for making "sound waves perceptible" in 1855.

Helmholtz's Berlin speech formed the culmination of decades of work on the cognitive agency of perception dating back to his time at Bonn University (1855–58).[104] In Great Britain, a parallel discourse on the role of *imagination* in scientific research ran alongside. Both make

101. Louis Köhler, "Kammer und Hausmusik für Pianoforte: F. Liszts *Années de pèlerinage*," *Neue Zeitschrift für Musik* 43 (1855): 69–70: "Der Menschengeist lernt die Natur erkennen, er sieht keine willkürliche Gewalt, sondern eine von unsichtbarer Macht geleitete Wesenheit in ihr; diese unsichtbare Macht, wie sie in den immerwirkenden und webenden Naturgesetzen lebendig ist, bleibt der Erkenntniß als sein letztes Unerkennbares übrig."

102. Köhler, "Kammer und Hausmusik," 69–70: "Will man nun diesen geheimnißvollen Geist in *der* Weise innerlich erschauen und wiedererleben, wie er auf den Gebirgen und in den Thälern, in Wolken und Wassern der schönen Schweiz lebt und webt, wie er durch den erhabenen Geist eines wahrhaft idealen Künstlers in bezaubernden Klängen wiedergegeben wurde, so höre man die klingenden Tonbilder . . . denn da singt es und da klingt wieder, was wohl so manches entzückten Wandrers Brust erfüllte. . . . Man athmet die frische Gebirgsluft und die Pflanzendüfte der Thäler, man gleitet über die Seen und sieht die Spiegelung der Gletscher darin."

103. See, for instance, Vladimir Jankélévitch's description of "the great streams and fountain jets of Liszt" that break down into "showers of drops" in Ravel's pointillist music in his critique of the latter's *Jeux d'eau* a century later. Vladimir Jankélévitch, *Ravel*, trans. Margaret Crosland (London: John Calder, 1959), 120.

104. It would prove particularly influential for the neo-Kantian movement, and continues to exert influence on the philosophy of perception today. See R. Brian Tracz, "Helmholtz on Perceptual Properties," *Journal for the History of Analytical Philosophy* 6 (2018): 64–78.

claims for the role of cognitive agency, though they have different emphases: where Helmholtz's focus was physiological and—ultimately—semiotic, British writers such as Walter Pater retained a literary focus for the imagination in 1873, bringing the question of how the mind makes sense of sensory stimuli right to the brink of solipsism:

> Experience seems to bury us under a flood of external objects, pressing upon us with a sharp importunate reality. . . . [I]f we continue to dwell on this world, not of objects in the solidity with which language invests them, but of impressions unstable, flickering, inconsistent, which burn and are extinguished with our consciousness of them, it contracts still further; the whole scope of observation is dwarfed to the narrow chamber of the individual mind.[105]

These strands—Helmholtz, Pater, scientific apprehension, artistic perception—have rarely been linked, but they provide insight into a residual skepticism over seeable sonic ontologies.[106] To remind ourselves briefly of their genealogy, when a poet such as William Blake wrote of "Creating Space, Creating Time according to the wonders Divine of Human Imagination" in *Jerusalem* (1808), he reinforced the long-standing idea that scientific realism was created first in the imagination, itself not subject to the measurement and abstract dominion of seemingly immutable laws in nature.[107] Underlying this is the rejection of a mind-independent world *outside* ("Imagination is My World; this world of dross is beneath my Notice"), and a corresponding belief in the perfection of a common agency operating between world and mind that is most concisely expressed in Friedrich Schelling's core ambition for *Naturphilosophie*, that "nature should be visible mind, mind visible nature."[108]

105. Walter H. Pater, *Studies in the History of the Renaissance* (London: Macmillan, 1873), 208–9. The roots of this literary strand of thought point to the imagination as the central theme of Romantic poetry itself. See the extended commentary in James Engell, *The Creative Imagination: Enlightenment to Romanticism* (Cambridge, MA: Harvard University Press, 1981), 265.

106. On the relation of Pater and Helmholtz, see David Coombs, "The Sense and Reference of Sound; or, Walter Pater's Kinky Literalism," *Nineteenth-Century Literature* 72 (2018): 487–514, at 491.

107. William Blake, *Jerusalem*, 98.31–32.

108. William Blake, "Public Address," in *The Complete Poetry and Prose of William Blake*, ed. David Erdman (Berkeley: University of California Press, 2008), 571–82, at 580; Friedrich Schelling, *Ideen zu einer Philosophie der Natur* (1797), in Friedrich Schelling, *Sämtliche Werke*, 13 vols. (Stuttgart: Cotta, 1856), I/2:56: "Die Natur soll der sichtbare Geist, der Geist die unsichtbare Natur seyn." Schelling's *Naturphilosophie* itself built on Spinoza's revival of a *natura naturans* (naturing nature), a plastic, forming spirit at work in both God and the human mind. See Baruch Spinoza, "Short Treatise on God, Man and His Wellbeing," in *Collected Works of Spinoza*, ed. and trans. Edwin Curley, 2 vols. (Princeton: Princeton University Press, 1985), 1:91.

By the 1850s, however, belief in a common agency had weakened, and the hierarchy between Blake's imagination and observation had been reversed: it was less a mind-created world nudged and informed by stimuli, and more a sense-detected world, whose rational comprehension (especially in its imperceptible components) was aided by a faculty of imagination.[109] To take a signal statement from the president of London's Royal Society: "Physical investigations . . . help to teach us the actual value and the right use of the imagination . . . which, properly restrained by experience and reflection, becomes the noblest attribute of man—the source of the poetic genius, the instrument of discovery in science."[110] These words were delivered in 1859 by the physicist and surgeon Sir Benjamin Brodie (1783–1862), at the end of his annual lecture. Listening to this was British physicist John Tyndall, who had been elected to the society six years earlier, and who had begun his own experiments in the visualization of sound by 1857.[111] A decade later he delivered a set of eight public lectures on sound to the Royal Institution that effectively put Brodie's call into action, explicitly blurring acts of observation and imagination, and with them the distinction between vibration as a primary ontological unit in the world and the agency of mind picturing this:

> Scientific education ought to teach us to see the invisible as well as the visible in nature; to picture with the eye of the mind those operations which entirely elude the eye of the body; to look at the very atoms of matter in motion and at rest, and to follow them forth, without ever once losing sight of them, into the world of the senses, and see them there integrating themselves in natural phenomena. . . . [Y]ou will, I trust, endeavour to form a definite image of a wave of sound. *You ought* to see mentally the air particles when urged outwards by the explosion of our balloon crowding closely together; but immediately behind this condensation *you ought* to see the particles separated more widely apart. *You ought,* in short, to be able to seize the conception that a sonorous wave consists of two portions . . . [a] condensation and a rarefaction.[112]

This string of exhortations ("you ought") indicates Tyndall's view that the visualization of sound was not an objective capture of something

109. An early statement is Rudolf Hermann Lotze's *Medizinische Psychologie,* whose driving question was how the relationship between mental life and physical activity could be determined. Rudolf Hermann Lotze, *Medizinische Psychologie, oder Physiologie der Seele* (Leipzig: Wiedmann, 1852), vi.

110. Benjamin C. Brodie, "Anniversary Meeting" (November 30, 1859), *Proceedings of the Royal Society of London* 10 (1859–60): 160–80, at 165.

111. On June 5, 1857, Tyndall gave a demonstration of "Lissajous" figures to the Royal Institution. See John Tyndall, "On M. Lissajous' Acoustic Experiments," *Proceedings of the Royal Institution* 2 (1857): 441–43.

112. John Tyndall, *Sound: A Course of Eight Lectures Delivered at the Royal Institution of Great Britain* (London: Longmans, Green, 1867), 5 (my emphasis).

ontological, but an active task for the perceiver, whose creative agency is positively solicited in *endeavoring* to form, *seeing* mentally and *seizing* connections. As such it falls into the category of "agentic realism" that physicist Karen Barad uses to connote a shared agency between viewer and thing, generating a relational ontology, rather than maintaining a boundary between external (real) wave and interior mind: "*a relationality between specific material (re)configurings of the world through which boundaries, properties, and meanings are differentially enacted.*"[113] Of course, Kant had long since disavowed the naive realism of eighteenth-century materialists who argued that what is perceived by the human senses is all that can be known and therefore constitutes what is real—something repeated by nineteenth-century materialists and that Helmholtz felt obliged to qualify politely in his 1878 address.[114] Tyndall's message, interpreted in this context, is on the cusp of asserting sonic vibration as a mentally constructed image, just a decade after his first public demonstration of sound figures at the Royal Insitution, and nearly two decades after the proclamation "Sound Visible!"

By 1870 his position had become explicit. In a lecture entitled *On the Scientific Use of the Imagination* Tyndall attributed sound's visual forms exclusively to the mind: "The bodily eye . . . cannot see the condensations and rarefactions of the waves of sound. We construct them in thought, and we believe as firmly in their existence as in that of the air itself."[115] That is, to picture sound moving through air meant supplying infinitely multipliable moiré patterns of a shape that can never be seen. To do so was legitimate, he affirms, for when dealing with imperceptible matter, the imagination becomes nothing less than "the architect of physical theory."[116] This followed his difficult experience of demonstrating pendular motion at the Royal Institution: a twenty-eight-foot sand-filled rubber tube resulted in "imperfect" shapes that passed into one another (circle, ellipse, elongated ellipse, parabola, oblong, figure of eight), with the changing period of vibration, he confessed, further underscoring their status as abstract symbols.[117] The case for verisimilitude had never looked so weak. Its seeds are not hard to trace.

113. Barad, *Meeting the Universe Halfway*, 139.

114. Helmholtz, "Facts in Perception," 360: "the realistic hypothesis is . . . superbly useful and precise . . . [but] we may not ascribe necessary truth to it, since in addition to it still other, irrefutable idealistic hypotheses are possible."

115. Tyndall, *On the Scientific Use of the Imagination*, 8.

116. John Tyndall, "Scientific Use of the Imagination," in *Fragments of Science: A Series of Detached Essays, Addresses and Reviews*, 6th ed., 2 vols. (London: Longmans, Green, 1879), 2:104. On the Anglo-German networks concerning poetry and science, see Gillian Beer, "Helmholtz, Tyndall, Gerard Manley Hopkins: Leaps of the Prepared Imagination," in *Open Fields: Science in Cultural Encounter* (Oxford: Oxford University Press, 1996), 242–72.

117. Tyndall, *Sound*, 307–17.

Lissajous, Skepticism, and "Waves of Inflection"

Back in 1855 Tyndall had served as a juror at the Paris Exposition Universelle, and was one of thirteen to award Schulze's *Wellen-Apparat* the silver medal in class 8, "Arts relating to the exact Sciences, and to Instruction." Their report declared it "sufficient for teaching" and noted its capacity to decompose compound waves and display longitudinal and transverse vibration alongside one another.[118] Two years later, when Schulze sent Tyndall an improved version of the apparatus and requested his public endorsement aimed at the grammar school market, Tyndall declined (much to the inventor's surprise: "I had quite confidently been counting on a 'Yes'").[119] To understand why, we need only look at the wider competition. In the same year as the Exposition Universelle, the French mathematician Jules Lissajous published a short paper on observing interference in sound vibrations.[120] He followed this with a second, illustrated paper on the optical study of sound vibrations in May 1856 and a third, much longer theoretical paper in 1857.[121] Tyndall read Lissajous's first two publications immediately, and asked for a copy of the electric lamp, mirrors, and forks to be sent to London so that he could repeat Lissajous's experiments at the Royal Institute. He also agreed to the inventor's subsequent request to come and deliver the demonstration himself. The resulting talk, entitled "On M. Lissajous' Acoustic Experiments," took place on June 5, 1857, as part of the Friday evening series. Lissajous conducted the acoustic experiments while Tyndall—in his words—"expounded them" for the audience.

In contrast to Schulze's preformed discs and strips, Lissajous used a sounding tuning fork to generate images of sonic vibration. As figure 7a shows, he placed a small mirror on a fork, with an electric light beam aimed at it, throwing the reflection onto a black screen. This produced a single straight line, as shown in the top left corner of figure 7b. When a second mirror was used to cast the resulting light beam sideways, it produced a sine wave. If this second mirror was not sideways but placed on a second tuning fork vibrating at 90 degrees to the first, the resulting compound wave produced a series of figures, which came to be known as

118. *Rapports du jury mixte international: Exposition universelle de 1855*, 2 vols. (Paris: Imprimerie Impériale, 1856), 1:438: "suffisante . . . pour l'enseignement."

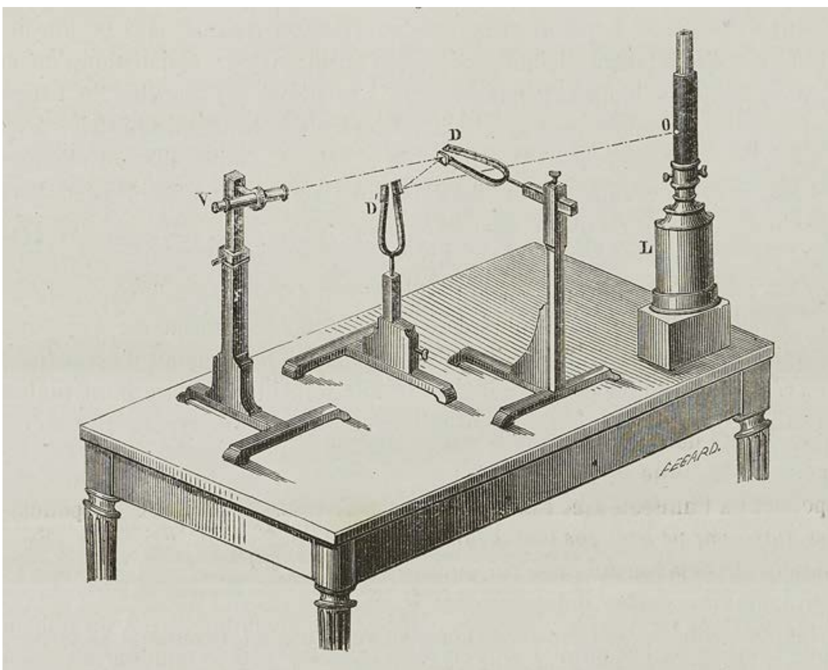
119. See Schulze to Tyndall, April 7, 1857, Paulinzella, in *Correspondence of John Tyndall*, 6:138–39. See also the letter of February 4, 1857, 6:80.

120. Jules Lissajous, "Note sur un appareil simple qui permet de constater l'interférence des ondes sonores," *Comptes rendus des séances de l'Académie des sciences* 40 (1855): 133–35.

121. Jules Lissajous, "Étude optique des mouvements vibratoires," *Bulletin de la Société d'encouragement pour l'industrie nationale* 55 (1856): 699–705; Lissajous, "Mémoire sur l'étude optique."

"Lissajous figures," whose patterns anticipate the modern oscilloscope. That similar figures had been created as early as 1815 by the American mathematician Nathanial Bowditch was mentioned by several contemporary historians but in no way diminished the renown of Lissajous's achievement.[122] Following his third paper, "Mémoire sur l'étude optique," Napoleon III appointed him Knight of the Imperial Order of the Legion of Honor on August 13, 1857.[123]

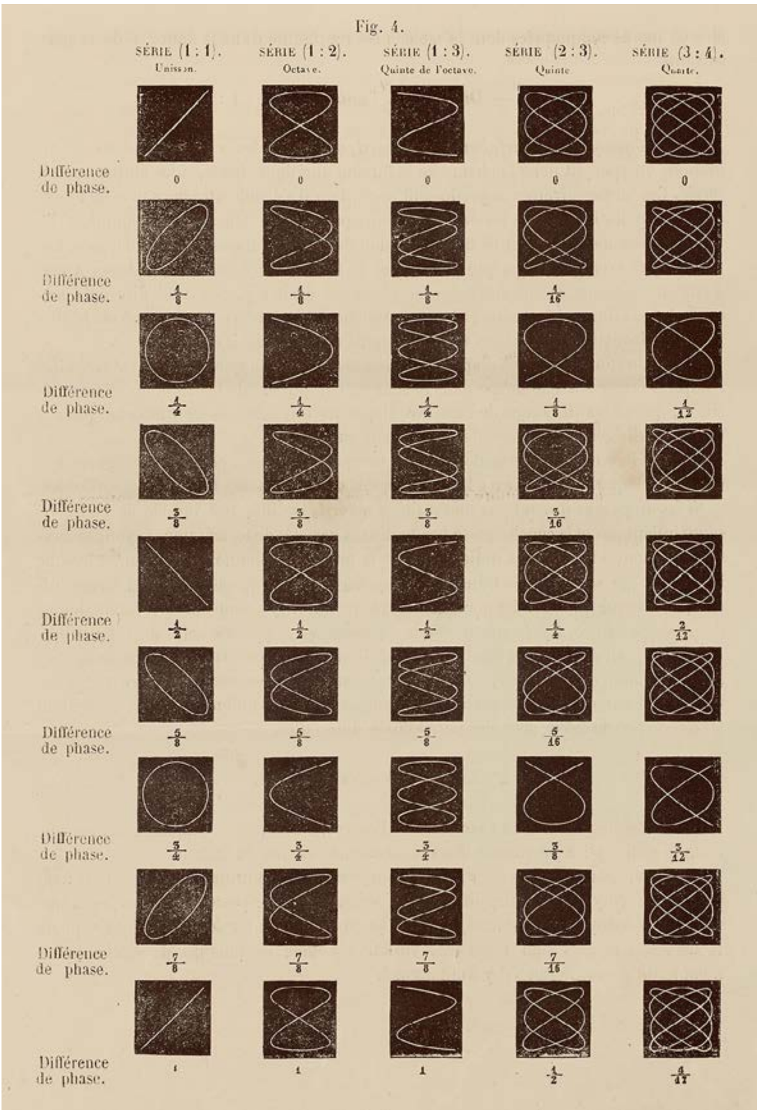
FIGURE 7A. Jules Lissajous's first illustration of his apparatus for producing optical "figures" based on two tuning forks placed perpendicular to one another. Jules Lissajous, "Étude optique des mouvements vibratoires," *Bulletin de la Société d'encouragement pour l'industrie nationale* 55 (1856), 701. By permission of the Master and Fellows of Trinity College, Cambridge.



122. See Joseph Lovering "Anticipation of the Lissajous Curves," *Proceedings of the American Academy of Arts and Sciences* 16 (1881): 292–98.

123. See Lissajous to Tyndall, November 17, 1857, in *Correspondence of John Tyndall,* 6:270.

FIGURE 7B. Lissajous's first illustration of the optical figures produced by his forks when tuned as (i) unison, (ii) octave, (iii) octave and a perfect fifth, (iv) perfect fifth, and (v) perfect fourth, and compared over nine measured phrase differences between vibrations. Lissajous, "Étude optique des mouvements vibratoires," 703. By permission of the Master and Fellows of Trinity College, Cambridge.



Lissajous's optical patterns were driven by a sounding fork, as noted, but from the very outset he saw this as a means to an end. The fork had no claim to sonic particularity, he explained: "This experiment, like those that follow, was carried out using tuning forks; of all the vibrating bodies this device is the most convenient to use, although the method can be applied to other bodies, such as lathes, gongs, bells, vibrating plates, etc."[124] Lissajous was not suggesting that visualized acoustic vibration was fictional, only that vibrations were not particular to sound. "This work was merely the particular application of a principle," as he put it in his third paper.[125]

During Tyndall's talk, frequent problems with the electric light beam meant he had to extemporize to "fill up chasms" of time for his audience, which included luminaries from Michael Faraday to the current and several former presidents of the Royal Society.[126] While we cannot know what he said off the cuff, it is tempting to suppose that the lack of sonic particularity ascribable to Lissajous's figures, and thus the experiments' lack of any claim for sonic ontology, may have served as plausible caveats to the dazzling optical display—a display whose array of patterns were certainly coupled to his later edict to picture sound "with the eye of the mind." Eight experiments were performed, of which six used electric light. Five different tuning forks were used in combination, controlled by Lissajous's "comparator," a device for supplying electromagnetic current to control the vibrational patterns of the forks, allowing for sustained visual scrutiny of their shapes.[127] The sheer variety and malleability of patterns produced is indicated in figure 7b, where their manipulability arising from phase difference and intervallic ratios only reinforces the notion that acoustic patterns were playful acts of experimental creativity, not newly unveiled ontologies of nature—that is, an expression of those mathematical fictions, as Helmholtz would put it, "permissible for calculating, but not necessarily having any corresponding actual meaning in things themselves." *In nuce*, the switch from iconic to symbolic signs had become all but irresistible.

124. Lissajous, "Étude optique," 699: "Cette expérience comme celles qui vont suivre ont été exécutées à l'aide de diapasons; cet appareil est de tous les corps vibrants le plus commode à employer, néanmoins la méthode peut s'appliquer à d'autres corps, tels que lames, timbres, cloches, plaques vibrantes, etc."

125. Lissajous, "Mémoire sur l'étude optique," 148: "ce n'était du reste que l'application particulière d'un principe."

126. See Tyndall, "On M. Lissajous' Acoustic Experiments." On the need to extemporize and the list of attendees, see Tyndall to Thomas Hirst, June 15, 1857, in *Correspondence of John Tyndall*, 6:179.

127. A list of apparatuses used in the demonstration is given in Lissajous to Tyndall, June 14, 1857, Paris, in *Correspondence of John Tyndall*, 6:177.

Half a century after the epoch-making awe inspired by Chladni's silent *Klangfiguren*, widely received as a cryptic cipher for the nature of sound itself, Lissajous's figures stand in sober contrast: as an aestheticized means of calibrating forks and building instruments. "I am convinced that it will be of real use, even in research relating to practical acoustics and the manufacture of musical instruments," he predicts, adding that it can already be used "to obtain as perfect an agreement as possible between two tuning forks without involving the ear," as well as detecting changes caused in forks by temperature or by "molecular modifications."[128] From the outset, then, the destiny of Lissajous's invention was assumed to be that of a refined measuring device. At no point did the optical patternings assume status as "sound visible"; they thus marked a shift away from the representationalist trap of geometrical optics.

Tyndall's refusal to endorse Schulze's wave apparatus, and his simultaneous support of Lissajous's visualizations of sound (which Lissajous himself took as a "benevolent . . . endorse[ment]"), suggests that by this point Tyndall was already persuaded that the new optical representations of waves were abstract symbols rather than objective recordings of an external sonic "reality."[129] Presented with the options of fixity (Schulze) and skepticism (Lissajous) he was swayed by the latter, finally concluding that it should be left to the imagination to "see mentally the air particles" in compressions and rarefactions. (The opinion was expressed in his 1867 lectures, whose principal German translator was none other than Helmholtz's wife Anna, implying a shared skepticism between Tyndall and Helmholtz.)[130] Not all readers were persuaded by the prospect of forming mental pictures of the invisible, however. At least one simply yearned for higher-precision lithographs: "I am afraid our 'mental pictures' are of the haziest description. The most perfect Photographer could not, I suppose, produce a clear image of ill-prepared paper."[131]

The influence of Lissajous's skepticism continued to be felt. The year of his presentation to the Royal Institute he was assigned to review the patent for what would later be recognized as the first acoustic recording apparatus, a "phonautograph," submitted on March 25, 1857, by fellow

128. Lissajous, "Étude optique," 699, 705: "je suis convaincu qu'elle présentera une utilité réelle, même dans des recherches relatives à l'acoustique pratique et à la fabrication des instruments de musique. . . . Nous pouvons, en effet, l'employer pour obtenir entre deux diapasons un accord aussi parfait que possible sans faire intervenir l'oreille. Nous pouvons mesurer, avec une grande exactitude, l'altération produite dans le son d'un diapason, soit par les changements de température, soit par des modifications moléculaires."

129. Lissajous to Tyndall, January 29, 1857, in *Correspondence of John Tyndall*, 6:67–68.

130. See Gustav Wiedemann to Tyndall, December 21, 1867, Carlsruhe, in *Correspondence of John Tyndall*, 10:227.

131. Mary Egerton to Tyndall, October 29, 1867, in *Correspondence of John Tyndall*, 10:177.

inventor Édouard-Léon Scott de Martinville. Martinville's device attached a stylus to vibrations created by a thin membrane ("tympanum") in order to model the transduction of sound within the ear, inscribing the resulting vibrations onto smoke-blackened paper, again turned by a crank handle. His claims went beyond those of Duhamel's vibroscope in that the phonautograph's wavy line tracings constituted a form of automatic stenography that promised to capture visually the intonation and articulations of singing and animated speech itself: "a process by means of which," his patent asserted, "one can *write and draw by sound* (acoustic)."[132] Critically, Martinville claimed that two different kinds of wave motion were traceable in the submitted test sheets (*épreuves*): the mathematical wave of condensation/rarefaction, *and* a second, hypothetical "wave of inflection" (*onde d'inflexion*) that he believed defined vocal expression. "You will notice in my *épreuves*," he confirms, "that the existence of this second motion . . . does not distort in any way the wave of condensation, the vibration properly so called; they coexist and this last does not cease to mark the tonality, the timbre, and, in ordinary cases, the intensity."[133] A sample test sheet for inscribing vocal inflections is reproduced as figure 8.

Seven months later Martinville took the principle further, asserting that visual tracings on phonautograms constitute "the human voice . . . written by itself (in a language peculiar to acoustics, of course)."[134] Here he was already dealing with sonic inscription as an ocular language—the phonautograms were to be *read* without any hint of a playback function[135]—and the idea proved persuasive. When the phonautograph was presented to a meeting of the British Association for the Advancement of Science in Aberdeen, the principle was immediately likened to a form of sonic photography: "Every instrument has its own peculiar character, as distinguishable by the eye as its quality of tone is by the ear. . . . We can only compare his invention to that of M. Daguerre, which, in its infancy, was treated as a mere toy, but which has now become one of our most valuable scientific instruments of observation."[136] The visualist trope in such reactions is telling, lending credence to the photographer Gaspard-Félix Tournachon's famous prediction of the same in 1849, explaining why phonography ("writing sound") was quite naturally conceived as a visual medium from the outset:

132. Reproduced in Patrick Feaster, ed. and trans., *Phonautographic Manuscripts of Édouard-Léon Scott de Martinville* (Bloomington: FirstSounds.org, 2009), 13, https://www.firstsounds.org/publications/articles/Phonautographic-Manuscripts.pdf.

133. Feaster, *Phonautographic Manuscripts*, 33.

134. Feaster, *Phonautographic Manuscripts*, 23.

135. On the disadvantages of focusing on playback rather than viewing phonautograms as visible archivable documents, see Patrick Feaster, "Enigmatic Proofs: The Archiving of Édouard-Léon Scott de Martinville's Phonautograms," *Technology and Culture* 60 (2019): S14–38, at S16.

136. "Acoustics," *London Literary Gazette*, October 8, 1859, 359.

FIGURE 8. Édouard-Léon Scott de Martinville's test sheet for a "study of vocal inflection" (Société d'Encouragement pour l'Industrie Nationale, Archives, 8/54-23), showing specifically the "waves of inflection" that Martinville saw alongside waves of compression/rarefaction. From his talk "Procedures for the Graphic Fixation of the Voice" (1857): https://www.firstsounds.org/publications/facsimiles/FirstSounds_Facsimile_04.pdf.

> I was amusing myself, daydreaming some fifteen years ago, writing . . . that one of these days it will come to pass that someone will present us with the daguerreotype of sound—the *phonograph*—something like a box within which melodies would be fixed and retained, the way the camera seizes and fixes images. . . . What I dreamed, I, an ignorant man, a man of imagination, was discovered by a man of science five or six years later. . . . It was sound waves, recorded (graphed by the learned Mr. Lissajoux)![137]

But as with Lissajous's experiments, the phonautograph's perceived use-value was as a measuring tool—a capturer of the mathematical wave of condensation and rarefaction. This again rendered any hint of sonic ontology an epiphenomenon, a mere sideshow to the main event of quantifying vibration.

Lissajous's markings show that he examined just three of Martinville's phonautograms. He accepted that frequency and timbre could

137. Félix Nadar, *À terre et en l'air . . . Mémoires du géant* (Paris: E. Dentu, 1864), 271–72: "Je m'amusais, dormant éveillé il y a quelque quinze ans, à écrire . . . qu'il se trouverait un de ces matins quelqu'un pour nous apporter le Daguerréotype du son—le *phonographe*—quelque chose comme une boîte dans laquelle se fixeraient et se retiendraient les mélodies, ainsi que la chambre noire surprend et fixe les images. . . . Ce que je rêvais, moi, ignorant, homme d'imagination, un homme de science le trouvait cinq ou six ans après. . . . C'étaient les ondes sonores, notées (graphiées par le savant M. Lissajoux)!"

be transcribed by the lines of the stylus, but stopped short of accepting that the expressive articulations of language had been represented by the apparatus: "We do not mean by this to declare the problem insoluble, but we do not see in the drawings provided by the author any serious information relating to its solution."[138] He acknowledged that all possible qualities of sonic articulations and song intonation were quantifiable in theory, that these "preexist in the air [and] can have no other origin than more or less complicated combinations of speeds for which graphic representations can be designed."[139] But the essence of his objection was simple, and it proved susceptible to further simplification in summaries by physicists like Franz Melde, who judged in 1864 that only simple tones of tuning forks could be accurately inscribed as sound itself: "The value of the phonautograms emerges from what has just been said regarding the fixing of *pitch* and regarding the forms of vibration-curves of the constituent sounds in themselves [*von selbst*]—providing the latter only consist of only a few simple tones."[140] Only recently, in 2008, did the accuracy of Martinville's sonic inscriptions become apparent, when their illegible inscriptions were converted into sound.[141] Lissajous's caution (amplified by Melde and others) had been misplaced, owing, it would seem, to wider late nineteenth-century skepticism over the visualization of the physical motion of sound waves.[142]

Testing Analogical Logic

Working *against* this skepticism was the enduring intuition that the tuning fork obeyed the laws of motion that Galileo had calculated in the pendulum; that it behaved like a miniature pendulum fixed at one point, producing audible sound at the other. Léon Foucault's insight in 1851 was to invert the fixed point, creating an upside-down fork, after his pendulum had been

138. Jules Lissajous, "Rapport fait par M. Lissajous, au nom du comité des arts économiques, sur les essais phonographiques de M. Scott," *Bulletin de la Société d'encouragement pour l'industrie nationale* 5 (1858): 140–45, at 144: "Nous n'entendons pas, par là, déclarer le problème insoluble, mais nous ne voyons dans les dessins fournis par l'auteur aucune indication sérieuse relativement à sa solution."

139. Lissajous, "Rapport fait par M. Lissajous," 141: "elle préexistent dans l'air, elles ne peuvent avoir d'autre origine que des combinaisons plus ou moins compliquées de vitesses dont il est possible de concevoir la représentation graphique."

140. Pisko, *Die neueren Apparate der Akustik*, 82: "Aus dem bisher Vorgetragenen ergibt sich der Werth der Phonautogramme bezüglich der Bestimmung der Ton*höhe* und bezüglich der Formen der Schwingungs-Curven der zusammengesetzten Klänge von selbst—vorausgesetzt, dass die letzteren aus nur wenigen einfachen Tönen bestehen." Emphasis in original.

141. See the research into Martinville's archive by David Giovannoni and Patrick Feaster at www.FirstSounds.org (accessed September 19, 2025).

142. See https://www.firstsounds.org/research/scott.php.

inspired by the uniform vibrations of Chladni's tuning fork gripped in a spinning lathe. Its analogical logic—the slow-swinging pendular motions made visible the identical, faster motions of tuning fork prongs—had no shortage of advocates. A year after Foucault's demonstration, Georg Ohm credited the Dutch physicist Christiaan Huygens (1629–95) with first applying the pendulum to sonic motion. Huygens must have believed he had hit on an ontology, Ohm intimates, for the Dutchman claimed that only fully pendular vibrations are heard as sound—that is, periodic vibrations with an "entirely regular course" of acceleration and retardation within each oscillation.[143] This is not strictly the case.[144] But a decade after Ohm no less an authority than Helmholtz added his imprimatur to the analogy ("its two prongs oscillate backwards and forwards in the same way and after the same law as a pendulum"), thereby endorsing a paradigm that Tyndall would use as the centerpiece of his public lectures in 1867.[145]

Since pendular motion was miniaturized in tuning forks, and fork vibrations were audible, their graphic tracing retained a claim to be the closest thing to "sound visible." By the mid-1870s, commentators were in no doubt that this link depended on heard sound: "Since the pendulum oscillates according to the same law as the free ends of the tuning forks . . . the movements of the latter can be represented by a pendulum in a slower form. . . . But no theoretical results can be derived from the tuning fork curves drawn by two pendulums," Hagen cautions, "precisely because the human ear does not perceive their sound waves."[146] Like a fig leaf, the pendulum's silence guaranteed sound's elusive ontology. Here, a mutual exclusivity was being instilled within our perceptual means: we hear sound but cannot see it; *or* we see its generative motions but cannot hear it. This exchange, in turn, created the space for representation, but kept alive the suspicion that more direct inscriptions of fork vibrations might yet render visible sonic ontologies.

143. Georg Ohm, *Grundzüge der Physik*, 2 vols. (Nuremberg: Schrag, 1853), 1:85: "ein völlig regelmäßiger Gang." Both Mersenne and Isaac Beeckman had also compared string vibration to the pendulum. See Dostrovsky, "Early Vibration Theory."

144. Irregular waveforms exist alongside sine waves as only the most "hypervisualized" of pressure waveforms. See Paul Hegarty, *Noise Music: A History* (New York: Continuum, 2007), 150, and Joanna Demers's work on the aesthetics of experimental electronic music, *Listening through the Noise: The Aesthetics of Experimental Electronic Music* (New York: Oxford University Press, 2010), 103–7.

145. Helmholtz, *On the Sensations of Tone*, 19; Tyndall, *Sound*, 92. See also Alfred Mayer's comment: "In my course of lectures on Acoustics, I thus show to my students that the prong of a tuning-fork vibrates like a pendulum." Mayer, "Researches in Acoustics," 82.

146. Hagen, "Ueber die Verwendung des Pendels," 288: "Da das Pendel nach demselben Gesetze schwingt, wie die freien Enden der Stimmgabeln . . . so lassen sich die Bewegungen der letzteren durch Pendelschwingungen in verlangsamter Form darstellen. . . . Aus den von zwei Pendeln gezeichneten Stimmgabelcurven wird man allerdings, eben weil das menschliche Ohr deren Schallwellen nicht wahrnimmt, keine theoretischen Resultate ableiten können."

Quite why such an episteme of incompleteness crystallized around fork-pendulum relations returns us to Martinville's phonautography. From 1860 he used sounding forks in two ways: (i) to calibrate irregular vocal declamation, creating a control for speed and amplitude, occasionally aided by a chronometer to mark regular points in time (see fig. 9); (ii) to inscribe vibration directly. Working with Rudolph Koenig in Paris, he fixed a brass stylus to one prong of a fork, inscribing its side-to-side vibration directly onto blackened paper or glass. Helmholtz celebrated such methods ("It is easy to see the meaning of such a curve"),[147] and offered his own simplified illustration (fig. 10). When Martinville expounded the theory behind this in a paper on the "automatic inscription of sound in air" (1861), his hand-drawn, annotated illustrations of transverse wave motion indicate that he fully accepted Herschel's particle model of wave motion (see fig. 11a). By contrast, his free-hand drawings of the resulting compound waves, calculated by ratio, were guided by the imagination though evidently informed by measuring devices. As figure 11b shows, he drew a thick black line for the compound wave of 4:5 (major third), showing an approximate aggregate of the dotted sine waves above and below. Its mechanical equivalent is arguably Koenig's 1862 vibrograph (fig. 11c), which combined the vibrations of two tuning

FIGURE 9. Martinville's test sheet setting vocal inflection alongside tuning fork vibration: "Acoustic effect of declamation with simultaneous tuning fork to show the inflection of the intonation . . . April 17, 1860" (Bibliothèque de l'Institut de France, MS 2935, no. 89095). From his talk "Fixation et transcription du chant" (1860): https://www.firstsounds.org/publications/facsimiles/FirstSounds_Facsimile_05.pdf.

147. Helmholtz, *On the Sensations of Tone*, 20.

FIGURE 10. Helmholtz's illustration of direct inscription of tuning fork vibrations associated with Rudolph Koenig and Martinville. Hermann von Helmholtz, *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik* (Brunswick: Vieweg & Sohn, 1863), 33. By permission of the Master and Fellows of Trinity College, Cambridge.

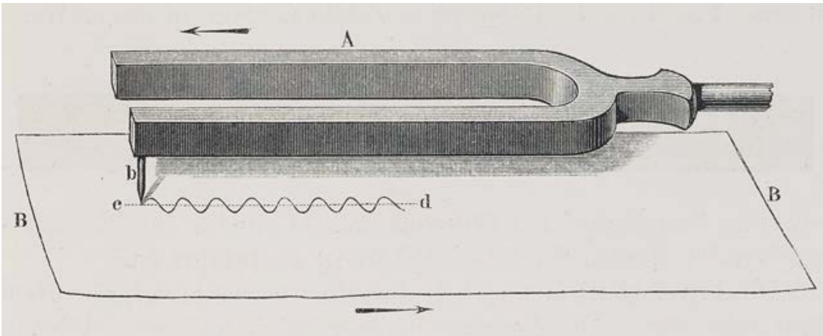


FIGURE 11A. Martinville's illustration of particle motion, agitated in the direction $a \rightarrow b$, in a transverse wave at 250Hz: "a, a′, a″ are the same position of the molecule which it comes back to occupy successively after equal moments" (Académie des sciences, no. 324). From his talk "Inscription automatique des sons de l'air au moyen d'une oreille artificielle" (1861): https://www.firstsounds.org/publications/facsimiles/FirstSounds_Facsimile_06.pdf.

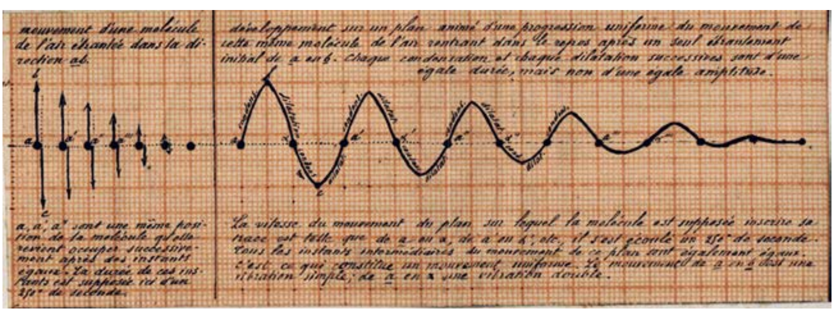
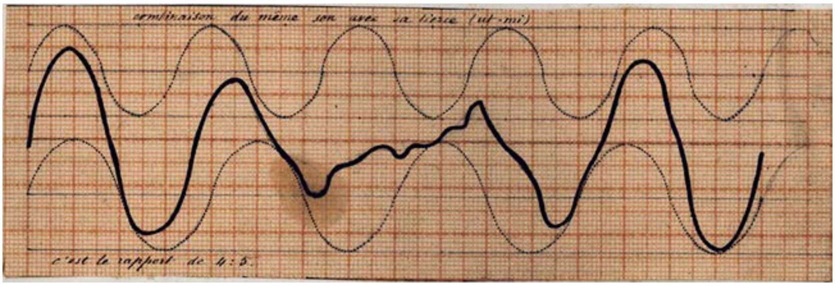
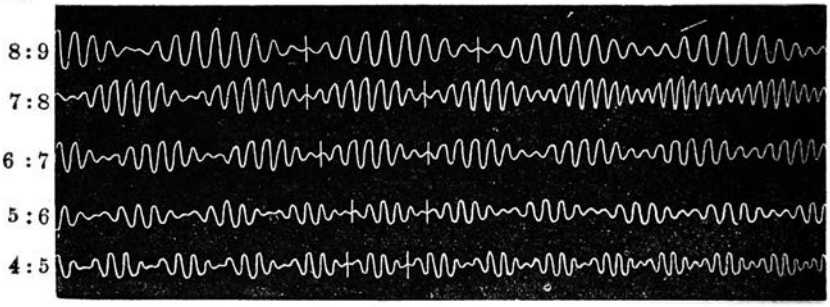


FIGURE 11B. Martinville's hand-drawn illustration of the compound wave he imagines resulting from the ratio 4:5 (major third). From his talk "Inscription automatique des sons de l'air au moyen d'une oreille artificielle" (1861): https://www.firstsounds.org/publications/facsimiles/FirstSounds_Facsimile_06.pdf.

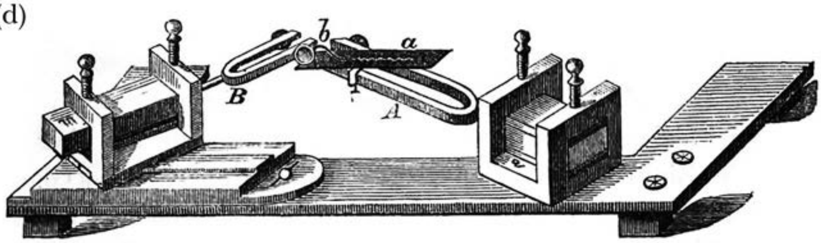


FIGURES 11C–D. Franz Josef Pisko's illustration (c) of the compound waves in different ratios created by Rudolph Koenig's vibrograph (d), in which two tuning forks are placed perpendicularly. Franz Josef Pisko, *Die neueren Apparate der Akustik* (Vienna: Carl Gerold's Sohn, 1865), 65, 86. Credit: HathiTrust Digital Library.

(c)



(d)



forks, placed perpendicularly, and engraved the motion via a steel pin onto blackened glass.[148] Figure 11d presents the same 4:5 ratio, when *not* guided by the imagination. Needless to say, the hand-drawn line looks like a faked-up copy of Koenig's mechanical tracing.

Critically, this web of representations ensured that the mind could not find its way to objects except through the often undetectable contingencies of viewing technique, apparatus, and language. It is hardly surprising, then, that at no point was the positive assertion made that pendular oscillations corresponded *without doubt* to the physical movements of sonic vibrations in air. On the contrary, doubts remained, not only about the shape of waveforms, but about their very existence. Hall, the New York–based experimentalist we met earlier, targeted Tyndall's public lectures on sound in a chapter-length assault on the concept of wave theory and the agency of the tuning fork in 1877. He ridiculed Tyndall's description of wave propagation with unflattering interpolations in brackets (e.g., "When a tuning-fork . . . vibrates, it *moulds the surrounding air into sonorous waves* [mark it, the '*sonorous waves*' are composed of '*air*,'] each of which consists of a condensation and a rarefaction"), citing a tuning fork with 56 vibrations per second that "*moulds* and *sends* off sonorous *airwaves* at a velocity of 1120 feet a second" as a conflict of sound's constant velocity vs. its initial generating motion. To paraphrase his argument, if each prong's motion is ⅛ of an inch, its total movement is 7 inches per second (56Hz ÷ 8), but the distance traveled is 13,440 inches per second (1,120 feet per second × 12 inches, based on 12 inches per foot), meaning the velocity is 1,920 times faster than its initiating motion in the prongs of a tuning fork (13,440 ÷ 7):

> Was there ever anything taught as science more transcendently or transparently preposterous than this? . . . [W]hile the most ordinary student must see that by no law of philosophy, and by no rules of mensuration known in heathen or Christian lands, could such a fork "send" off corporeal waves of any kind of substance *a distance of over seven inches in a second*, even if the friction and inertia of such substance were wholly abolished![149]

However misplaced, such bald skepticism was mathematically sound, if initiating fork motion equals maximum speed of propagation. A bullet from a gun could hardly travel 1,920 times faster than the gasses forcing it through the barrel, Hall continues. His arguments are confused yet telling; they could not have emerged outside of the conflicted, often

148. Rudolph Koenig unveiled his apparatus, driven by electromagnets, at the London Exhibition in 1862, and described it to a German readership a year later. Rudolph Koenig, "Apparat zur Messung der Geschuldigkeit des Schalls," *Annalen der physik und chemie* 118 (1863): 610–14.

149. Alexander Wilford Hall, *The Problem of Human Life: Embracing the "Evolution of Sound" and "Evolution Evolved"* (New York: Hall, 1877), 148.

contradictory public debates over the materiality of waveforms and particle motion traced above.

Doubts about the very existence of sound waves continued to be publicly debated in London at the Musical Association's Beethoven rooms and in the pages of the *English Mechanic* between 1889 and 1891.[150] And it is indicative that drawings produced by the most sophisticated and widely celebrated double-pendulum device of the period—S. C. Tisley's "harmonograph" of 1873—were now understood in purely aesthetic terms. The frequency/period of its two-meter-long pendulum rods, perpendicular to each other, could be adjusted by moving weights up or down the rods (see fig. 12a). This provided a means of programming the integer ratios of musical intervals but without a causal link to sound, and thus, like Lissajous's optical figures, Tisley's device never claimed to make "sound visible." Indeed, it had originally been conceived for the very purpose of "recording the figures shown in Lissajous's experiments with tuning-forks," Tisley explained.[151] Its inscribed symmetrical patterns appeared more intricate than Lissajous's optical display, underscoring the claim that *visual* acuity of graphed vibrations now exceeded aural acuity of pitch, even for the finest musical ears: "Physicists have always tried to make acoustic experiments accessible to the eye," Hagen reflected confidently, "and in fact the optical method has attained such perfection that . . . a deaf man is able to compare tones with greater accuracy than the finest ears will ever be able to."[152] Tisley cultivated the harmonograph's bewitching patterns for commercial gain at his optician's shop in London. At the equivalent of 400 marks per unit, "the price of this apparatus is in an unfavorable ratio to its scientific importance," observed Hagen wryly.[153] Figure 12b reproduces the same ratios 5:6 (minor third) and 4:5 (major third) as figure 11d, but from Tisley's apparatus, now as fully aestheticized pendular tracings of these metrical relations.

150. George Audsley gave two public talks and serialized an article. George Audsley, "What Is Sound? The Substantial Theory versus the Wave Theory of Acoustics," *Proceedings of the Musical Association* 16 (1889–90): 103–48, and "What Is Sound? The Substantial Theory versus the Wave Theory of Acoustics II," *Proceedings of the Musical Association* 17 (1890–91): 59–94. See also George Audsley, "Acoustics: A Review of the Old and New Theories of Sound," *English Mechanic and World of Science and Art,* November 1 and 21, December 6 and 20, January 10 and 24, and February 7, 1889–90, 191–92, 253–54, 291–92, 331–32, 395–96, 433–35, 473–74.

151. S. C. Tisley, "On a Compound-Pendulum Apparatus," *Report of the British Association for the Advancement of Science* (1873): 48 ("Notes and Abstracts of Miscellaneous Communications to the Sections").

152. Hagen, "Ueber die Verwendung des Pendels," 285–86: "Von jeher haben die Physiker sich bemüht, die akustischen Experimente auch dem Auge zugänglich zu machen, und in der That hat die optische Methode eine solche Vollkommenheit erlangt, dass . . . ein Tauber sei im Stande, Töne mit grösserer Genauigkeit zu vergleichen, als es dem feinsten Ohre je gelingen werde."

153. Hagen, "Ueber die Verwendung des Pendels," 287: "der Preis dieses Apparates [steht] mit dessen wissenschaftlicher Bedeutung in einem ungünstigen Verhältnisse."

FIGURE 12A. S. C. Tisley's harmonograph (1873), a compound pendulum for inscribing onto blackened paper or glass different compound waves. It was driven not by tuning forks but by the placement of weights on the metal rod of each pendulum. Gaston Tissandier, *Le ricreazioni scientifiche, ovvero L'insegnamento coi giuochi* (Milan, 1889), 99. Credit: Wellcome Collection.

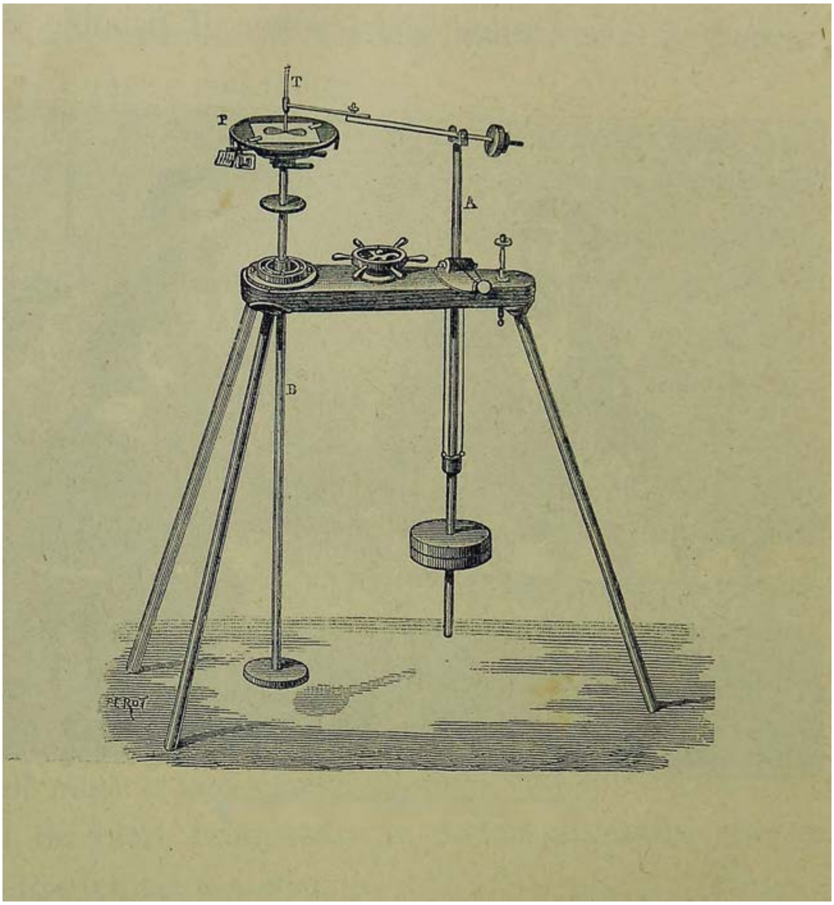
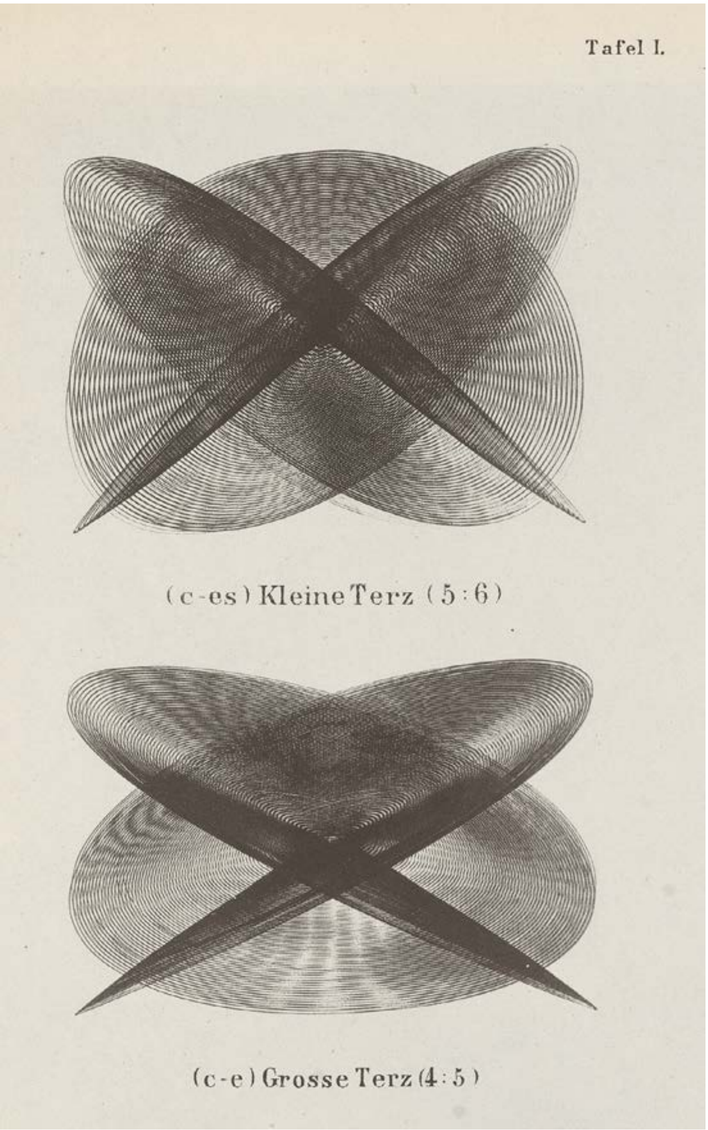


FIGURE 12B. Tisley's harmonograph tracings of the ratios of the minor third (above) and major third (below). Joachim Hagen, "Ueber die Verwendung des Pendels zur graphischen Darstellung der Stimmgabelcurven," *Zeitschrift für Mathematik und Physik* 24 (1879): 285–303, table 1. Credit: Cambridge University Library.



Reenchanting the World

Finally, if we return one last time to Helmholtz's claim that "the artist has beheld the real," the idea of waveform music initiated by Liszt's "Au lac de Wallenstadt" can be plausibly bookended by American composer Amy Beach's *By the Still Waters* (1925). While any continuity between the discourse on acoustic waves and her composition remains an imaginative leap, it is worth noting that Beach publicly burnished her education in acoustics and harmony ("More women are interested in the serious study of the science of music as well as the art than formerly") and was a longtime member of the American Association for the Advancement of Science.[154] Her programmatic keyboard piece is just fifty-two measures long, with the right hand mimicking the undulation of wave patterns throughout. Below this perceptible surface, the metrical ratios of Beach's patterns can be read in relation to the compound waves defined by integer ratios—that is, the same compound waves traced in Martinville's imagination, Koenig's double-fork apparatus, and Tisley's harmonograph. Notated in $\frac{4}{4}$, her piece begins with a pattern of ten eighth notes outlining first a minor ninth (mm. 1–4), followed by a half-diminished ninth chord (mm. 5–8). As example 2 shows, the opening eight measures obliquely present two metrical ratios: a five-beat pattern in $\frac{4}{4}$ (4:5), and a six-measure left-hand line consisting of five whole notes (5:6).[155] The former is differentiated by its major third (a♭–c^1), the latter by its minor third (a♭–c♭^{1}), whose mathematical ratios accord to the metrical relations of Beach's phrases: 4:5 and 5:6. This reading of metrical-intervallic parallelism is selective in its focus on rhythmic ratios, and as such it would seem procrustean were it not for the fact that the thirds that the two ratios delineate are also prominent harmonic characteristics within the two opening phrases.[156] By 1925 the representation of sound waves had been understood as symbolic for over half a century, virtually annulling the question of realism in Beach's waveforms as compared to those of Koenig or Tisley.

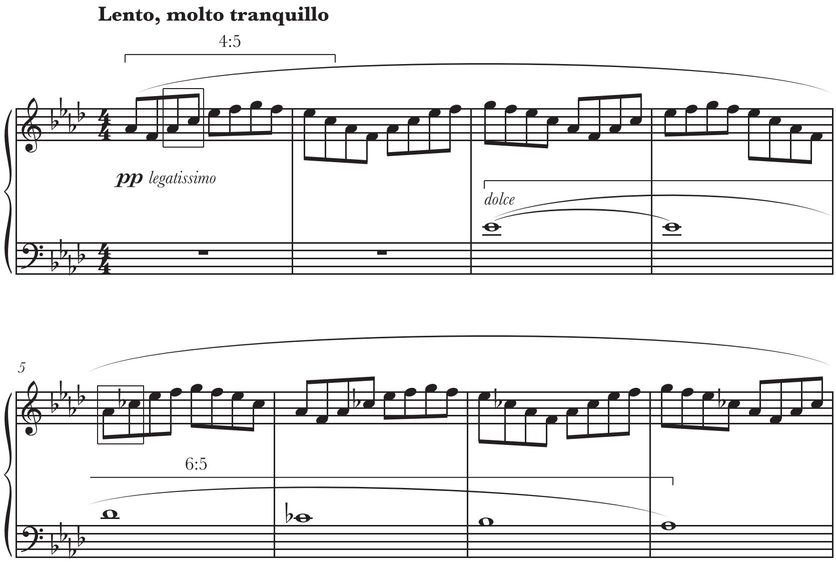
If, within the Foucauldian methods of this article, we now cast a sidelong glance across the archaeological shelf of pendular acoustics, a more direct connection between the musical interval ratios and pendular inscriptions crystallizes in the final decades of the century. Under the

154. See Adrienne Fried Block, *Amy Beach, Passionate Victorian: The Life and Work of an American Composer, 1867–1944* (New York: Oxford University Press, 1998), 45, 72.

155. Example 2 is transcribed from Amy Beach, *By the Still Waters* (St Louis: Art Publication Society, 1925).

156. The approach takes inspiration from David Lewin's redefinition of the music objects that intervals can connote in his "Generalized Interval Systems," including where "ratio-classes can be used as formal intervals." David Lewin, *Generalized Musical Intervals and Transformations* (1987; New York: Oxford University Press, 2011), 24.

EXAMPLE 2. Amy Beach, *By the Still Waters* (1925), mm. 1–8.

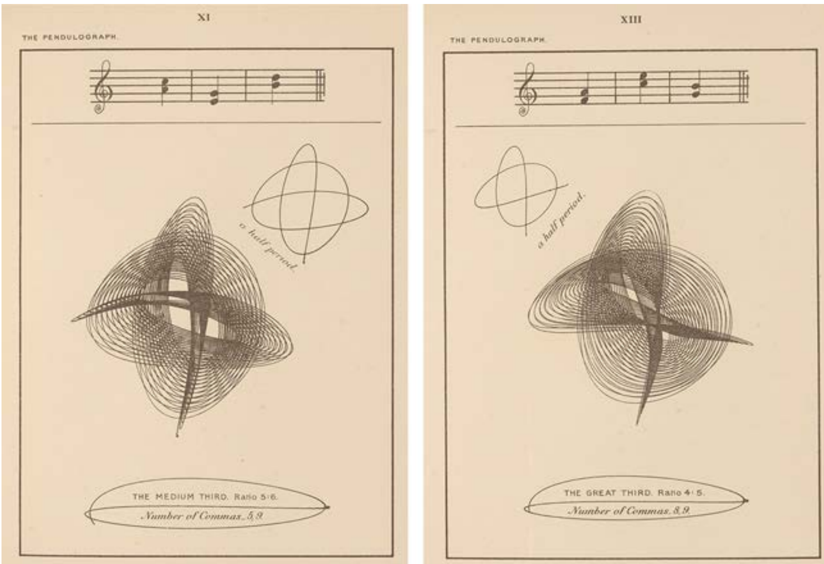


rubric of "sound seen in the silence," the Irish clergyman John Andrew argued for direct musical-visual comparisons of interval/pendulum tracings, as embodiments of a mathematical principle. His book *The Pendulograph* contains twenty such comparisons, including Beach's two third intervals, as figure 13 shows, and was dedicated to "students of Nature's analogical mysteries."[157] Such diagrams establish a link between composition and ratio tracing. Ultimately, however, the assumed rationalism of their mechanical inscription apparatus would be further undermined by the fact that the harmonographic images would soon be co-opted by prominent members of London's Theosophical Society as a means of externalizing "thought-forms," where integer ratios traced by the harmonograph were figured as cryptic tracings of an imagined meeting point between physical and mental "forces." In the words of theosophist and activist Annie Besant,

> It seems to us a most marvellous thing that some of the drawings, made apparently at random by the use of this machine, should exactly correspond to higher types of thought-forms created in meditation. We are sure that a wealth of significance lies behind this fact. . . . [I]t must surely

157. John Andrew, *The Pendulograph: A Series of Bi-pendulum Writings of the Twenty Ratios of the Musical System, or Sound Seen in the Silence* (London: George Bell and Sons, 1881), 17.

FIGURES 13A–B. The juxtaposition of musical intervals and their harmonographic counterparts produced using a compound pendulum. John Andrew, *The Pendulograph: A Series of Bi-pendulum Writings of the Twenty Ratios of the Musical System, or Sound Seen in the Silence* (London: George Bell and Sons, 1881), 11, 13. Credit: Cambridge University Library.



> imply this much—that, if two forces on the physical plane bearing a certain ratio one to the other can draw a form which exactly corresponds to that produced on the mental plane by a complex thought, we may infer that that thought sets in motion on its own plane two forces which are in the same ratio one to the other.[158]

With no less interpretive freedom, religious commentators including Reverend Andrew saw in harmonographic illustrations evidence of God himself: “Thine image bear they all / Or more or less,” he writes in 1881, invoking “heaven-born MUSIC, as Thine ordinance in air and ear.”[159] In light of the skepticism of Helmholtz and Lissajous noted above, this radical shift away from objectivity raises the possibility that the nineteenth-century discourse on pendular vibration may have contained the seeds of its own *irrationality* from the outset—and that acts of

158. Annie Besant and C. W. Leadbeater, *Thought-Forms* (Bradford: Percy Lund et al., 1901), 30.

159. Andrew, *Pendulograph*, 6.

imagination and faith were always implicated within those of reason and objectivity.[160]

* * *

To ask whether the mechanical tracings of Koenig's or Tisley's fork-driven apparatuses are more accurate or objective than Martinville's pen sketch or Liszt's and Beach's evocations of wave motion is to set off in the wrong direction, for it assumes a semiotics in which representation relates to a reality behind the sign, where what exists in nature is full of inherent resemblances, signatures of identity that are inscribed on the face of the world. The path we have traced shows how the model of pendular motion switched from an iconic to a symbolic sign when depicting sound waves. This switch was permanent. A recent cultural history of the pendulum sets out from the premise that "these representations are not like a video of the motion in the space of our real world, but are pictures . . . in various mathematical spaces," though others persist in arguing that "Lissajous' experiment and its connection to the harmonic movements of the pendulum . . . have literally made it possible to 'see the sound.'"[161] Perhaps this ongoing equivocation only underscores the tendency toward reflexivity—the intellectual gesture of the uncertain—in arguments about representation. If so, it is undermined by the verdicts of historical contemporaries such as Tyndall, Helmholtz, and Lissajous himself.

By ultimately rejecting representationalism we might conclude that the implications for pendular motion embodied in turning forks were "two-pronged": (i) this motion conveyed the pendulum's immaterial shape into sound, embodying the paradox of an immaterial space or a vibratory motion without material process, but remained unvisualizable *in actu* and contradictory for particle physicists; (ii) it rendered graphic tracings that lent optical precision to the measurement of sonic vibration, before being subsumed by a primarily aesthetic fascination from the mid-1850s. From the moment of Swan's sparking double pendulum, aesthetic patterning offered an empirical basis for calibrating instruments but required acts of

160. Witness the pendulum games in E. T. A. Hoffmann's novella *Signor Formica* (1819), which drive the protagonist mad after he wills a suspended ring into oscillation by "thinking as hard as I could" (all the while suspecting it could be the wind) and later uses pendular swinging to divine the future: "If such and such a thing is going to happen, let it swing at right angles." E. T. A. Hoffmann, *The Best Tales of Hoffmann*, ed. E. F. Bleiler (New York: Dover, 1967), 71. Or the irrational science behind Jean-Martin Charcot's "la médecine vibratoire," tuning-fork-driven medical therapies with a "surprisingly long afterlife," as Carmel Raz has shown in "Of Sound Minds and Tuning Forks: Neuroscience's Vibratory Histories," in *The Science-Music Borderlands: Reckoning with the Past and Imagining the Future*, ed. Elizabeth Margulis, Psyche Loui, and Deirdre Loughridge (Cambridge, MA: MIT Press, 2023), 115–29, at 124.

161. Gregory L. Baker, *Seven Tales of the Pendulum* (New York: Oxford University Press, 2011), 14; Gallozzi and Stollo, "Between Mechanics and Harmony," 214.

perception that returned human agency to the heart of the matter, soliciting techniques of imagination that would imbricate with occult fantasy. If this marks the limit of a modern rationalism, it also thereby qualifies the absolute terms in which wider anxieties over an advancing means of calculation, emblematized in Max Weber's oft-cited diagnosis of a progressive "disenchantment of the world" ("Entzauberung der Welt"), are accepted.[162] Here, by contrast, pendular experiments to trace sonic vibrations chart an interdependency of measurement and imagination that saw claims for a transduced medium, or "sound visible," abandoned within two decades.

ABSTRACT

Early nineteenth-century attempts to visualize sound waves are traceable across experimentalists from William Swan and John Tyndall to Helmholtz, Jules Lissajous, and Édouard-Léon Scott de Martinville. A combination of optical and graphic methods proliferated during the 1850s and 1860s, all of which relied—directly or indirectly—on the isochrony of the pendulum. Léon Foucault's 1851 pendulum experiment to demonstrate the imperceptible rotation of the earth was followed by a flurry of attempts to capture the equivalent invisible motion of sound in space. But from the outset confusions arose over whether the resulting sinusoids and symmetrical patterns were to be understood as describing the shape of sound waves in themselves or merely as symbolic representations, implicating the role of the imagination and viewing technique in experimental work. This led some to doubt the validity of waveforms entirely, returning the discourse on sound to an Aristotelian distinction between immaterial form and material thing, which formed the basis of contentious debates in New York and London between 1877 and 1890. Drawing on experimentalists, composers, mathematicians, and early particle physicists, this article traces debate and disagreement within attempts to visualize sound from Swan's Y-shaped pendulum in 1848 to Tisley's harmonograph in 1873, and the latter's subsequent appropriation by the London Theosophical Society. It also explores Helmholtz's claim that within the century's culture of experimentation it is the artist "who has beheld the real," a proposition tested in programmatic keyboard works concerning waveform by Franz Liszt and Amy Beach.

Keywords: sound waves, visualization, pendulum, creative imagination, Hermann von Helmholtz, Jules Lissajous

162. Max Weber, *The Vocation Lectures*, ed. David S. Owen, trans. Rodney Livingstone (Indianapolis: Hackett, 2004), 12–13.