Thomas Young's Musical Optics:
Translating Sound into Light

by Peter Pesic*

ABSTRACT

Thomas Young's interest in music affected his scientific work throughout his career. His 1800–1803 papers interrelate musical, acoustic, and optical topics to translate the wave theory from sound to light, as does his synoptic *Lectures on Natural Philosophy* (1807) in justifying his discoveries to a larger audience. Returning to optics in 1817, in the aftermath of the work of Fresnel, Young grounded in musico-acoustical studies his suggestion that light may be a transverse (rather than longitudinal) wave, along with its paradoxical implications for the ether, which he discussed in 1823. Young's decipherment of Egyptian hieroglyphs also rested on phonology.

Thomas Young (1773–1826) made crucial interventions in the development and application of wave theory to light. Throughout his career, he used studies of music and sound to advance the theory of wave motion, especially the concept of interference, which he worked out in sound and then applied to light. Sir John Herschel singled out Young's insight into sound interference as "the key to all the more abstruse and puzzling properties of light, which would alone have sufficed to place its author in the highest ranks of scientific immortality, even were his other almost innumerable claims to such a distinction disregarded."[1]

Young's accomplishment should be placed in the context of Newton's skepticism about the wave theory of light, which shadowed the century after his *Opticks* (1704).[2] In general, Continental writers adopted wave theories, following Descartes's picture of an all-pervasive fluid continuum, whose vortices moved the planets and whose vibrations were visible as light. In contrast, British scholars preferred Newton's particle theory. They followed him in considering Francesco Grimaldi's experiments as not fully sufficient to prove the wave theory, hence leaving the particle theory as the

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[1] Quoted in George Peacock, *Life of Thomas Young, M.D., F.R.S.* (London, 1855), 128.

[2] Henry Steffens, *The Development of Newtonian Optics in England* (New York, 1977); Geoffrey N. Cantor, *Optics after Newton: Theories of Light in Britain and Ireland, 1704–1840* (Manchester, 1983); Jed Z. Buchwald, *The Rise of the Wave Theory of Light: Optical Theory and Experiment in the Early Nineteenth Century* (Chicago, 1989).

"simpler," more obviously "mechanical" explanation for light, absent more powerful evidence to the contrary.

The crucial arguments did not emerge until around 1800 in the work of an amazingly multitalented individual who, though unique in his constellation of abilities, manifests the fruitful breadth of scope so important in the advances made by other contemporary natural philosophers. Among the rich diversity of his serious interests, music occupied a special place for Young, helping him formulate and advance his advocacy of the wave theory as he translated it into the realm of light. I will show how musical concerns emerged in each phase of his work, first in the overt context of vibrating bodies and pipes, then applied by analogy to light. To illuminate how his thinking carried forward these acoustical archetypes into progressively more elaborate optical formulations, I shall follow the intertwined development of these musical and optical themes chronologically through Young's writings, with close attention to their timing and arrangement. The specific order and placement he gave these issues reflects their interplay and influence as he took these analogies ever deeper, for music functioned both as an "external" and an "internal" force in the detailed development of Young's work on acoustics and optics. I will argue that, point by point, his optical innovations were prepared by his prior studies in sound and music, which began as external artistic studies that soon became embedded in the internal development of Young's natural philosophy.

Accordingly, my treatment will be guided by the detailed sequence of his arguments. After discussing Young's musical background, I will give a close reading of his papers during 1800–1803, which illuminate the role of musical concerns in his unfolding optical discoveries. Then I will discuss Young's retrospective account of these same developments as he justified them to a broader public in his lectures at the Royal Institution. A decade later, Young's sonic analogy affected his final thoughts on light as a transverse wave. Throughout, his interest in translation and linguistics bore on his rendition of music and sound into optics and light. Conversely, his concern for sound also affected his pioneering work in deciphering Egyptian hieroglyphics.

YOUNG'S MUSICAL BACKGROUND

Young's intellectual development should be considered against his background as the eldest of ten children in a pious Society of Friends (Quaker) family. His uncle was an eminent physician and member of the Royal Society. Young showed a prodigious early talent for languages. Though basically self-taught (his family could not afford the elite public schools and their specialized tutoring), by age nineteen he was fluent in Latin and Greek, had a good command of the principal European living languages, could read biblical Hebrew, and had even studied Chaldean, Syriac, and Arabic.[3] For instance, his youthful rendition of a speech from Shakespeare into

[3] See Peacock, *Life of Thomas Young* (cit. n. 1, on 12), which remains a valuable source from a near-contemporary (though Peacock did not know Young personally), along with Hudson Gurney, *Memoir of the Life of Thomas Young* (London, 1831). Both are ultimately reliant on Young's own autobiographical notes; see Victor L. Hilts, "Thomas Young's 'Autobiographical Sketch,'" *Proceedings of the American Philosophical Society* 122 (1978): 248–60. The most complete modern biography is Alexander Wood and Frank Oldham, *Thomas Young, Natural Philosopher, 1773–1829* (Cambridge, 1954), which notes that Young's father and grandmother "were not merely nominal Quakers, but active members of the Society" and adduces "a certain affinity between the Quaker pursuit of truth, with its emphasis on verification in personal experience, and the scientific method" (3). More re-

classical Greek (fig. 1) exemplifies his lifelong interest in the problem of translation, a recurrent theme in his later work, along with general issues of phonology and comparative linguistics.

During those years, Young also taught himself mathematics and developed an interest in science. He read Newton's *Principia* by himself, a notable feat, for this formidably difficult book (the bible of contemporary science) was usually treated at the university level as a work of extraordinary difficulty, only accessible through specialized commentary and tutoring. Nor were his studies purely theoretical; he ground colors, studied drawing, and constructed scientific instruments. After leaving one of the local schools, he devoted himself "almost entirely to the study of Hebrew and to the practice of turning and telescope-making."[4] Yet despite his amazing breadth and depth of learning, Young was quite unaware of popular literature; his Quaker upbringing removed him from the ordinary activities of his contemporaries.

Whatever may have been his personal preferences, his family's finances dictated that he take up a career in medicine, following his uncle's lead. This he did without complaint, seemingly considering it a continuation of his interests in physics and mathematics, now extended to a physiological sphere. Following the practices of the time, Young first served an apprenticeship in London as a pupil in St. Bartholomew's Hospital and showed extraordinary abilities in anatomy. In 1793, at age twenty, he made a major discovery about the function of the lens in accommodation, the process through which the eye adjusts its focus from near to distant objects.[5] In studying the eye of an ox, Young thought he found evidence of fibers inside the lens that could plausibly act as focusing muscles, which earlier anatomists had conjectured but not seen definitively. Through the good offices of his uncle, Young read a paper on his discovery to the Royal Society, which led to his being elected a fellow at age twenty-one, though this accolade was overshadowed by controversy. Young's discovery was claimed by an eminent anatomist, John Hunter, as his own, while another anatomist asserted that he could find no such muscular structures in the lens. At that point, Young withdrew his discovery, in deference to this authority, though he later reasserted it in light of further research.

Young's medical apprenticeship led him next to Edinburgh, where many Quakers chose to study, excluded from Oxford and Cambridge on account of their faith.[6] Still, at Edinburgh Young began to play the flute and to take dancing lessons, which disobeyed Quaker precepts, as did his incipient experiments in theatergoing.[7] Not

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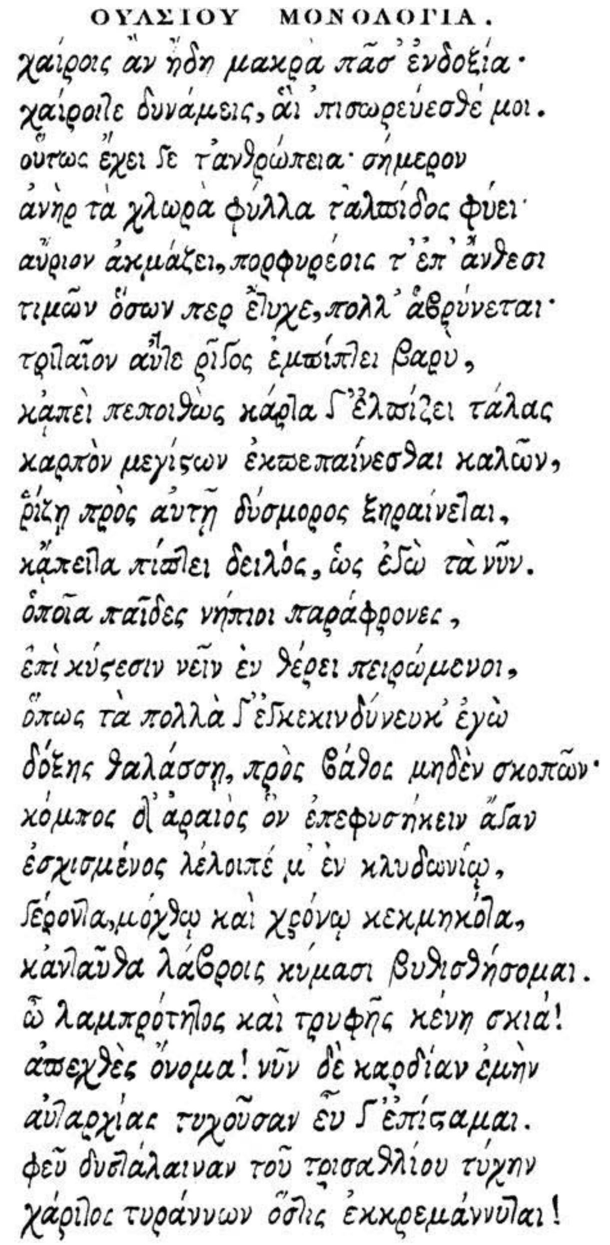
cently, see Andrew Robinson, *The Last Man Who Knew Everything: Thomas Young, the Anonymous Polymath Who Proved Newton Wrong, Explained How We See, Cured the Sick, and Deciphered the Rosetta Stone, among Other Feats of Genius* (New York, 2006). Regarding the Quaker background, see Elizabeth Allo Isichei, *Victorian Quakers* (London, 1970); Geoffrey Cantor, "Real Disabilities? Quaker Schools as 'Nurseries' of Science," in *Science and Dissent in England, 1688–1945*, ed. Paul Wood (Aldershot, 2004), 147–66; Cantor, *Quakers, Jews, and Science: Religious Responses to Modernity and the Sciences in Britain, 1650–1900* (Oxford, 2005), 64, 82–3, 111; Genevieve Mathieson, "Thomas Young, Quaker Scientist," (MA thesis, Case Western Reserve Univ., 2007), available at http://etd.ohiolink.edu/view.cgi?acc_num=case1196288181 (accessed 7 Nov. 2012).

[4] Peacock, *Life of Thomas Young* (cit. n. 1), 7.

[5] Ibid., 35–41; Robinson, *Last Man Who Knew Everything* (cit. n. 3), 36–40.

[6] Cantor, "Real Disabilities?" (cit. n. 3), 147–9.

[7] Regarding a Quaker doctor of the generation before Young, it was noted that "music, dancing, the theatre, the opera, wine, women and song, gambling, attendance at cock-fights, bull-baitings, race meetings, all the rough hearty joys of the Englishman of the time were incompatible with the Quaker costume he wore." Wood and Oldham, *Thomas Young* (cit. n. 3), 35.


ΟΥΛΣΙΟΥ ΜΟΝΟΛΟΓΙΑ.

χαίροις ἂν ἤδη μακρὰ πᾶσ᾽ εὐδοξία·
χαίροιτε δυνάμεις, αἳ πιστωρεύεσθέ μοι.
οὕτως ἔχει γε τἀνθρώπεια· σήμερον
ἀνὴρ τὰ χλωρὰ φύλλα τἀλπίδος φύει·
αὔριον ἀκμάζει, πορφυρέοις τ᾽ ἐπ᾽ ἄνθεσι
τιμῶν ὅσων περ ἔτυχε, πολλ᾽ ἁβρύνεται·
τρίταιον αὖτε ῥῖγος ἐμπίπτει βαρύ,
κἄπει πεποιθὼς κάρτα γ᾽ ἐλπίζει τάλας
καρπὸν μεγίστων ἐκπεπαίνεσθαι καλῶν,
ῥίζῃ πρὸς αὐτῇ δύσμορος ξηραίνεται,
κἄπειτα πίπτει δειλός, ὡς ἐγὼ τὰ νῦν.
ὁποῖα παῖδες νήπιοι παράφρονες,
ἐπὶ κύστεσιν νεῖν ἐν θέρει πειρώμενοι,
ὅπως τὰ πολλὰ γ᾽ ἐγκεκινδύνευκ᾽ ἐγὼ
δόξης θαλάσσῃ, πρὸς βάθος μηδὲν σκοπῶν·
κόμπος δ᾽ ἀραιὸς ὃν ἐπεφυσήκειν ἄγαν
ἐσχισμένος λέλοιπέ μ᾽ ἐν κλυδωνίῳ,
γέροντα, μόχθῳ καὶ χρόνῳ κεκμηκότα,
κἀνταῦθα λάβροις κύμασι βυθισθήσομαι.
ὦ λαμπρότητος καὶ τρυφῆς κενὴ σκιά!
ἀπεχθὲς ὄνομα! νῦν δὲ καρδίαν ἐμὴν
αὐταρχίας τυχοῦσαν εὖ γ᾽ ἐπίσταμαι.
φεῦ δυστάλαιναν τοῦ τρισαθλίου τύχην
χάριτος τυράννων ὅστις ἐκκρεμάννυται!

Figure 1. *Young's translation into classical Greek verse of a speech given by Cardinal Woolsey in Shakespeare's* Henry VIII*, in Young's handwriting; reprinted from Peacock,* Life of Thomas Young *(cit. n. 1), facing 23.*

surprisingly, the experience of new places and people helped Young break away from the doctrinal limitations of his upbringing. His succeeding stay in Göttingen further broadened his horizons. His doctoral dissertation, "De Corporis Humani Viribus Conservatricibus" (1796), concerned the physiology of the human voice and included an alphabet of forty-seven letters intended to convey every sound of which the voice is capable.[8] In this work, his interests in sound directly address his ongoing linguistic and phonological concerns.

Young's disorientation in adjusting to foreign customs paradoxically intensified his pursuit of the social and artistic activities excluded from his Quaker upbringing. He began to take dancing lessons five or six times every week, as he wrote an English friend, nor was he "very punctual in some of the medical courses." George Peacock, Young's early biographer, noted that he had been precluded from the pursuit of the "personal accomplishments" that he now followed so avidly. "It was in vain that his fellow-students, whether in banter or in earnest, told him that his musical ear was not good, and that he would fail to acquire ease and grace as a dancer. A difficulty thus presented to him as insuperable was a sufficient motive to attempt to conquer it; and though different opinions have been expressed with respect to the entire success of the experiment, there is no doubt that the mastery of those arts, which he really attained, was another triumph of his unconquerable perseverance."[9]

Precisely because it was a relatively late interest that emerged in his formative years and spoke to a side of his nature that had been underdeveloped, the musical side of Young deserves special attention as his bridge to a common social life with others, whose previous absence he may have felt acutely. By the time he left Germany, he could dance the complexities of a cotillion and ride a horse with ease, passions he cultivated the rest of his life.[10] He noted in Germany "the love of new inventions singularly combined with a pedantic habit of systematizing the old," so that Young felt that "the general spirit of the country rather tended to confirm than to correct the habits of his earlier education."[11] Young remained critical of German thought; though Schiller and Goethe were "rare luminaries among an infinite number of twinkling stars and obscure nebulae," he thought Goethe's *Wilhelm Meister* "vanishes in comparison with some of our English novels."[12] In his later work, Young never used the phrase "unity of nature," so dear to German *Naturphilosophie*, and he wrote a strong critique of Goethe's color theory as "a striking example of the perversion of the human faculties."[13] Young's own efforts to bring the wave theory of sound to bear on light may be compared with his interest in translating between different languages, rather than with a prior commitment to the unity of nature.

Young's final stage of medical apprenticeship led him to matriculate at Cambridge in 1797 because the Royal College of Physicians would only admit as fellows those who had attended Oxford or Cambridge. Thus, though already a fellow of the Royal

[8] Ibid., 49–50.

[9] Ibid., 49.

[10] Peacock, *Life of Thomas Young* (cit. n. 1), 114. For comparison of Young's experience in Germany with that of other contemporaries, see Linde Katritzky, "Coleridge's Links with Leading Men of Science," *Notes and Records of the Royal Society* 49 (1995): 261–76.

[11] Hilts, "Thomas Young's 'Autobiographical Sketch'" (cit. n. 3), 252.

[12] Peacock, *Life of Thomas Young* (cit. n. 1), 109.

[13] Young, "Zur Farbenlehre: On the Doctrine of Colours; By Goethe," *Quarterly Review* 10 (1814): 427–8. See also Frederick Burwick, *The Damnation of Newton: Goethe's Color Theory and Romantic Perception* (Berlin, 1986), 30–3.

Society, Young had still years to wait before he completed the statutory requirements for a full medical degree. His Cambridge matriculation required him to profess Anglican orthodoxy, abjuring Quaker nonconformism. Though the Westminster Quaker meeting formally disowned him in 1798, Young still struck his Cambridge classmates as having "something of the stiffness of the Quakers"; he did not much associate with the other young men, who called him "Phænomenon Young," indicating both their respect and their disdain.[14] One of them recalled that "he read little, and though he had access to the college and university libraries, he was seldom seen in them. There were no books piled on his floor, no papers scattered on his table, and his room had all the appearance of belonging to an idle man. I once found him blowing smoke through long tubes [though Young never smoked tobacco], and I afterwards saw a representation of the effect in the *Transactions of the Royal Society* to illustrate one of his papers upon sound; but he was not in the habit of making experiments."[15] We will shortly return to this scene. Young himself noted, shortly after arriving in Cambridge, that, starting with his Göttingen thesis on "the various sounds of all the languages that I can gain knowledge of," he had "of late been diverging a little into the physical and mathematical theory of sound in general. I fancy I have made some singular observations on vibrating strings, and I mean to pursue my experiments."[16]

YOUNG'S PIPES AND ORGANS

In 1797, Young's uncle died, leaving generous bequests to his friends (and patients) Edmund Burke and Samuel Johnson, as well as to Young himself, who now was free to follow his own interests without financial concerns.[17] The following year, after an accident and broken bone that kept him from his usual exercise, Young devoted himself to what he called "observations of harmonics," by which he meant experimental studies of wave motion in sound.[18] During his recovery, he also read contemporary French and German mathematics and noted that "Britain is very much behind its neighbours in many branches of the mathematics; were I to apply deeply to them I would become a disciple of the French and German school; but the field is too wide and too barren for me."[19] His choice not to engage further with Continental mathematics had lasting consequences, as we shall see.

As he thought through the problem of sound during his work on harmonics, Young thereby prepared himself to apply the very same physical models and mathematical description to light. As shall emerge, his famous two-slit experiment for light was a translation of parallel experiments for sound, rather than a direct transcription, reflecting the differences between the "languages" of light and sound. Yet Young's awareness of sonic and musical phenomena prepared the ground for his work on light, down to the precise details of the experiment that would finally satisfy Newton's demand

[14] Peacock, *Life of Thomas Young* (cit. n. 1), 115–20, on 118, 120. For Young's expulsion, see Westminster Monthly Meeting Minutes, 15 Feb. 1798, Library of the Society of Friends, London (reference: 11 b 7), and Mathieson, "Thomas Young, Quaker Scientist" (cit. n. 3), 15–6.

[15] Peacock, *Life of Thomas Young* (cit. n. 1), 121.

[16] Wood and Oldham, *Thomas Young* (cit. n. 3), 50.

[17] Young himself attributed "the ultimate extent of his uncle's protection" to Burke's "friendly and indulgent" interest and his "good offices"; Hilts, "Thomas Young's 'Autobiographical Sketch'" (cit. n. 3), 251.

[18] Peacock, *Life of Thomas Young* (cit. n. 1), 129.

[19] Wood and Oldham, *Thomas Young* (cit. n. 3), 65.

that light be shown positively bending around obstacles. As Olivier Darrigol has emphasized, "Young realized that the fruitful development of the analogy between sound and light required a prior improvement of acoustic knowledge."[20]

The course of Young's work in the years after his early paper on the accommodation of the eye clearly shows the interweaving of music, sound, and light. Three essays he published in the year 1800 show the remarkable overlay and simultaneity of his thinking in these domains. In January 1800, while still at Emmanuel College, Cambridge, he read to the Royal Society his "Outlines of Experiments and Inquiries Respecting Sound and Light," which in essence lays out the fundamental premise of his ensuing research and whose title emphasizes the yoking of these two fields.[21] Young begins with nine topics in acoustics, presenting a series of experiments that measured the quantity of air discharged through an aperture, the direction and velocity of the airstream, the velocity of sound, its degree of spatial divergence, and the harmonic sounds of pipes and the decay of their sounds, ending with a general discussion of the vibration of various elastic fluids. He often connects his work with those who preceded him, especially Leonhard Euler, whose arguments about the wave theory in sound and light he had studied closely.[22] Here, and throughout the later works we will discuss, Young often interweaves musical references very naturally, as if he clearly expected his audience to find them familiar and congenial. Apparently, such connections between music and more general scientific topics were not wholly idiosyncratic but were well known to learned writers and their educated readers. Thus, our account goes beyond Young alone to describe this larger current of thought as it emerged in his work.

Young first studied how pipes make harmonic sounds. His mystified classmate had observed him measuring the flow of air through a pipe, recording the varying pressures required to sound various overtones by "overblowing" it, exciting higher overtones with greater air pressure, a familiar technique to him as a flute player (see fig. 2).[23] With these acoustic investigations in mind, Young's tenth section addresses "the analogy between light and sound," first listing the evidence that light is a wave, including "Newton's rings," the pattern of concentric rings between two glass surfaces compressed against each other (one curved, the other flat) that very nearly moved Newton himself to accept a wave theory.[24] Young notes the difficulty and complexity of Newton's putative "fits of transmission and reflection" and adds that the recurrence of the same color in Newton's rings is "very nearly similar to the production

[20] Darrigol, "The Analogy between Light and Sound in the History of Optics from Malebranche to Thomas Young [Part 2]," *Physis* 46 (2009): 111–217, on 114. The present article aims to extend Darrigol's outstanding work on this analogy by deepening the musical background and indicating some facets of Young's work beyond Darrigol's treatment.

[21] Young, "Outlines of Experiments and Inquiries Respecting Sound and Light," in *Thomas Young's Lectures on Natural Philosophy and the Mechanical Arts*, 4 vols. (Bristol, 2002), 4:531–54.

[22] See Euler, *Letters on Different Subjects in Natural Philosophy: Addressed to a German Princess*, 2 vols. (New York, 1837), 1:34–56, 83–7, which first appeared in English in 1795, and Cantor, *Optics after Newton* (cit. n. 2), 117–23. On Euler, see Darrigol, "Analogy between Light and Sound [Part 2]" (cit. n. 20), 169–80; Peter Pesic, "Euler's Musical Mathematics," *Mathematical Intelligencer* 35, no. 2 (2013): 35–43.

[23] For the sound of an overblown c″ on an alto recorder, performed by the author in Santa Fe, N.M., 2013, hear audio 1 (123 KB; MP3) in the electronic version of this article.

[24] For the preceding history of this analogy, see Olivier Darrigol, "The Analogy between Light and Sound in the History of Optics from the Ancient Greeks to Isaac Newton: Part 1," *Centaurus* 52 (2010): 117–55; see also Darrigol, "Analogy between Light and Sound [Part 2]" (cit. n. 20), which treats Young on 185–217.

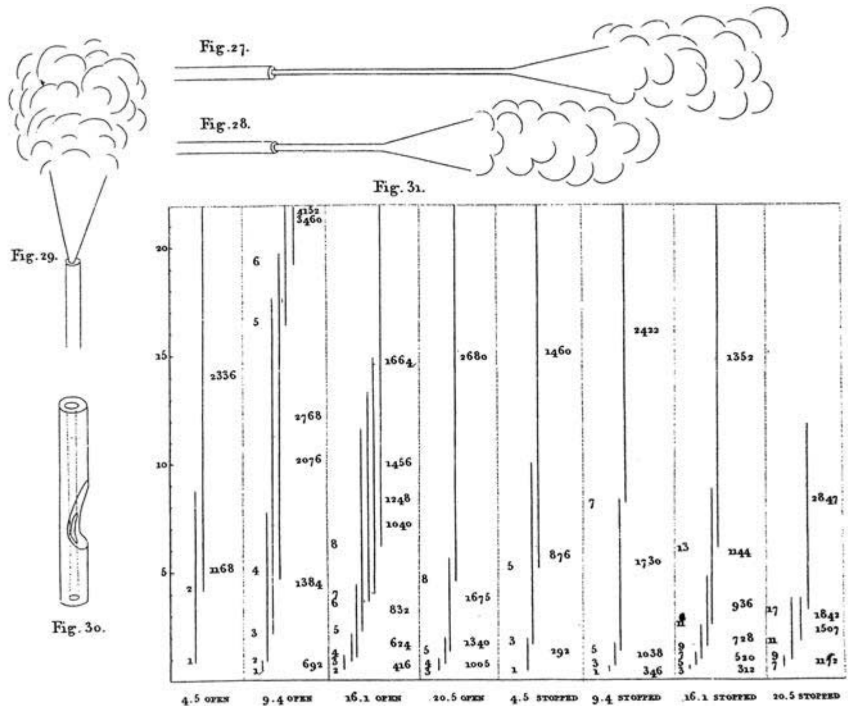


Figure 2. *Plate 3 from Young's "Outlines of Experiments and Inquiries" (cit. n. 21), which he captioned: "Fig. 27. The appearance of a stream of smoke forced very gently from a fine tube. Fig. 28 and 29, the same appearance when the pressure is gradually increased. Fig. 30. A mouth piece for a sonorous cavity. Fig. 31. The perpendicular lines over each division of the horizontal line show, by their length and distance from that line, the extent of pressure capable of producing, from the respective pipes, the harmonic notes indicated by the figures placed opposite the beginning of each, according to the scale of 22 inches parallel to them. The larger numbers, opposite the middle of each of these lines, show the number of vibrations of the corresponding sound in a second."*

of the same sound, by means of a uniform blast, from organ pipes which are different multiples of the same length," showing his knowledge of pipe organs as well as of the recurrent overtones in woodwind overblowing.[25] Young considers this "very nearly similar" to the fact that "the same colour recurs, whenever the thickness [of the pressed glass plate or lens used to show Newton's rings] answers to the terms of an arithmetical proportion," such as 1, 2, 3, . . . He also notes "the analogy between the colours of a thin plate and the sounds of a series of organ pipes, which, indeed, Euler adduces as an argument in favour of [the wave theory of light], although he states the phenomena very inaccurately."[26] Young leaves his exact analogy unclear; he does not seem bothered that Newton's rings follow an arithmetic proportion (1, 3, 5, . . .), whereas the organ pipes are governed by a geometric proportion (2, 4, 8, . . .). Even

[25] Young, "Outlines of Experiments and Inquiries" (cit. n. 21), 543. For instance, pipes in eight-foot and four-foot organ stops can each sound middle C. See the section titled "Of the Harmonic Sounds of Pipes," ibid., on 539–40, esp. table 11. Cf. Darrigol, "Analogy between Light and Sound [Part 2]" (cit. n. 20), 188–90, which does not discuss overblowing.

[26] Young, "Outlines of Experiments and Inquiries" (cit. n. 21), 543.

so, he considers the recurrence of colors in Newton's rings to be precisely comparable to the "recurrence" of pitches produced by organ pipes, which is only comprehensible on the grounds of a wave theory.[27]

In his later writing about various musical instruments, Young notes that the "various compoundings of the stops" give the organ its particular "quality of sound, sometimes called its tone, register, colour, or *timbre*." This "fourth component part of music" Young esteems highly, for "much of the pleasure derived from music depends on it; but as it is capable of little diversity on the same instrument, it is seldom considered in treating of the theory of music." This sound-color "depends on the law by which the sounding body, and the particles of the air, are governed with respect to the velocity of their progress and regress in each vibration, or in different successive vibrations." Young considers the true appreciation of timbre to be a question for natural philosophy, though "all this relates to the quality of sound, and whoever adequately relishes the works of the great modern masters, will be fully competent to judge of its practical importance."[28]

Thus, when Young compares Newton's rings to an organ, we realize the full appropriateness of his application of timbre or sound-color to visual color, for Newton himself had noted the importance of the recurrent pattern of the coloration in his rings. Young "hears" Newton's rings as resembling an organ's cyclical structure of pitches, overtones, and stops, in which the pressure of the airstream can excite recurrent harmonic pitches as the pressure exerted on the glass can evoke the recurrent colors of the rings. Note also that, implicitly, Young here translates a temporal phenomenon (the frequencies of the organ pipes) to a spatial one (the varying lens thicknesses producing Newton's rings).[29]

ADVANCING THE MUSICO-OPTICAL ANALOGY

Having established this fundamental analogy between music and light, Young then turns to a musical phenomenon that will provide a crucial insight into light. His point of departure is a troubling assertion by Robert Smith, the eminent Cambridge astronomer, in his *Harmonics, or, The Philosophy of Musical Sounds* (1749) that "the vibrations constituting different sounds should be able to cross each other in all directions, without affecting the same individual particles of air by their joint forces." On the contrary, Young notes, "undoubtedly they [the vibrations] cross, without disturbing each other's progress; but this can be no otherwise effected than by each particle's partaking of both motions." As proof, he instances "the phenomena of beats" as observed by the violinist Giuseppe Tartini and discussed by Smith himself.[30] To illustrate them, Young devises a kind of thought experiment, supposing "what

[27] Newton's rings appear even with incoherent light, thus allowing Young's analogy with coherent musical tones to go forward, whereas other optical setups would depend on the issue of coherence (the correlation between different waves in space or time). I thank Jed Buchwald for drawing my attention to this point.

[28] All quotations are from Young, "An Essay on Music," in *Young's Lectures* (cit. n. 21), 4:563–72, on 565; the history of the organ is in *A Course of Lectures on Natural Philosophy*, vols. 1–3 in *Young's Lectures*, on 1:404.

[29] For the relation of spatial and temporal interference, see also Darrigol, "Analogy between Light and Sound [Part 2]" (cit. n. 20), 197.

[30] For an example of the beats between two tones that are close in frequency (262 and 272 Hz), generated electronically by the author using the music-notation software Finale, hear audio 2 (273 KB; MP3) in the electronic version of this article.

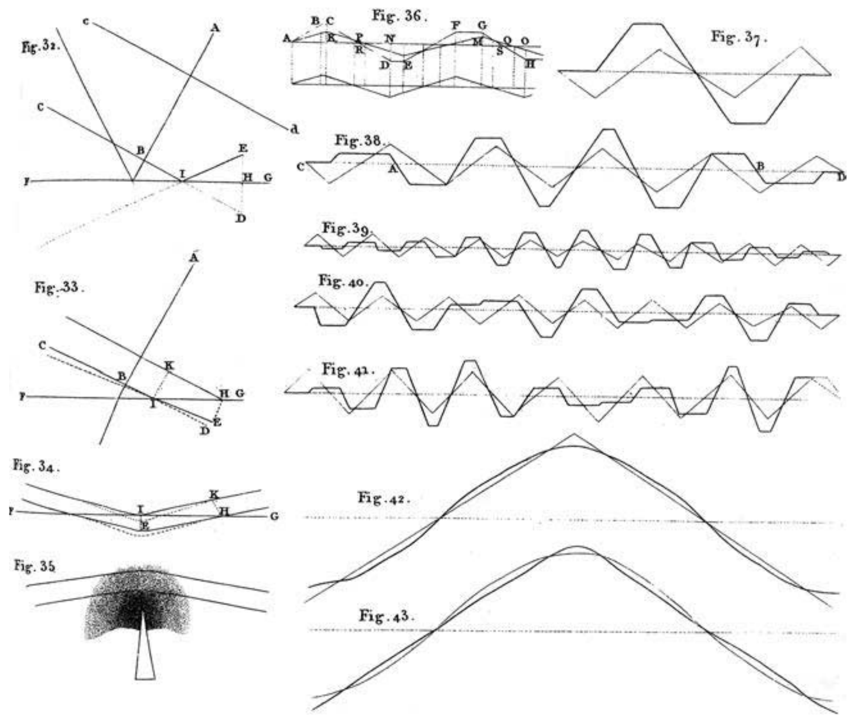


Figure 3. *Plate 4 from Young's "Outlines of Experiments and Inquiries" (cit. n. 21). Figs. 32–5 show "affections of light": its reflection (32), refraction (33), total reflection (34), and light passing "near an inflecting body" (35); figs. 36–43 show the waveforms of various combinations of two sounds: an octave (37), a major third (38), a major tone (39), a minor sixth (40), a fourth "tempered about two commas" (41), a fourth further tempered by "subordinate vibrations of the same kind in the ratios of 3, 5, and 7" (42), and a vibration "corresponding with the motion of a cycloidal pendulum" (43).*

probably never precisely happens, that the particles of air, in transmitting the pulses [of sound], proceed and return with uniform motions," and in a series of figures he draws their motion along the horizontal axis, their displacement along the vertical (see fig. 3).[31] Young includes a number of different cases in which, "by supposing any two or more vibrations in the same direction to be combined, the joint motion will be represented by the sum or difference of the ordinates." Thus, two sounds of nearly the same strength and pitch will produce a "joint sound" called a "beat" that reaches its maximum (the sum of the maximum of each component) on a slow rhythm determined by the difference between their respective frequencies or pitches. Young's sequence of cases shows the graphic difference between the joint sounds produced by different components, and he notes that "the greater the difference in the pitch of two sounds, the more rapid the beats, till at last, like the distinct puffs of air in the experiments already related, they communicate the idea of a continued

[31] Young, "Outlines of Experiments and Inquiries" (cit. n. 21), 544. For discussion of the controversy with Smith, see also Darrigol, "Analogy between Light and Sound [Part 2]" (cit. n. 20), 188–93.

sound; and this is the fundamental harmonic described by Tartini."[32] His diagrams show "snapshots" of the vibrating string, translating its temporal motion into instantaneous spatial waveforms.

At this point, Young's description breaks free from the presumption that sound is a vibrating *body* by noting that sufficiently frequent puffs of air by themselves "communicate the idea of a continued sound."[33] Thus, the locus of the investigation of sound has been shifted to the vibrating air, away from the body no longer needed to produce it. We now realize that, in his student rooms, Young had been producing not just puffs of smoke but a sound of very low frequency, as if he had slowed the phenomenon of musical sounds emitted by a pipe down to an immensely slower time scale on which it could be carefully observed and thoroughly compared with the flowing air that caused it.

Young immediately draws a musical corollary from his description of beats. Returning to the addition of two almost equal sounds, "the momentum of the joint sound is double that of the simple sound only at the middle of the beat, but not throughout its duration." Therefore, "the strength of sound in a concert will not be in exact proportion to the number of instruments composing it." Young has reached this counterintuitive result from his thought experiment, rather than any actual observation, but he now realizes its possible significance as evidence of the wave theory. "Could any method be devised for ascertaining this by experiment, it would assist in the comparison of sound with light" by demonstrating the palpable reality of beats in waves, whether of sound or light.[34] Young will seek evidence of the "beating" of light waves that will be as clear as that of the beating of sound; to do so, he will arrange a "concert" of light.

Indeed, his whole plate of diagrams (in fig. 3) richly illustrates the way he juxtaposes light and sound. Where the diagrams on the right illustrate various possible sound forms, those on the left show "the affections of light," its behavior in reflection, refraction, and passing "near an inflecting body," perhaps a string or knife's edge. The very layout of the plate invites us to contemplate sound and light together. To that end, he returns to the problem of determining the frequency of vibrations, shape, and state of motion of a "chord," a stretched string. Here the visual appearance of a sounding body illuminates its vibrations.

In fact, Young may have been among the first to use the piano, a rather recent arrival among musical instruments, as a *scientific* instrument. He used "one of the lowest [wire-wrapped] strings of a square piano forte" to make an optical experiment:

> Contract the light of a window, so that, when the eye is placed in a proper position, the image of the light may appear small, bright, and well defined, on each of the convolutions of the wire [due to its wrapping]. Let the chord be now made to vibrate, and the luminous point will delineate its path, like a burning coal whirled round, and will present to the eye a line of light, which, by the assistance of a microscope, may be very accurately observed. According to the different ways by which the wire is put in motion, the form of this path is no less diversified and amusing, than the multifarious forms of the quiescent lines of vibrating plates, discovered by Professor Chladni.[35]

[32] Young, "Outlines of Experiments and Inquiries" (cit. n. 21), 544.
[33] Ibid.
[34] Ibid.
[35] Ibid., 546–7.

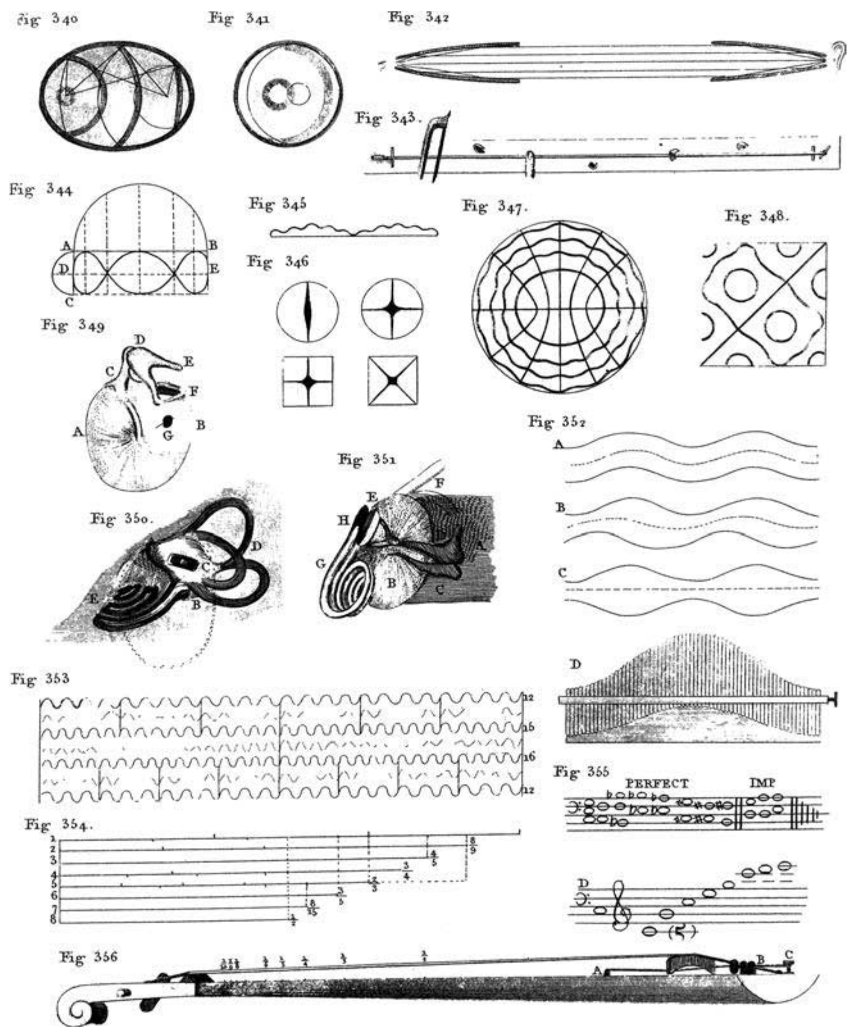


Figure 4. Plate 25 from Young's Course of Lectures *(cit. n. 28), showing three-dimensional contours of sound waves (figs. 340, 341), speaking and hearing trumpets (342), a bow exciting a violin string (343), Chladni patterns of sand on vibrating plates (346–8), the mechanism of the human ear (350, 351), Young's own temperament (355), and the "trumpet of Marigni" or tromba marina (356), a kind of bowed monochord, here illustrating overtones.*

Young positions himself in relation to Chladni, whose striking demonstration of standing waves made visible the sonorous modes of vibrating plates (see Young's figs. 346–8 in my fig. 4), a translational artifice Young considers the direct antecedent of his own work. Though his primary object was to gauge the shape of the vibrating string, the details of Young's experimental arrangement are, in fact, very close to what will turn out to be his crucial demonstration of light interference: a thin string illuminated by a small, well-defined light source. Young's own illustration of light passing "near an inflecting body" (in fig. 3) gives evidence that he was aware of this parallelism, even though in this paper he does not take the next step, to allow the vibrating string to come to rest and then to see the vibrations of light surrounding it, as if that were silence made visible.

Young connects his studies of pipes with the problem of the human voice, "the object originally proposed to be illustrated by these researches." This recalls the physiological and medical aspects of his Göttingen dissertation, though here Young seems more interested in purely musical aspects of timbre and resonance. He connects the voice with his smoke pipes by noticing that, analogous to his rhythmic pipe puffs, the human glottis can produce a slow vibration "making a distinct clicking sound" that can be made more continuous "but of an extremely grave pitch: it may, by a good ear, be distinguished two octaves below the lowest A of a common bass voice, consisting in that case of about 26 vibrations in a second." Young connects this glottal clicking with the methods used by ventriloquists to "throw" their voices and also (at still higher pitches) with falsetto singing. Though he refers to anatomy and physiology, he more often relies on "a good ear"; he tells us he can hear four harmonics above the fundamental sung by "a loud bass voice."[36]

The finale of this remarkable paper returns to one of the oldest musical conundrums. Young, like so many before him, became fascinated with the question of temperament and here offers his own solution to its age-old problems in his astutely practical variant of well temperament, which has been revived in recent performances of late eighteenth-century music that emphasize authenticity.[37] Young illustrates his own temperament in a diagram comparing various systems of tuning (see fig. 5), using spatial visualization to illustrate sonic issues. His wide-ranging comparative musical investigations closely resemble, in scope and structure, his concurrent comparative work on languages, as if they were various possible "temperaments" of living speech.

Only four months later (April 1800), Young published "An Essay on Music," giving important evidence of his ongoing interest in music during the height of his optical researches. He begins this essay by acknowledging "the agreeable effect of melodious sounds, not only on the human ear, but on the feelings and on the passions," yet he considers music far more than "delicate titillation" or even than "giving expression to poetical and impassioned diction," which Coleridge and other romantic thinkers emphasized. Contra Kant, Young argues that the study of music is not "amusement only" but reveals a science "scarcely less intricate or more easily acquired than the most profound of the more regular occupations of the schools." Those who show "superior brilliancy" in music "seem almost to require the faculties of a superior order of beings." Young's essay shows considerable familiarity with the history and theory of music, as well as the importance he ascribed to it. He emphasizes the role of harmonics or overtones for the common triads and scales of contemporary musical practice. Finally, he discusses the terminology of musical tempo and gives a detailed table of

[36] Ibid., 549–50. For Young's example of the 26 Hz low A as generated electronically in Finale by the author, hear audio 3 (97 KB; MP3) in the electronic version of this article.

[37] Myles W. Jackson, *Harmonious Triads: Physicists, Musicians, and Instrument Makers in Nineteenth-Century Germany* (Cambridge, Mass., 2006), 172–6. For performances in Young's temperament, hear Enid Katahn (piano), *Beethoven in the Temperaments*, recorded Peterborough, N.H., 1997, Gasparo GSCD-332, and *Six Degrees of Tonality*, recorded Peterborough, N.H., 2000, Gasparo GSCD-344, compact discs. Compare Katahn's performance in Young's temperament of Beethoven's Sonata in C Major, op. 53, introduction to the second movement (reproduced courtesy of Gasparo), with the same passage played in equal temperament, recorded live by the author, Santa Fe, N.M., 2003, in audio 4 (5 MB; MP3) and audio 5 (4.1 MB; MP3), respectively, in the electronic version of this article.

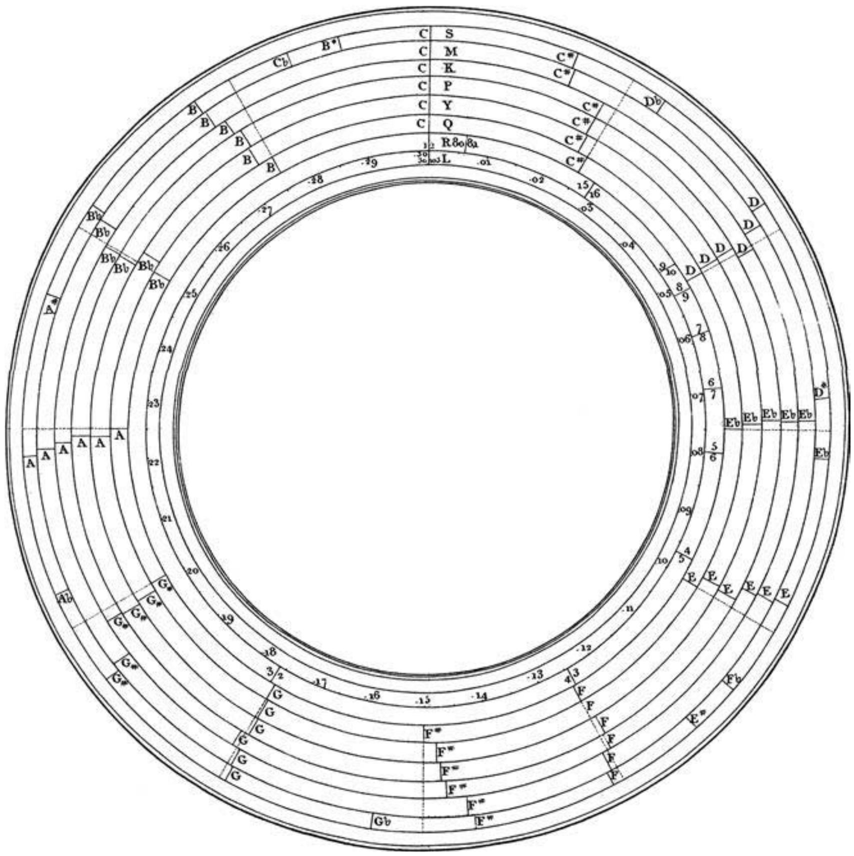


Figure 5. *Young's comparison of different schemes of musical temperament (plate 6 from "Outlines of Experiments and Inquiries" [cit. n. 21]), including his own temperament (the ring labeled Y); the entire circle spans an octave around C, shown at the top.*

the number of measures per minute used in various tempi and meters by composers such as Handel, Haydn, and Mozart.[38]

Seven months later, in November 1800, Young presented his paper "On the Mechanism of the Eye" to the Royal Society.[39] Revisiting his maiden discovery about the accommodation of the eye, Young argues that he had been fundamentally right that changes in the shape of the lens were responsible for accommodation, not the cornea nor the length of the eyeball, as had been suggested by others. To measure these changes, Young pressed instruments against his sclera, the white of his own eye, as Newton had inserted a bodkin behind his own eyeball.[40] Though these excruciating measurements and Young's ensuing physiological deductions make up the bulk of his paper, he first lays his groundwork on another extended comparison of sound and

[38] See Young, "Essay on Music" (cit. n. 28), here quoted at 562, 565–7; Peter Pesic, "Thomas Young and Eighteenth Century Tempi" (unpublished manuscript, St. John's College).
[39] Young, "On the Mechanism of the Eye," in *Young's Lectures* (cit. n. 21), 4:573–606.
[40] Peter Pesic, *Sky in a Bottle* (Cambridge, Mass., 2005), 167–9.

sight. He judges that the ear is "the only organ that can be strictly compared" with the eye, for the other senses operate through more immediate contact of their objects with the nerves.[41]

For Young, contrast with the ear illuminates the eye's functioning. He calculates the quantitative difference between the ear's ability to discriminate the angular direction from which sounds are coming (only within about 5º) and the eye's far sharper directional abilities (90,000 times finer). On the other hand, the eye's "field of perfect vision, for each position of the eye, is not very great," whereas "the sense of hearing is equally perfect in almost every direction." Using these comparisons between eye and ear as an initial point of reference, Young then goes on to devise what he calls a new optometer that will allow precise measurement of the eye's focal distances, as well as the other parameters needed to make his argument about accommodation fully detailed and complete.[42] Thus, all three papers of Young's *annus mirabilis* of 1800 invoke sound, hearing, and music in fundamental ways that inform and shape his arguments about seeing and light.

HEARING COLORS

In August 1801, Young published a letter reaffirming his account of sound and his new musical temperament against the criticisms of a Professor Robinson in Edinburgh. In November, his paper "On the Theory of Light and Colours" juxtaposed excerpts from Newton's writings with Young's own series of new propositions, presented in Euclidean-style hypotheses and demonstrations.[43] Young's rhetoric enlists Newton on the side of the wave theory of light, defusing Newton's objections to it by juxtaposing them with the many passages in which he recognized its merits.

As the essential background for his argument in favor of an ether carrying the vibrations of light, Young assumes the prior case of air as the medium for sound vibrations. "Every experiment, relative to sound, coincides with the observation already quoted from Newton, that all undulations are propagated through the air with equal velocity," which Young thought a capital point in favor of the wave theory of light that Euler himself did not seem to understand when he maintained incorrectly that waves of higher frequency travel faster. Here and throughout, Young uses the wave theory of sound to establish the essential results he will apply to light; returning to his earlier arguments against Smith, he notes that "it is obvious, from the phenomena of elastic bodies and sound, that the undulations may cross each other without interruption" by "uniting their motions," though different frequencies of wave will not intermix. Likewise, he relies on the example of sound to establish that waves expand spherically through a homogeneous medium.[44]

Though Young claims not to "propose any opinions which are absolutely new," he offers an important suggestion that color vision relies on only "three principal colours, red, yellow, and blue," which he chooses because their "undulations are related in magnitude nearly as the numbers 8, 7, and 6," whose integral ratios recall those of

[41] Young, "On the Mechanism of the Eye" (cit. n. 39), 574.
[42] Ibid., 574–5; for his optometer, see 575–7.
[43] For his "Letter to Mr. Nicholson . . . Respecting Sound and Light," see *Young's Lectures* (cit. n. 21), 4:607–12; "On the Theory of Light and Colours," ibid., 4:613–31.
[44] Young, "On the Theory of Light and Colours" (cit. n. 43), 618–20; Geoffrey Cantor, "The Changing Role of Young's Ether," *British Journal for the History of Science* 5 (1970): 44–62.

music theory.[45] Thus, green light, whose frequencies are about 6.5 in terms of these ratios, "will affect equally the particles in unison with yellow and blue, and produce the same effect as a light composed of those two species: and each sensitive filament of the nerve may consist of three portions, one for each principal colour."[46]

Young continues to follow what Newton called "the analogy of nature" closely, noting that, on the basis of his own argument, "any attempt, to produce a musical effect from colours, must be unsuccessful, or at least . . . nothing more than a very simple melody could be imitated by them" because the ratios of the primary colors limit the range of any such "color melody" to less than an octave, for anything wider would go "wholly without [outside] the limits of sympathy of the retina, and would lose its effect; in the same manner as the harmony of a third or a fourth is destroyed, by depressing it to the lowest notes of the scale." That is, musical melodies would not translate directly to colors because musical intervals become indistinguishable when transposed to the extreme limits of audible frequencies. The analogy between the ear and the eye guides Young's hypothesizing even when he becomes aware of their important differences, which are no less significant to him than their similarities. "In hearing, there seems to be no permanent vibration of any part of the organ," implying its greater simplicity and unity, compared to the eye as a two-dimensional field of sensors that, at every point, cannot possibly have the range of vibrations available to the ear in its single canal. His three-color hypothesis emerges under the direct pressure of the pitch-distinguishing capabilities of the ear.[47]

Young goes on to offer additional evidence in favor of the wave theory of light, drawing especially on the arguments about the superposition of waves he had earlier made against Smith, and culminating in his proposition VIII: "*When two Undulations, from different Origins, coincide either perfectly or very nearly in Direction, their joint effect is a Combination of the Motions belonging to each*." Young notes that he had earlier "insisted at large on the application of this principle to harmonics; and it will appear to be of still more extensive utility in explaining the phenomena of colours." He applies it now to "Mr. Coventry's exquisite micrometers; such of them as consist of parallel lines drawn on glass, at the distance of one five hundredth of an inch," what we now call diffraction gratings.[48]

From proposition VIII, Young derives a simple mathematical criterion for the light waves of a given monochromatic wavelength (coming from a point source of red light, say) to combine constructively and yield a bright red spot whenever the sine of the angle of that spot is an integral multiple of the ratio of the spacing between lines on the grating and the wavelength of light. Because the incident red light can reflect constructively off the grating at a whole series of angles, we will see not one but a series of red spots, each corresponding to a different integer in Young's formula. He notes that the particle theory of light would not produce any such periodic and recurrent spots, so that "it is impossible to deduce any explanation of it from any hypothe-

[45] Young, "On the Theory of Light and Colours" (cit. n. 43), 617; in his next paper, "An Account of Some Cases of the Production of Colours," Young will change these three primaries to red, green, and violet, whose ratios are as 7, 6, and 5, to meet William Wollaston's corrections of the spectral ratios.

[46] Ibid.

[47] The Newton quote about "the analogy of nature" is cited ibid.; the following quotes come from 618 (emphasis in the original).

[48] Ibid., 624–6. For the development of the technology of these gratings, see Myles W. Jackson, *Spectrum of Belief: Joseph Von Fraunhofer and the Craft of Precision Optics* (Cambridge, Mass., 2000).

sis hitherto advanced; and I believe it would be difficult to invent any other that would account for it. There is a striking analogy between this separation of colours, and the production of a musical note by successive echoes from equidistant iron palisades; which I have found to correspond pretty accurately with the known velocity of sound, and the distances of the surfaces." Once again, music gives the point of departure for his optical analogy. As he contemplates the lines of the grating, he analogizes them as "echoing" the light, as if audition and vision had merged.[49] Here again, a sonic, temporal phenomenon translates into a spatial, optical one.

Young's account of his sound experiment also suggests that he could have used it to connect the speed of sound with its wavelength and the spacing between the iron palisades. Though Young was quite aware of the significance of determining the wavelength of light experimentally, he does not do it here, reserving it for his reconsideration of Newton's rings, which (as noted above) Young had earlier instanced as the linchpin of his analogy with the recurrent frequencies of organ pipes. In "On the Theory of Light and Colours," Young obviously attaches special significance to determining the wavelength of light from Newton's own data, as if seeking Newton's support even in the process of overthrowing his conclusions.

Newton had framed his spectral colors by assuming that they formed an octave; he did not seem to recognize that his own ring data contradicted such a 2:1 ratio.[50] But now Young corrects Newton's musical mistake: "The whole visible spectrum appears to be comprised within the ratio of three to five, which is that of a major sixth in music; and the undulations of red, yellow, and blue, to be related in magnitude as the numbers 8, 7, and 6; so that the interval from red to blue is a fourth."[51] Thus, Young specifically returns to the same musical analogy that Newton had used, though Newton had mistakenly substituted the octave for the major sixth. By getting right what Newton had mistaken, Young is able to retrieve the accurate wavelengths of the optical spectrum, which he goes on to state in musical terminology:

> The absolute frequency [of light] expressed in numbers is too great to be distinctly conceived, but it may be better imagined by a comparison with sound. If a chord [vibrating string] sounding the tenor c, could be continually bisected 40 times, and should then vibrate, it would afford a yellow green light: this being denoted by c^{41}, the extreme red would be a^{40}, and the blue d^{41}.[52]

Even the identity of these colors is "better imagined" by giving their musical-note names, as if Young preferred to "hear" than to see them, though the "pitches" involved are enormously higher than any audible sound. The resultant synesthesia goes far beyond our normal senses: Young concludes that C is "yellow-green" and D is "blue," as if we were able to hear forty octaves above middle C. He also provides a table stating the "absolute length and frequency of each vibration" of different colors of light, thereby reminding us of their sheer physical reality in space and time.

[49] Young, "On the Theory of Light and Colours" (cit. n. 43), 626.
[50] Peter Pesic, "Isaac Newton and the Mystery of the Major Sixth: A Transcription of His Manuscript 'Of Musick' with Commentary," *Interdisciplinary Science Reviews* 31 (2006): 291–306. See also Alan E. Shapiro, "The Evolving Structure of Newton's Theory of White Light and Color," *Isis* 71 (1980): 211–35.
[51] Young, "On the Theory of Light and Colours" (cit. n. 43), 627.
[52] Ibid.

Against the background of these 1801 musico-optical results, the following July Young distilled his proposition VIII into "a simple and general law":

> Wherever two portions of the same light arrive at the eye by different routes, either exactly or very nearly in the same direction, the light becomes most intense when the difference of the routes is any multiple of a certain length, and least intense in the intermediate state of the interfering portions; and this length is different for light of different colours.[53]

Using this law, Young returns to simple experiments mentioned by Newton and Francesco Maria Grimaldi, from which he now can deduce the exact wavelengths they themselves did not calculate. Recounting an experiment in which he observed the "fine parallel lines of light which are seen upon the margin of an object held near the eye," Young notes "that they were sometimes accompanied by coloured fringes, much broader and more distinct." To make these fringes more distinct still, he observed a horse hair, then a wool fiber, then a single strand of silk, which gave the clearest, broadest pattern. Young made a rectangular hole in a card and bent the card's edges to support a hair parallel to the sides of the hole, a stabilizing mounting that allowed him to measure the deviations of the various colored fringes, which coincided with those he had measured in Newton's rings.[54]

In November 1803 Young took these experiments a step further in his final paper before the Royal Society, which begins by noting "that fringes of colour are produced by the interference of two portions of light," proving "*the general Law of the Interference of Light*" and hence the wave theory in a "decisive" way.[55] His new experiment was even simpler: making a small hole in a window shade, on which a mirror directed the sun's light, he used his artificial sunbeam to illuminate "a slip of card, about one thirtieth of an inch in breadth, and observed its shadow, either on the wall, or on other cards held at different distances." Young now proves that the fringes were the joint effects of light passing on both sides of the card, not just one. He used "a little screen" to block the light coming on one side of the card and notes that "all the fringes which had before been observed in the shadow on the wall immediately disappeared, although the light inflected on the other side was allowed to retain its course." Therefore the fringes could only be produced by the joint action of light "passing on each side of the slip of card, and inflected, or rather diffracted, into the shadow."[56] He goes on to show that his results are quantitatively consistent with his "general law" and that the distances between the dark lines in his fringed shadows agree accurately with analogous distances that he calculates from Newton's own observations of the shadow of a knife's edge and of a hair.[57]

[53] Young, "An Account of Some Cases of the Production of Colours Not Hitherto Described," in *Young's Lectures* (cit. n. 21), 4:633–38, on 633.

[54] Ibid. He also adduces "coloured atmospherical halos" and supernumerary rainbows as meteorological examples of his colored fringes, writ large in the heavens; ibid., 634–5, 643–5.

[55] Young, "Experiments and Calculations Relative to Physical Optics," in *Young's Lectures* (cit. n. 21), 4:639–48, on 639; emphasis in the original. See also J. D. Mollon, "The Origins of the Concept of Interference," *Philosophical Transactions of the Royal Society of London* 360 (2002): 807–19, and especially Naum S. Kipnis, *History of the Principle of Interference of Light* (Basel, 1991).

[56] Young, "Experiments and Calculations Relative to Physical Optics" (cit. n. 55), 639–40.

[57] Oddly, Young does not calculate the value of the incident wavelength of light for any of these cases, as he had done in his 1801 paper for Newton's rings and for the diffraction grating. Though some have therefore questioned whether he really performed the measurements, the table shown seems perfectly

Young concludes that light "is possessed of opposite qualities, capable of neutralising or destroying each other, and of extinguishing the light, where they happen to be united," so that light plus light may yield darkness. As he emphasizes, this paradoxical-seeming conclusion is the essence of the wave theory, which gives it the power to explain the recurrences, fringes, and inner rainbows he identified. The concert of light is now complete; Young's conclusion takes him full circle, back to the musical hypotheses with which he began:

> But, since we know that sound diverges in concentric superficies [surfaces], and that musical sounds consist of opposite qualities, capable of neutralising each other, and succeeding at certain equal intervals, which are different according to the difference of the note, we are fully authorized to conclude, that there must be some strong resemblance between the nature of sound and that of light.[58]

YOUNG'S SYMPHONIC LECTURES

In 1801, in the midst of this series of papers, Young became professor of natural philosophy at the Royal Institution, where he delivered the talks that were later published in his *Course of Lectures on Natural Philosophy and the Mechanical Arts* (1807), one of the first attempts at general synthesis in the aftermath of Newton.[59] Addressing a broad audience, including women and others excluded from the universities, Young presented a general picture, emphasizing the leading concepts and omitting mathematical details. His 1800–1803 papers showed the importance of music and sound as he discovered his new insights; his Royal Institution lectures show how he continued to rely on sound and music in the context of their public justification and popularization.[60]

The fifteen hundred quarto pages that gather Young's lectures integrate natural philosophy with practical arts such as machinery, carpentry, and shipbuilding, as well as drawing, engraving, printing, and even "the art of writing" (here including his linguistic concerns).[61] Music occupies a special place in his encyclopedic edifice as the core of his central series of lectures on hydrodynamics, even though acoustics "has usually been considered as exceedingly abstruse and intricate."[62] This is an understatement; by the end of the eighteenth century, acoustics had become a quiet backwater of natural philosophy, not a center of controversy (in contrast to optics). As part of his symphonic synthesis, Young revived the study of sound by connecting it to the larger issues of wave motion.

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definite, unless one doubts that the numbers listed there really were observed by Young (rather than cooked up after the fact). See John Worrall, "Thomas Young and the 'Refutation' of Newtonian Optics: A Case-Study in the Interaction of Philosophy of Science and History of Science," in *Method and Appraisal in the Physical Sciences*, ed. Colin Howson (Cambridge, 1976), 107–80; cf. Kipnis, *History of the Principle* (cit. n. 55), 118–24. Young may have thought it sufficient to show the consistency of his new experiment with those of Newton, relying on his 1801 determination of wavelength from Newton's rings and diffraction gratings to establish that number's value.

[58] Young, "Experiments and Calculations Relative to Physical Optics" (cit. n. 55), 645.

[59] Bence Jones, *The Royal Institution, Its Founder and Its First Professors* (New York, 1975).

[60] Regarding Young's work at the Royal Institution, see Peacock, *Life of Thomas Young* (cit. n. 1), 134–7, G. N. Cantor, "Thomas Young's Lectures at the Royal Institution," *Notes Rec. Roy. Soc. Lond.* 25 (1970): 87–112, and Robinson, *Last Man Who Knew Everything* (cit. n. 3), 85–94.

[61] Young, *Course of Lectures* (cit. n. 28); Robinson, *Last Man Who Knew Everything* (cit. n. 3), 120–1.

[62] Young, *Course of Lectures* (cit. n. 28), 1:367.

Young interweaves his own successive discoveries with his account of sound waves. His presentation of the overtones characterizing various orchestral instruments leads him to speculate that the human ear is a musical instrument composed of fibers ready to respond sympathetically to external sounds (see Young's figs. 350 and 351 in my fig. 4). A close link between physics and physiology also characterizes his work on the eye. At the same time, Young proceeds without complete knowledge of the central mechanism by which the ear (or the eye) functions. Even so, his use of musical instruments allowed him access to other organs, made of pipes whose structure was fully open to inspection, and thus helped bridge over the central lacunae in his analogies, the unknown mechanisms of hearing and vision themselves.

Young treats harmony in considerable detail, adducing the phenomenon of beats as an example of rhythmic recurrence:

> The most barbarous nations have a pleasure in dancing; and in this case, a great part of the amusement, as far as sentiment and grace are not concerned, is derived from the recurrence of sensations and actions at regular periods of time. Hence not only the elementary parts of music, or the single notes, are more pleasing than any irregular noise, but the whole of a composition is governed by a rhythm, or a recurrence of periods of greater or less extent.[63]

He surveys the sound quality of every common instrument, including the human voice, and the shapes of organ pipes that might sound the vowels, such as the *vox humana* stop he describes as part of the modern organ (see fig. 6).[64] Here his discourse circles back to language, as if the study of music could somehow generate speech itself.

His next chapter turns to optics, showing how the study of sound leads naturally to the study of light. He systematically takes the scientific insights he grounded in musical experience and applies them to solve the enigmas of light. Young's treatment of the nature of light and color forms the climax of the second part of his *Course of Lectures*, from which he then builds the case for the wave theory; as in his 1800–1803 papers, his lecture figures also rhetorically juxtapose sound with light (fig. 6).[65] He uses arguments about the constancy of the speed of sound to justify the constancy of the speed of light.[66] Likewise, Young compares phosphorescent substances, which reradiate light earlier shone on them, to the sympathetic vibration of strings "which are agitated by other sounds conveyed to them through the air."[67]

In his climactic lecture, Young expresses the general principle of interference as emerging from "the case of the waves of water, and the pulses of sound," in which "the beating of two sounds has been explained from a similar interference." Young seals his case by presenting the "beating" of two light sources, exactly as he had shown the beating of two sounds, including his precise determination of the wavelengths of red and violet light.[68] He learned from Robert Hooke that "red and blue

[63] Ibid., 392.

[64] For the sound of this stop in the Möller organ at the Culver Academies Chapel, Culver, Ind., played in 2009 by John Gouwens (and reproduced with his permission), hear audio 6 (203 KB; MP3) in the electronic version of this article.

[65] Ibid., 457.

[66] Ibid., 459–60.

[67] Ibid., 462; Young calls this phenomenon "solar phosphori."

[68] Ibid., 464–5.

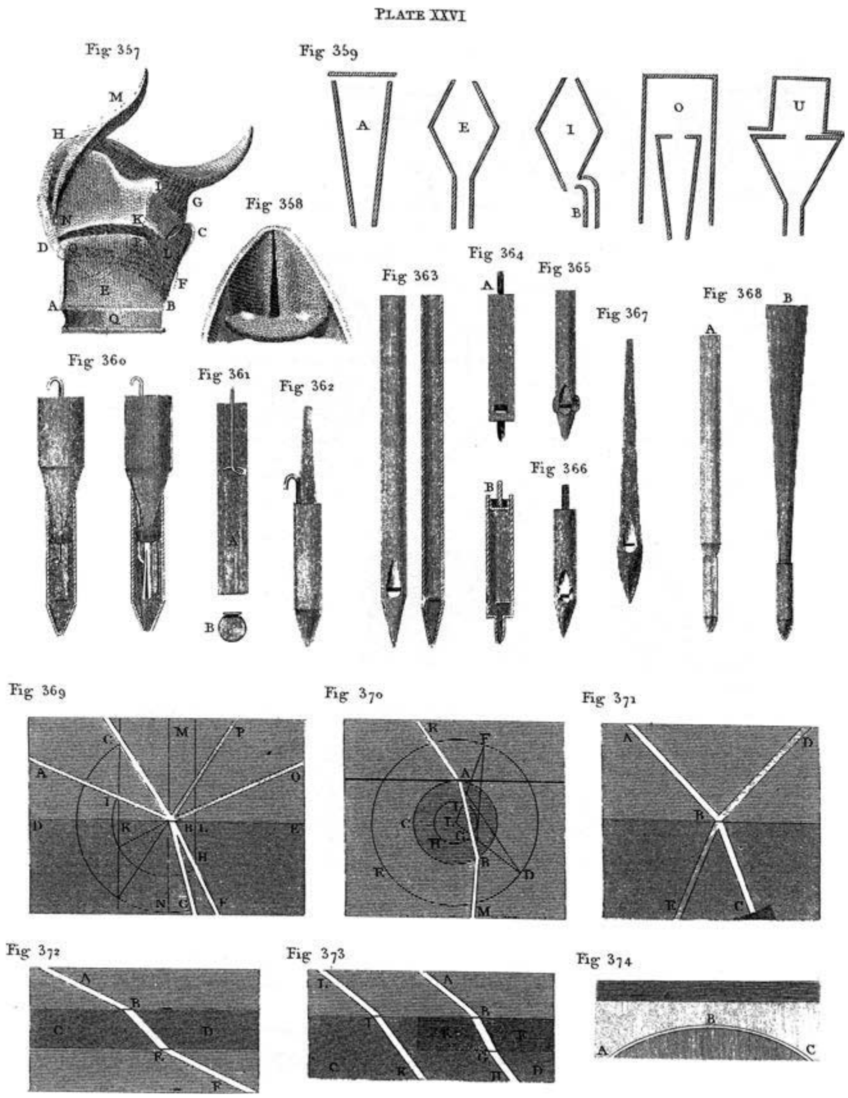

Figure 6. *Plate 26 from Young's* Course of Lectures *(cit. n. 28); the top registers compare the human glottis (figs. 357, 358) with organ pipes of various kinds, including the* vox humana *(360); the bottom registers illustrate various optical phenomena, such as reflection and refraction.*

differ from each other in the same manner as the sound of a violin and of a flute," a hypothesis then refined by Newton to mean "that the difference of colours, like that of tones in music, depends on the different frequency of the vibrations constituting light."[69] For Young, the full realization of the wave theory of light rested on the power of the musical analogy he had grasped better than Newton.

[69] Ibid., 475 (Hooke), 479 (Newton).

LONGITUDINAL VERSUS TRANSVERSE WAVES

After 1803, Young left the Royal Institution and active research in optics, discouraged by vitriolic attacks by Lord Brougham, an immovable adherent of the particle theory of light. Young subsequently wrote on medical subjects and increasingly worked on the decipherment of hieroglyphics. Later, he was greatly encouraged by the recognition and praise given him by younger French researchers in optics, especially Dominique Arago and Augustin Fresnel. The "Young-Fresnel theory," as it came to be called, prevailed by the 1820s, having converted all except for a few stubborn partisans of Newtonian orthodoxy (such as Brougham). In 1817, Young surveyed these confirmations in a magisterial review article for the *Encyclopaedia Britannica* on chromatics.[70]

The discovery of the polarization of light by Étienne-Louise Malus in 1807, however, seemed to raise problems for the undulatory theory. Gazing through an Iceland spar (calcite) crystal, Malus noticed that the two images of the reflected sunlight from a neighboring glass window would alternately disappear and appear as he rotated the crystal. Somehow, the reflected light had some kind of directionality that the crystal could only transmit when correctly oriented. The crystal would split the incoming reflected light into two separate beams, each "polarized" differently, as Malus phrased it. If indeed light was a wave, how could it exist in the different states of orientation Malus had discovered?[71]

By 1815, Young doubted that his theory could account for this new phenomenon, as he wrote in his private correspondence at the time. But in a letter of 1817, he himself proposed a solution that both used and reversed the analogy with sound. Writing to Arago, he noted that

> it is a principle in this [wave] theory, that all undulations are simply propagated through homogenous mediums in concentric spherical surfaces like the undulations of sound, consisting simply in the direct and retrograde motions of the particles in the direction of the radius [i.e., the direction of propagation of the wave], with the concomitant condensation and rarefactions.[72]

That is, sound is a *longitudinal* wave, causing fluctuations of density of the air along the direction of propagation. In his 1807 *Course of Lectures*, Young had noted that "Dr. Chladni has discovered that solids, of all kinds, are capable of longitudinal vibrations," though "the vibrations which most bodies produce are, however, not longitudinal but lateral."[73] Thus, Chladni's vibrating plates showed Young visible evidence of both longitudinal and lateral (transverse) motion. In 1817, though Young clearly

[70] Young's penchant for encyclopedism led him to contribute articles not just on optics but also on Egypt (a seminal work in the beginnings of Egyptology), bridges, and tides, among many others; see Robinson, *Last Man Who Knew Everything* (cit. n. 3), 179–88, which discusses the reception of Young by the French school on 165–78. See also F. Arago, *Éloge historique du Docteur Young* (Paris, 1832); Eugene Frankel, "Corpuscular Optics and the Wave Theory of Light: The Science and Politics of a Revolution in Physics," *Social Studies of Science* 6 (1976): 141–84; Frank A. J. L. James, "The Physical Interpretation of the Wave Theory of Light," *Brit. J. Hist. Sci.* 17 (1984): 47–60.

[71] For Malus and polarization, see Pesic, *Sky in a Bottle* (cit. n. 40), 84–9. See also David Park, *The Fire within the Eye: A Historical Essay on the Nature and Meaning of Light* (Princeton, N.J., 1997), 252–3, 273–4.

[72] Young, *Miscellaneous Works of the Late Thomas Young*, 3 vols. (London, 1855), 1:383.

[73] Young, *Course of Lectures* (cit. n. 28), 1:380.

understood the force of the example of sound, he now realized that light waves might operate in an importantly different manner: "And yet it is possible to explain in this theory a transverse vibration, propagated also in the direction of the radius, and with equal velocity, the motions of the particles being in a certain constant direction with respect to that radius: and this is a *polarization*."[74]

If the vibrations of the light wave are transverse (perpendicular) to their direction of propagation, they can then be polarized in the plane transverse to that direction. The two split beams transmitted by Iceland spar turned out to exemplify the two orthogonal directions in that plane: Malus's images appeared and disappeared as the crystal was rotated, first transmitting the polarized light, then not.[75] Thus, Young suggested, as did André-Marie Ampère, Arago, and Fresnel independently, light could be a transverse wave, compared to sound waves as longitudinal.[76] Though several of Young's biographers assert at this point that he and Arago had been "blinded" by the analogy with sound, Young's letter suggests the opposite, for he says that he was led to his new suggestion precisely by sound itself.[77] Note that he speaks, in both the case of transverse and of longitudinal waves, of "this theory" in the singular, indicating that the general characteristics of undulatory theory are shared by both, including the concepts of wavelength, frequency, velocity, and direction of propagation.

Returning to this issue in 1823, Young again represents himself as "strongly impressed with the analogy of the properties of sound," but now notices that the possibility of transverse light waves leads to a "perfectly *appalling*" consequence: because they had always been formulated in terms of the vibrations of a solid, "it might be inferred that the lumeniferous ether, pervading all space, and almost all substances, is not only elastic, but absolutely solid!!!"[78] Though Young's biographers take this as even stronger evidence of his blinding by the analogy to sound, his objection indicates the very difficulties with the ether that loomed so large by the end of the nineteenth century. In 1878, James Clerk Maxwell noted the "difficulties we may have in forming a consistent idea of the constitution of the aether" as both dilute and rigid, "certainly the largest, and probably the most uniform body of which we have any knowledge."[79] He and Young both accepted that mysterious body, but Young had realized its profoundly paradoxical character long before. As with the earlier issue of transversality, Young credited this final contribution to optics to his consideration of the "undulations of sound."

This concluding example confronts us with the full richness of Young's translation of sound vibrations into light waves. His youthful rendition of Shakespeare into classical Greek surely involved his awareness of both the possibilities and the perils

[74] Young, *Miscellaneous Works* (cit. n. 72), 1:383.

[75] For detailed discussion, including the work of Fresnel and Arago, see Buchwald, *Rise of the Wave Theory of Light* (cit. n. 2), 205–32.

[76] Ibid., 203–14.

[77] See Wood and Oldham, *Thomas Young*, 186, quoted and echoed by Robinson, *Last Man Who Knew Everything*, 173 (Both cit. n. 3). Darrigol, "Analogy between Light and Sound [Part 2]" (cit. n. 20, on 114 n. 2), also notes that "it could even be argued that the analogy blocked the understanding of polarization."

[78] A supplement to the *Encyclopaedia Britannica* entitled "Theoretical Investigations Intended to Illustrate the Phenomenon of Polarisation," reprinted in Young, *Miscellaneous Works* (cit. n. 72), 1:412–7, on 414, 415.

[79] Maxwell, *The Scientific Papers of James Clerk Maxwell*, 2 vols. (Cambridge, 1890), 2:763–75, on 775.

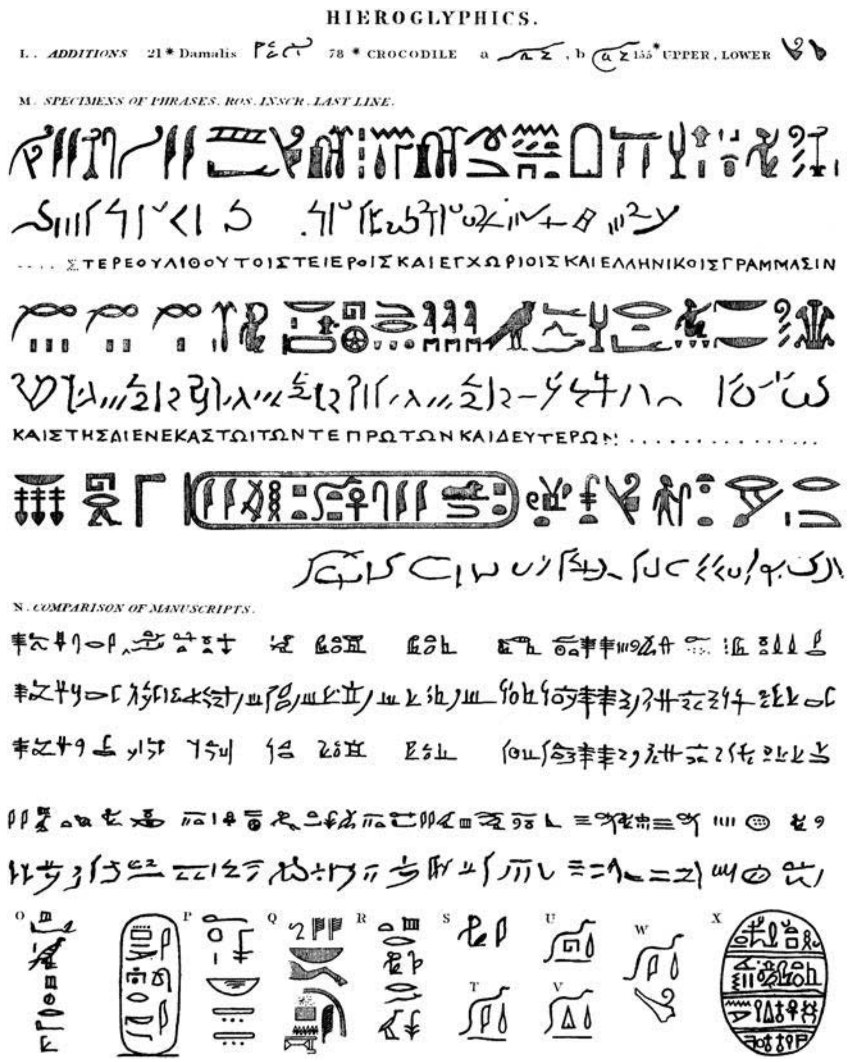

Figure 7. *Young's illustration of the translation between Egyptian hieroglyphics and classical Greek, from his article on Egypt for the* Encyclopaedia Britannica *(1819), reprinted as plate 5 in Young,* Miscellaneous Works *(cit. n. 72), 3: facing 197.*

of such translation.[80] In the present case, his translation yielded both the possibility of transverse light waves but also the attending paradox of the ether. Young was content to follow this translation from sound to light far enough to contemplate these new, "appalling" implications; characteristically, he left to Fresnel and Arago the detailed mathematical exploration of the new terrain.[81] Similarly, in his subsequent work on Egyptian hieroglyphics, Young discovered that the language was phonetic and cor-

[80] For Young's attitude toward this translation, see Peacock, *Life of Thomas Young* (cit. n. 1), 20–3.
[81] For Fresnel's final understanding of transversality, see Buchwald, *Rise of the Wave Theory of Light* (cit. n. 2), 228–31.

rectly identified many characters on the Rosetta stone, such as the cartouche of the pharaoh Ptolemy, leaving to Champollion the full decipherment of the text and the attendant *réclame* (fig. 7).[82] As with his work on light, Young's great linguistic discovery essentially involved sound.

Ironically, French acclaim for Young's light theories was accompanied by British neglect; conversely, the British magnified and the French minimized his achievements in hieroglyphics, compared to those of Champollion. In the tumult of the Napoleonic era, Young experienced the frustrations of a cosmopolitan polymath traversing the British-French divide. The crucial moment of breakthrough in translation may have been more satisfying for Young than the subsequent labor to fill in the gaps and continue the work to the bitter end. Ultimately, he may have been most hampered by his aversion to the "too wide and too barren" mathematical language Fresnel used so powerfully. Though admired for knowing so many tongues, Young may have known one too few, insofar as he eschewed the Continental mathematical language. Perhaps his disinclination may reflect his education, steeped in Newton's intentionally archaizing, anti-Cartesian geometrical language, rather than the algebraic symbology associated with Gottfried Wilhelm Leibniz. This may have been not mere imitation of Newton, though, but rather a reflection of Young's (and Newton's) deep respect for antiquity, their shared curiosity about *prisca sapientia*, strongly manifest in Young's work on hieroglyphics, Newton's on ancient chronology.

However one reads his own wide-ranging quest, Young himself thought that "it is probably best for mankind that the researches of some investigators should be conceived within a narrow compass, while others pass more rapidly through a more extensive sphere of research."[83] Though this elegant statement does not make explicit the difficulties and frustrations involved, Young was the exemplar of this second path, poised between languages in ways that parallel his fundamental role in translating the wave theory between sound and light. As he pursued these multiple projects, his experience with music at many points affected not only his approach to acoustics but the way he then deployed its analogy with light. His sensitivity to sound clearly affected his approach to the problem of translating Egyptian hieroglyphs. No less richly did the successive stages of his acoustical and optical work show a keen interplay between the force of his musical experience and the ensuing dialectic of translation that characterizes the emergent innovations he brought to the theory of interference and its application from sound to light.

[82] Cyrus Herzl Gordon, *Forgotten Scripts: Their Ongoing Discovery and Decipherment* (New York, 1982), 27–30: "Young established the principle of homophony" (28). See also Jed Z. Buchwald and Diane Greco Josefowicz, *The Zodiac of Paris: How an Improbable Controversy over an Ancient Egyptian Artifact Provoked a Modern Debate between Religion and Science* (Princeton, N.J., 2010), 316–27.

[83] Hilts, "Thomas Young's 'Autobiographical Sketch'" (cit. n. 3), 254.