Changeable Ears:
Ernst Mach's and Max Planck's Studies of Accommodation in Hearing

*by Alexandra Hui**

ABSTRACT

This article offers an examination of the psychophysical studies of accommodation in hearing by Ernst Mach and Max Planck, natural scientists better known for their accomplishments in physics and philosophy. Early in his career, Mach sought to experimentally locate the possible mechanism of accommodation in hearing, the phenomenon in which individuals can alter their experience of sound by changing their attention. Planck, employing a microtonal harmonium, studied the role of attention in vocalists' abilities to hear tempered intervals—what *he* termed accommodation in hearing. Both mobilized music as a means of argument and experiment. This article shows how each physicist's conception of accommodation in hearing drew on music and, in turn, informed his ideas about the historicity of hearing, the universality of the nineteenth-century Western musical aesthetic, and the nature of knowledge itself.

INTRODUCTION

When presenting his work on accommodation in hearing, the young physicist Ernst Mach would employ the following demonstration of the phenomenon. He urged his reader to play the chord $E + G^{\sharp} + B + e'$ followed by the chord $a + A + c^{\sharp\prime} + e'$ (see fig. 1 for a visual aid) on a guitar or keyboard instrument.[1] Then, the reader was to play the chord sequence again but this time was instructed to listen carefully to the highest tone in each chord (that high E). The reader, according to Mach, would have the

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[1] *Do* try this. A recording can be heard in audio 1 (300 KB; MP3) in the electronic version of this article. Performed by the author on an M-Audio Keystation 49e USB MIDI keyboard in Los Angeles, Calif., 2006. Special thanks to Daniel Crosby.

***Figure 1**. Chord example used to demonstrate the phenomenon of accommodation in hearing. Mach, "Bemerkungen über die Accommodation des Ohres"(cit. n. 2), 344. Mach used this same example in his 1865 lecture "Erklärung der Harmonie" (cit. n. 40).*

impression that the tones remained the same and only the tone quality had changed between chords. Playing the chord sequence one last time, the reader was asked to instead focus on the lowest tones (that transition from the low E to the low A). In this case she would hear a clear step down in pitch, as if the entire chord had dropped down significantly. Mach explained that because the tones of the piano were even, and because the ear was not fatigued by such constant tones, there was no explanation for the reader's changed sound sensation other than that she had changed her attention.[2]

I offer this example of Mach's to highlight his use of music to examine a psychophysical phenomenon. For Mach, music was the best way to demonstrate the phenomenon of accommodation in hearing: the individual's changed experience of sound in relation to the individual's changed attention to sound. Deliberately directed attention altered an individual's aural experience. Accommodation explained the listener's ability to hear, for example, the cello part in a symphonic performance once the listener chose to direct his or her attention to the cellos. The role of the individual in both creating and experiencing accommodation made it a particularly difficult phenomenon to study in others. Accommodation in hearing was also a difficult phenomenon to explain convincingly; better to mobilize readers' subjective experience by walking them through a demonstration.

Did you hear it? If you have had musical training then you likely did. Mach's readers would have. Their *Bildungsbürger* upbringing would have guaranteed them facility with at least one musical instrument as well as music-reading ability. His readers seeing this example in print would know of the phenomenon that he was referring to. For Mach, a discussion of one of the more curious features of sound sensation was also, necessarily, a discussion of music.

The bulk of this article focuses on the sound-sensation work of Mach and examines the motivations and means by which he mobilized music toward his goal of locating the mechanism of accommodation in hearing. Mach's use of music had implications for his historicism and, later, his epistemological thinking. I then turn to Mach's great critic, the physicist Max Planck, to discuss his use of a microtonal harmonium to understand the role of accommodation in the hearing of tempered rather than pure intervals, and I attempt to contextualize Planck's experiments in relation to his own epistemological thinking. The article ends with a short discussion of the work of the twentieth-century American composer Harry Partch, presented as an example of the continuing tension between Western musical aesthetics, the dominance of equal temperament in particular, and the individual's experience of sound. Ultimately Partch was able to accomplish his compositional goals by abandoning known sounds. Partch's hard-won freedom to forsake tradition and develop his own tuning systems,

[2] Mach, "Bemerkungen über die Accommodation des Ohres," in *Sitzungsberichte der kaiserlichen Akademie der Wissenschaften* 51 (1865): 343–6, on 344.

complete with innovative new musical instruments, was only possible upon his dual realization that (as Mach believed) hearing was historical and that (as Planck argued, though not in quite such negative terms) creators of music were "both the exponents and victims of system, philosophy, and attitude determined for them by their milieu."[3]

More broadly, this article shows how psychophysical studies of sound sensation were bound up with practitioners' relationships with music and music culture, both material and immaterial. These relationships allowed Mach and Planck to comfortably employ music as a means of both argument and experiment. They applied their respective ideas about accommodation in hearing to theories on the origins and development of musical systems. At stake in these theories were such issues as the historicity of sound sensation, the universality and supremacy of the nineteenth-century German musical aesthetic, and, potentially, the nature of knowledge itself.

The world of sound in the second half of the nineteenth century was highly unstable. New tuning systems, new tones, new music, and the fledgling discipline of musicology all jostled to establish position. The transition from earlier forms of tuning to equal temperament meant that the pitches themselves were not fixed, standardized neither between instruments nor within individual ones. Later, a growing interest in non-Western music introduced entirely new sounds.

The development of new acoustic instruments, the tuning fork tonometer being perhaps the most important, had brought great promise of standardization and equivalence both within individual instruments and between them. Equal temperament, with its associated freedoms of composition and performance (its use meant that concert programs or even single works could modulate between a greater variety of keys without requiring the instruments to be retuned), was practicable, no longer mere theory.[4] It was the latest of several attempts at a solution to the problems presented by the Western tuning system's adherence to a scale in which intervals were based on pure ratios that were repeatable over many octaves.[5] The twelve acoustically pure fifths were almost, but not quite, equivalent to seven acoustically pure octaves. A twelve-tone scale in which all tones were related by pure fifths could not be enclosed within an octave. Before the developments in the late nineteenth century, the Western tuning system had prioritized keeping certain intervals pure—the most commonly played ones—by sacrificing others. The Pythagorean tuning system, used through the Renaissance, made fourths and fifths pure. In order to do so, the Pythagorean "comma," or the microtonal discrepancy between twelve perfect-fifth ratios and seven octaves, was placed where it would not be noticed. So to listeners at the time, thirds and sixths in this system sounded quite jarring and out of tune. Alternative systems, those of just intonation and mean tone temperament, instead prioritized

[3] Partch, *Genesis of a Music: An Account of a Creative Work, Its Roots, and Its Fulfillments*, 2nd ed. (New York, 1974), xvii.

[4] Aristoxenus, a pupil of Aristotle, first proposed the theory of equidistant smallest intervals for Western scales. It was embraced by some lutenists as early as the fifteenth century, mostly motivated by convenience. Equal semitones allowed the same fret to mark off a diatonic semitone on one string (a B♭ on an open A string, for example) and a chromatic semitone on another (an F♯ on an open F string), commonly required in Renaissance lute music. Mark Lindley and Ronald Turner-Smith, *Mathematical Models of Musical Scales* (Bonn, 1993), 44–6.

[5] A harmonic interval in music is the distance between two pitches heard simultaneously. The number of steps between the pitches in a scale traditionally determines the name of the interval. From the pitch C up to E or down to A is a third. Further up to G or down to F is a fifth. From C to the C above or below is a perfect octave, an eighth.

triads (and therefore thirds) as well as fourths and fifths as pure, distributing the Pythagorean comma among other intervals. Equal temperament sought to distribute the comma evenly—equally—among all the twelve tones of the scale.

It was, however, inconsistently applied. This was in part due to the fact that while the means of measuring equal temperament did exist, the techniques for equal-tempering a piano or organ of eighty-eight or more keys with precision did not. For some, that was just fine. Many believed that the ease of transposition achieved with equal temperament did not outweigh aesthetic sacrifices of coloration and tonality. With previous tuning systems, while limiting the intervals and therefore keys (of diatonic scales) on the instrument that could be performed without a complete retuning, those keys were said to have distinct coloration and character of sound, a quality coveted by composers and listeners alike.[6] Many lamented the abandonment of pure intervals and the associated loss of key coloration with the tempering of the Western scale. Equal temperament's treatment of the Pythagorean comma could, for example, be cynically understood as spreading the error everywhere. Helmholtz, for one, went so far as to document the beats—his criterion for dissonance—of the tempered triad, implying that equal temperament was unnatural and unmusical.[7] Partch would describe Helmholtz's impatience with equal temperament as "a salutary and long-overdue influence."[8]

In addition to shifting tones within the Western tuning system, sounds altogether new to Europe were introduced toward the end of the nineteenth century. Increasingly, non-Western music ensembles visited Europe to perform. The introduction of the phonograph to field studies in the late 1870s granted music further ability to travel; field ethnomusicologists returned to Europe with wax cylinders containing never-before-heard music. This non-Western music, some of which was based on highly complex scale systems, undermined European beliefs in the inherent superiority of Western intonation and fueled the development of new questions and theories about Western musical aesthetics.

In this same period, certainly related to the instability of sound in the music world, there was a growing interest in the role of attention in hearing, and the phenomenon of accommodation in particular. The phenomenon had already been established and physiologically explained for vision. Helmholtz's sign theory of vision had showed (very much building on Hermann Lotze's model) that the contraction of the muscles of the eye allowed an individual to spatially locate the object of his or her focused observation.[9] Many believed that this model for the role of attention in vision could be extended to the sensation of sound.

[6] When questioned as to whether an individual key had absolute character or only relative character in comparison to another, Hermann von Helmholtz raised the possibility that the distinct character of keys was due, in part, to a particularity of the human ear. But, at least for pianos and bowed and wind instruments, the more likely cause of the different characters of keys, according to Helmholtz, was the way in which a particular key was played on the instrument. Piano keys, for instance, were struck differently depending on whether they were the black or white keys. For bowed and wind instruments, the different lengths of the strings or wind chamber as a particular tone was sounded contributed to the supposed character of the key. Helmholtz, *Die Lehre von den Tonempfindungen als Physiologische Grundlage für die Theorie der Musik*, 3rd ed. (Brunswick, 1870), 501–4.

[7] He complained: "I do not know that it was so necessary to sacrifice correctness of intonation to the convenience of musical instruments." Ibid., 529.

[8] Partch, *Genesis of a Music* (cit. n. 3), 389.

[9] Helmholtz had presented a broadly sketched "theory of signs" in his 1855 lecture celebrating the centennial of Kant's inaugural lecture at Königsberg, "Über das Sehen des Menschen," based on the

Historian Michael Hagner sees mid-nineteenth-century psychophysical studies of attention as an indicator of the extent to which attention was redefined from late eighteenth-century conceptions.[10] He explains that attention had previously been a virtue, making individuals masters of themselves and the exploration of their world. The early work of the psychophysicist Gustav Fechner, however, showed that attention was actually quite difficult to control and maintain and threw into relief the instability of the human perceptual condition. Hagner points to Mach specifically and his belief that attention was a purely motor-based phenomenon.[11] He argues that this was part of a growing acceptance among psychophysicists that conscious control and self-discipline influenced perception as motor skills. If Fechner had determined that perception changed in spite of, possibly even because of, focused attention, Mach's interest in accommodation was to determine why this happened.

To study the means by which an individual's deliberately altered attention to sound affected his or her aural experience would be difficult enough under any circumstances. Doing so in a period of dramatic sonic upheaval both confounded and further advanced Mach's and Planck's studies. It follows, then, that their respective explorations of accommodation in hearing must be understood in relation to the shifting music world. If the sounds and harmonies of music were changeable and if hearing itself was changeable, then the individual, subjective experience of sound was potentially valid, perhaps even more valid than the theories and aesthetics advanced by music critics. For Mach, this validity buttressed his phenomenological view of the world. For Planck, it supported his antipositivist stance. An awareness of the connections between Mach's and Planck's differing conceptions of sound sensation, and of accommodation in particular, allows for a new approach—and hopefully new insight—into the two giants' later epistemological clash. The world appears different when it includes sound.

MACH'S ACCOMMODATION EXPERIMENTS

Much of the historiographical work on Mach has focused on his physics, in particular his work on the shock waves of supersonic projectile motion, and his philosophy, the fields for which he was so well respected. His phenomenology, which Mach insisted could be reconciled with experimental science, drew the ire of Planck, among several others. Historians of science often point to Mach's 1872 treatise *Die Geschichte und die Wurzel des Satzes von der Erhaltung der Arbeit* (History and root of the principle of the conservation of energy) as the first full articulation of his position on

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idea of "local signs" proposed by Lotze and others. He believed that vision operated according to an optimization principle. The contraction of the eye muscles as the eye arced from a specific peripheral spot to a spot of sharpest vision (moving the eye so that the object of observation was most clearly visible) corresponded to a series of changing feelings of position. This series of feelings was stored in the memory and recalled whenever that specific peripheral spot was stimulated. The local sign consisted of the physical and physiological actions required to orient each spot on the retina to the visual axis. Gary Hatfield, *The Natural and the Normative: Theories of Spatial Perception from Kant to Helmholtz* (Cambridge, Mass., 1990); Timothy Lenoir, "The Eye as a Mathematician: Clinical Practice, Instrumentation, and Helmholtz's Construction of an Empiricist Theory of Vision," in *Hermann von Helmholtz and the Foundations of Nineteenth-Century Science*, ed. David Cahan (Berkeley, Calif., 1993), 109–53.

[10] Hagner, "Toward a History of Attention in Culture and Science," *Modern Language Notes* 118, no. 3 (2003): 670–87.

[11] Ibid., 680, 681.

the historicist nature of ideas; that is, that ideas were specific to time and place. This historicism directly informed the logical positivist movement that developed in the twentieth century.

The musical aspect of Mach's psychophysical work has never been the focus of serious study by historians of science, and it is interesting. But perhaps even more exciting is that Mach's engagement with the music world and mobilization of music to scientific ends contributed to the maturation of his historicist thinking. Mach's use of music in his psychophysical experiments on accommodation—at a time when established musical aesthetics were being called into question—in turn informed his eventual belief that hearing was historically contingent. Mach came to believe that the sensation of sound was not just psychophysical, and certainly not just a physiological mechanism, but also cultivated and cultured. This ultimately eliminated the need to locate a mechanism of accommodation, as it would be changing constantly anyway, which explains why Mach was no longer discussing the accommodation mechanism in 1885. The following examination of Mach's use of music in his study of accommodation in hearing suggests that he was thinking in a historicist way, at least about sensory perception of sound, much earlier than credited by historians of science. As early as 1863 Mach believed that hearing—how one heard, what one heard, what one focused one's attention on—was bound to culture and therefore specific to time and place. Hearing itself was historical.

Mach began his career interested in acoustic phenomena. His earliest work was an examination of the controversy between Christian Doppler and Joseph Petzval over the relation of motion to changes in color or tone.[12] Recall that the Doppler effect is the phenomenon in which the tone or color of a wave changes as an observer moves in relation to the source of the wave. Now, Mach's study dealt mostly with the physics and mathematics of the Doppler-Petzval controversy, but it should be noted that from the very beginning he was dealing with problems that involved the specificity of the observer's experience; the explanation of the Doppler effect was bound to the location of the observer relative to the wave source.

In the following year, Mach began to study the observer's experience more directly, undertaking his initial work on the phenomenon of accommodation in hearing. He first developed a model of the mechanism of accommodation in hearing analogous to Helmholtz's sign theory of vision. Just as the eye muscles allowed the individual to spatially orient, Mach posited that the individual differentiated tone pitch through the contraction of various muscles in the ear in response to changed attention. He believed that the phenomenon of accommodation in hearing was psychophysical but the mechanism was physiological.

Mach suspected that the accommodation mechanism was rooted in the tensor tympani and possibly also the stapedius muscles, which would contract in response to altered attention, changing the transmission of sound waves to the cochlea. In his 1863 article "Zur Theorie des Gehörorgans," Mach sought to reconcile physiological theory with investigative technique through a kymographic theory of the ear.[13] Like the kymograph, which recorded blood pressure through a stylus on a rotating band

[12] Mach, "Ueber die Kontroverse zwischen Doppler und Petzval, bezüglich der Aenderung des Tones und der Farbe durch Bewegung," *Zeitschrift für Mathematik und Physik* 6 (1861): 120–6.

[13] Mach, "Zur Theorie des Gehörorgans," *Sitzungsberichte der kaiserlichen Akademie der Wissenschaften* 48, no. 2 (1863): 283–300.

of paper, Mach believed that the ear drew (*zeichnen*) sound waves in the labyrinthian fluid of the inner ear. These sound waves were then absorbed by the auditory nerve. The entire ear—the eardrum, the middle ear muscles and bones, and the labyrinthian fluid—functioned to transcribe the sound waves from the medium of air molecules to the medium of labyrinthian fluid. Though the sound wave was modified (regulated and damped), the system did not perform an analysis of it. Mach demonstrated all of this through a series of experiments and mathematical derivations.[14]

One of the implications of this kymographic theory that was of particular interest to Mach was the simultaneous reflection of the sound waves transmitted by the eardrum, an analogue to Gustav Kirchhoff's theorem of the equal absorption and emission of light waves. Mach performed a series of experiments mobilizing this effect toward direct observation of the accommodation phenomenon in another person.[15] Placing an assistant with a long rubber tube in his ear in another room, Mach very softly sang a constant tone while moving the other end of the tube back and forth, relative to his own ear. The tone was loudest, according to the assistant, when Mach's end of the rubber tube was nearest Mach's ear, when the sung tone was amplified by the reflection of its sound waves in Mach's ear. In another experiment, Mach softly sang a tone with one end of the rubber tube in each of his own ears. When he pinched off the tube in the middle he noticed a decrease in the volume of the sung tone, presumably because his pinching had eliminated the reflection of the sound waves back and forth between his ears through the tube.[16]

Thus, Mach believed he had both theoretically derived and experimentally demonstrated the mechanics of his kymographic model of the ear, the transmission of sound waves through the ossicles to be transcribed in the labyrinthian fluid. But the model did not necessarily explain the ability of the listener to actively distinguish a single tone from other tones sounding simultaneously. It could not explain accommodation in hearing. The musical examples clearly demonstrated the phenomenon of accommodation, and yet Mach could not locate and directly observe the mechanism. Still, he maintained his belief that attention was a bodily function and that, therefore, the phenomenon of accommodation had its foundation in the mechanisms of the body.[17] So he continued with his search.

Elaborating on these early investigations, Mach performed a series of experiments in the summer of 1863 with Joseph Popper and students of the Vienna Physical

[14] Mach's physical proof was a mathematical demonstration that the eardrum, ossicles, and labyrinthian fluid all vibrate to regulate the transmission of sound waves in two significant ways: even absorption and quick dissipation of the initial state of the sound waves. Mach showed that the restoring force of the vibrating ear bones and the viscosity of the labyrinthian fluid both equalize the absorption of sound waves of varying frequency (tones of different pitch) and also damp resonance (harmonic overtones of the original sound wave), allowing for the transmission of a quick succession of tones. Mach further posited the possibility that different types of transmission occur in the ear depending on the wavelength of the sound waves. He suggested that the eardrum, ossicles, and labyrinthian fluid all vibrate together to transmit lower tones but vibrate separately to transmit higher tones. Although this hypothesis did not provide a mechanism of accommodation, it was at least a physical explanation in which different pitches were treated differently in the ear. Ibid., 285–7.

[15] Ibid., 289.

[16] Mach later revisited this experiment and concluded that it was more likely that the pinching created reflected waves in the tube and that the interference of these waves with the original ones caused the weakened volume of the sung tone in his ears. Mach, "Über einige der physiologischen Akustik angehörige Erscheinungen," *Sitzungsberichte der kaiserlichen Akademie der Wissenschaften* 50 (1864): 342–62.

[17] Mach, "Zur Theorie des Gehörorgans" (cit. n. 13), 297.

Institute. For these experiments Mach placed a vibrating tuning fork in his teeth and one end of a rubber tube in one of his ears.[18] The other end of the rubber tube was placed in an assistant's ear. As the tuning fork sounded Mach slowly changed his attention from the fundamental or ground tone to various harmonic overtones. Mach could hear these overtones as strong and distinct from the ground tone as he moved his attention from one overtone to the next. But the assistant could not. Although other experimental work electrically stimulating the tensor tympani had established the muscle's ability to change the tension on a prepared (nonliving) eardrum, and although Mach had mathematically demonstrated that changed tension on the eardrum would result in higher tones appearing louder, Mach's tuning-fork experiment could not confirm that changed attention correlated with changed eardrum tension, which in turn correlated with changed sound sensation (hearing the overtones more strongly). He was left to conclude that while his kymographic theory held promise, further experimental proof was required to show that it explained the phenomenon of accommodation.[19]

In the 1870s Mach began a series of collaborative projects in relation to sound sensation with Johann Kessel. Developing earlier animal-based research by physiologists Charles-Édouard Brown-Séquard, Jean Pierre Marie Flourens, and Friedrich Goltz, Kessel was investigating the role of the semicircular canals and labyrinth in individuals' ability to balance. He believed this function of the hearing organ could be employed to better understand inner-ear diseases and injuries.[20] Mach would, in the next few years, publish two articles on further physiological experiments on the sense of balance in humans, as well as a lengthier piece on the sense of acceleration.[21]

In relation to this work on balance, Mach was also examining the mechanics of the middle ear, the rotation points and axes of movement, as well as making experiments on the eustachian tube that consisted of observing the function of hearing through rapidly changing air pressure.[22] This study of the topography of the middle ear was developed more extensively with Kessel in a series of measurements and experiments on the ligature and musculature of middle ears removed from cadavers.[23] Incorporating a stroboscopic apparatus and technique for determining pitch developed by Mach, the two scientists then made a series of observations on the middle ear system in motion.[24] One set of these cadaver experiments focused on the influence of the middle ear muscles on the movement and vibration of the eardrum, a relationship that could provide Mach insight in his search for the accommodation mechanism.[25]

The experimental preparation for Mach and Kessel's accommodation experiments

[18] Mach, "Bemerkungen über die Accommodation des Ohres" (cit. n. 2), 345.

[19] Mach, "Zur Theorie des Gehörorgans" (cit. n. 13), 299–300.

[20] Mach, "Vereinsangelegenheiten," *Lotos* 21 (1871): 196–8.

[21] Mach, "Physikalische Versuche über den Gleichgewichtssinn des Menschen," *Sitzungsberichte der kaiserlichen Akademie der Wissenschaften* 68 (1873): 124–40; Mach, "Über den Gleichgewichtssinn," *Sitzungsberichte der kaiserlichen Akademie der Wissenschaften* 69 (1874): 44–51; Mach, *Bewegungsempfindungen* (Leipzig, 1875).

[22] Mach, "Vereinsangelegenheiten" (cit. n. 20).

[23] Mach and Kessel, "Beiträge zur Topographie und Mechanik des Mittelohres," *Sitzungsberichte der kaiserlichen Akademie der Wissenschaften* 69 (1874): 221–43.

[24] Mach, "Über die stroboskopische Bestimmung der Tonhöhe," *Sitzungsberichte der kaiserlichen Akademie der Wissenschaften* 66 (1872): 67–74.

[25] Kessel, "Ueber den Einfluss der Binnenmuskeln der Paukenhöhle auf die Bewegung und Schwingungen des Trommelfels am todten Ohre," *Archiv für Ohrenheilkunde* 2 (1874): 80–92. Kessel dated this article July 1873.

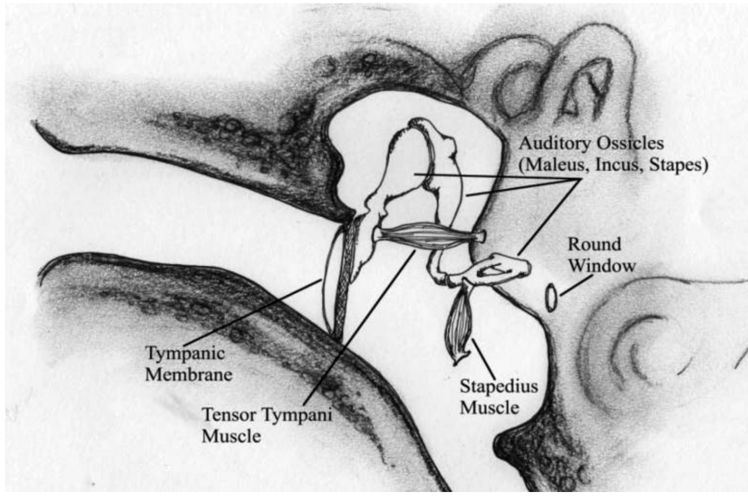

Figure 2. *The middle ear. Hui,* Psychophysical Ear *(cit. n. *), 99.*

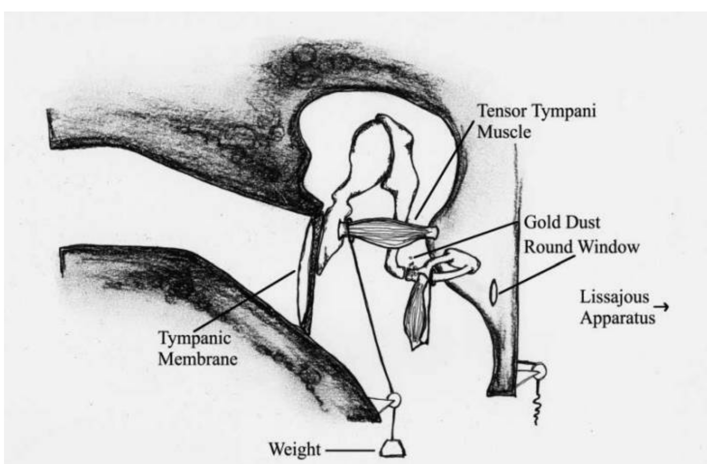

Figure 3. *Mach and Kessel's prepared ear. Hui,* Psychophysical Ear *(cit. n. *), 100.*

on middle ears was as follows (see figs. 2 and 3). First they carefully removed the tensor tympani in order to attach a thread to it. Once it was reinserted into the middle ear cavity, weight on the order of a few grams could be added to the other end of the thread in order to produce tension in the muscle. The lower, bony portion of the middle ear cavity was cut out to allow space for the thread to pass over a pulley and hang vertically. Another thread was attached to the head of the stirrup bone. This thread was passed through the canal alongside the stapedius muscle (the connection of this muscle to the stirrup bone was left intact). Most of the bony portion of the inner ear—everything past the oval and round windows—was cut away to provide space both for the stirrup thread to pass over a pulley and hang vertically and for a microscope and ocular micrometer to measure the displacement of the stirrup thread and view the movement of the ossicles, which were dusted with gold flakes, through the round window. Lastly, one end of a rubber tube was placed in the outer ear canal with its other end attached to the opening of an organ pipe.

In the first series of experiments Mach and Kessel measured the displacement of the stirrup thread, which correlated to the movement of the ossicles, when an organ pipe of 256 cycles per second was sounded with a 3-gram weight on the tensor tympani thread. This created tension on the eardrum and constrained the movement of the ossicles, approximating the assumed influence that attention would have on the tensor tympani. When they ran the experiment again with an organ pipe of 1,024 cycles per second, they found that the displacement of the stirrup thread was less. When they pulled on the stapedius muscle, further constraining the movement of the ossicles, the displacement of the stirrup thread was reduced further still. Mach and Kessel believed that this demonstrated that changed tension on the eardrum resulted in changed transmission of the sound waves through the ossicles.[26]

Next, Mach and Kessel attached both organ pipes via rubber tubes to the single rubber tube in the outer ear canal. A Lissajous vibration microscope was also attached to the system and set up to project two-dimensional images of the stirrup-thread displacement.[27] First, with no weight on the tensor tympani thread, the low pipe was sounded. The image projected by the vibration microscope can be seen in the first of the set of figures shown in figure 4. When the same pipe was sounded while there was tension on the tensor tympani (weight was added), the second image was seen. When just the higher pipe was sounded, with no weight on the tensor tympani, the third image was seen. When both pipes were sounded simultaneously, again with no weight on the tensor tympani, the fourth image resulted. They then tried sounding both pipes and weighting the tensor tympani. The image that resulted was the third, the same image as when the higher pipe sounded with no weight. Changing the tension on the tensor tympani while two tones were sounding simultaneously altered the movement of the ossicles to appear as if only the higher tone was sounding. It appeared that Mach and Kessel had located the accommodation mechanism; it was, as suspected, the tensor tympani.[28]

Mach and Kessel then attempted to replicate this series of experiments on a living ear. They of course could not cut away bone in order to attach little pulleys and weights on a living person, and so they instead constructed an "ear mirror" (*Ohrenspiegel*) with which to observe the displacement of gold flecks on the outside of the eardrum. The vibration microscope images of the displacement of the eardrum for

[26] Mach and Kessel, "Versuche über die Accommodation des Ohres," *Sitzungsberichte der kaiserlichen Akademie der Wissenschaften* 66 (1872): 337–43.

[27] The vibration microscope, first developed in 1855 by Jules Lissajous, who would later become the scientific consultant on Napoleon III's commission to establish a standard pitch, consisted of a small lens attached by an arm to a vibrating object, traditionally a tuning fork. Objects (a light beam or stylus mark on another tuning fork) viewed through this lens would thus appear to vibrate, tracing out a one-dimensional path of oscillation. If the object viewed through the lens also vibrated perpendicular to the plane of the primary vibrating tuning fork, then a two-dimensional curve would appear to be traced out. These Lissajous curves or figures could then be analyzed relative to the known frequency of the primary tuning fork. For his accommodation experiments, Mach viewed the oscillating stirrup thread through the vibrating lens of the vibration microscope and then projected the two-dimensional path onto a screen. See Steven Turner's article on the development of Lissajous apparatuses, "Demonstrating Harmony: Some of the Many Devices Used to Produce Lissajous Curves before the Oscilloscope," *Rittenhaus* 11, no. 2 (1997): 33–51.

[28] Mach and Kessel, "Versuche über die Accommodation des Ohres" (cit. n. 26).

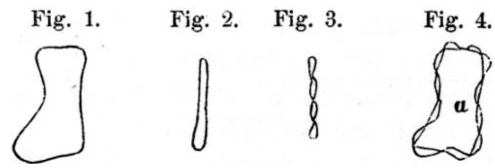

Figure 4. *The Lissajous microscope images. Mach and Kessel, "Versuche über die Accommodation des Ohres" (cit. n. 26), 339.*

lower tones were the same as those for the prepared ear. They were not, however, the same for higher tones. Mach and Kessel could not recreate the mechanism of accommodation in a living ear. This discrepancy between results on a nonliving ear and a living one, Mach claimed, indicated that listening and hearing were not the same thing. Attention and accommodation could not be replicated by merely adding a weight-and-pulley system to the tensor tympani.[29] The psychophysical nature of accommodation in hearing limited its study to individuals' subjective observation of the phenomenon. Its mechanism could not be located by outside observers.

MACH AS SELF-APPOINTED BRIDGE BETWEEN PHYSICS AND MUSIC

Mach relied heavily on music in his science. He employed musical examples to demonstrate the phenomenon of accommodation to his audience, and he turned to music-theoretical arguments to support his assertion that the phenomenon did, in fact, exist. While his efforts to locate the accommodation mechanism of sound sensation remained fruitless, music was a means of demonstrating and discussing the otherwise inaccessible psychophysical phenomenon. Music was a proxy scientific language. For Mach, it was not simply that sound and music were interchangeable, but rather, that it was critical that they be interchangeable, for both demonstrating and testing certain phenomena of the sensory perception of sound required employing music as sound. As a consequence, the search for the accommodation mechanism of hearing was also a study of musical aesthetics informed by Mach's relationship with music.

While he toiled away with Kessel in the laboratory, Mach simultaneously offered up his findings to the music world. Further, Mach was in regular communication with his close friend, the Viennese music critic Eduard Kulke, about his work, as Kulke, too, was struggling with issues surrounding the individual's subjective experience of sound. Mach's use of music in his search for the accommodation mechanism in hearing was not simply a consequence of his musical milieu. It was critical that he use music *as* music to study accommodation in hearing. For one, music was the best way to convincingly demonstrate the existence of the phenomenon of accommodation. And, in turn, locating the mechanism of accommodation could potentially buttress efforts to explain and validate individuals' subjective experience of sound.

Mach moderated and moved with ease through the worlds of natural science and music, actively engaging both socially and intellectually. He used musical examples in his scientific writings, and he reached out to the music world with the results of his research on sound sensation. Mach saw his work and himself as a bridge between

[29] Ibid., 342.

physics and music, overlapping and intersecting with several issues important to music theoreticians at the time.[30] In 1866, he published *Einleitung in die Helmholtz'sche Musiktheorie*, a reworking of Helmholtz's much-heralded 1863 text *Die Lehre von den Tonempfindungen* in terms a musician could understand. Throughout the 1860s and 1870s, he wrote articles for music and musicology journals, and also contributed to the *Musikalisches Conversations-Lexikon*, a twelve-volume music encyclopedia published between 1870 and 1879 (as well as an 1888 supplemental volume). In all of these writings but most explicitly in *Einleitung in die Helmholtz'sche Musiktheorie*, Mach sought to clarify scientific concepts in the service of musicians and music theorists. He explained that he hoped the text would result in cooperation between musicians and physicists and that it would help some musicians overcome their initial reticence about studying Helmholtz's technical work. Mach was making a self-conscious effort to place himself at the intersection of the natural science and music worlds.[31]

An 1867 review of Mach's reworking of Helmholtz in the *Leipziger allgemeine musikalische Zeitung* claimed to welcome any work that would help the musician befriend the work of Helmholtz through further illumination.[32] The author hesitantly allowed that it remained to be seen, however, whether Mach's text would provide such illumination, especially the section on harmony. Three months later the same journal ran an extended article titled "Zur Theorie der Musik: Die Physiker und die Musiker" that explored the overlap between the intellectual circles of Helmholtz's and Moritz Hauptmann's physiological acoustics and that of music philosophy. A third of the text was devoted to a discussion of Mach's efforts. The editors recommended Mach's book to anyone hoping to gain insight into Helmholtz's theories.[33] But the editors also explained that, while Mach's work was both instructive and convincing, it missed Helmholtz's main points.[34] So in 1867, although the musicologists cautiously welcomed Mach's presence in the music world, they were also willing to question and challenge his theories.

Mach's participation in the *Musikalisches Conversations-Lexikon* indicates the extent to which his prestige had grown since his initial efforts to engage the scholarly music community with his text on Helmholtz. Mach was now regarded as an expert. The "Mach" entry in *Musikalisches Conversations-Lexikon* described him as one of the "most worthy scholars of the science of music." His text on Helmholtz was declared extraordinarily worthwhile.[35] In 1887, one of the leading musicology journals, *Vierteljahrsschrift für Musikwissenschaft*, published a lengthy excerpt of Mach's *Analyse der Empfindungen*. Mach's efforts to construct a bridge of ideas between physicists and musicians appeared to have been successful.

Perhaps the most concrete example of Mach's exchange of ideas with the world

[30] Mach, *Einleitung in die Helmholtz'sche Musiktheorie* (Graz, 1866), v–4.
[31] Ibid., vii.
[32] Unsigned review of *Einleitung in die Helmholtz'sche Musiktheorie*, by Mach, *Leipziger allgemeine musikalische Zeitung*, no. 7 (1867): 58.
[33] "Zur Theorie der Musik: Die Physiker und die Musiker," *Leipziger allgemeine musikalische Zeitung*, no. 21 (1867): 165–9.
[34] These main points were, apparently, that Helmholtz's "physical-psychological" theory was internally consistent and that this theory was in full harmony with the art of music. Ibid., 166–7.
[35] *Musikalisches Conversations-Lexikon*, vol. 7, ed. Hermann Mendel (Berlin, 1875), s.v. "Mach, Ernst."

of music is found in his friendship with Eduard Kulke. They met in 1863 when Mach was drawn into a lively discussion among musicians over the nature of musical tones at a Viennese café.[36] When later describing his initial encounter with the group, Mach recalled that he had chosen to side with Kulke due to Kulke's more sober, more *wissenschaftlich* position on sound sensation.[37] Kulke was part of a circle of Viennese Wagnerians that included Anton Bruckner and Peter Cornelius, among others. A moving performance of Wagner's *Tannhäuser* in 1854 had prompted what Kulke described as his "aesthetic heresy" (*ästhetische Ketzerei*). He found Wagner's music to be pleasing, but his personal reaction was countered by acoustic and music-theoretical arguments and accusations that no one of taste or aesthetic education could possibly find Wagnerian music beautiful. Kulke was troubled by the accepted belief that there could be correct and incorrect taste despite overwhelming evidence that musical tastes varied greatly among individuals. The Wagnerian opera motivated a lifelong effort by Kulke to reconcile the music-theoretical analyses that condemned Wagner's harmonies as ugly with his own, individual enjoyment of Wagnerian music.[38]

Mach and Kulke's friendship and the intellectual exchange with which it began on that day in the café illustrate the extent to which the individual, subjective experience of sound sensation presented issues common to both psychophysics and music.[39] Kulke sought to develop an aesthetic of music that would explain the individual's subjective appreciation of music. Correspondingly, Mach worked to locate and explain accommodation in hearing, the locus of an individual's subjective experience of sound. An individual could, for example, by focusing on certain tones, hear the opening chords of *Tannhäuser* as quite beautiful and moving. Another, directing her attention to different harmonies, could find Wagner's opera to be jarring and dissonant. It should be little wonder, then, that Mach and Kulke began such a close friendship over a discussion of musical tones that day at the café; they were working out similar problems.

From the very beginning of his psychophysical studies of accommodation in hearing, Mach had relied on music to practice his science. He employed the chord

[36] These rowdy and informal café gatherings were apparently a regular occurrence, and Mach continued to frequent them. Ludwig Karpath wrote: "A close relative has told me a lot about a Vienna coffeehouse which I can no longer remember, the 'Café Elephant,' which was located in a narrow passage between Stephen's Place and the Graben. Every day, scholars, artists, and doctors of medicine and law would gather together. The regulars (*Stammgaesten*) included such later famous people as Professor Mach, Lynkeus (Popper), a group of Wagner-oriented musicians: Peter Cornelius, Heinrich Proges, the music critic Grad, the composer Goldmark, and many others. People wandered in around 2 p.m. and stayed until 2 in the morning, that is, some were always leaving while others were arriving. Unbroken wit and argument on philosophical, scientific, and artistic matters kept the discussion sharp and stimulating. To a certain extent the young Dozent Ernst Mach presided over the gathering. His profound understanding and reflective manner impressed everyone. According to my relative he was one of the first to occupy himself deeply with the recently published work of Helmholtz on tone perceptions about which he formed many interesting and instructive conclusions." This letter is part of the private collection of Ernst Anton Lederer (Mach's grandson) at his home in Essex Fells, N.J. Quoted and translated in John Blackmore, *Ernst Mach: His Work, Life, and Influence* (Berkeley, Calif., 1972), 23.

[37] Mach, foreword, in Kulke, *Kritik der Philosophie des Schönen* (Leipzig, 1906), x–xi.

[38] Kulke, foreword (written in 1896), in *Kritik der Philosophie des Schönen* (cit. n. 37), vii–viii.

[39] I discuss Mach and Kulke's lifelong correspondence more extensively in Hui, *Psychophysical Ear* (cit. n. *).

demonstration of the accommodation phenomenon discussed at the beginning of this article both in his writings and in public lectures.[40] In addition to mobilizing music (and the music training of his audience) to demonstrate the phenomenon of accommodation in hearing, Mach also regularly employed music to explain the phenomenon, as best seen in his popular lectures on musical acoustics, "Über die Cortischen Fasern des Ohres" and "Die Erklärung der Harmonie."

In the first, "Über die Cortischen Fasern des Ohres," Mach employed the piano as a model for the concept of sympathetic vibration.[41] Standing two pianos next to each other, lifting the dampers on one piano (by pressing the sostenuto pedal), and striking a key on the other resulted in the same note ringing on the undamped piano. Similar results occurred in response to a major triad, and so on. The undamped piano, Mach explained, separated the sounded tone in the air into its individual component parts, performing a spectral analysis of sound.[42]

According to Mach, the ear had the same ability to perform a spectral analysis of sound. Mobilizing the same analogy as employed by Helmholtz, Mach directed his audience to imagine the undamped piano as, instead, the cortical fibers of the ear. Just as a string on the undamped piano would sound in response to a tone sounded by the other piano, so too would a single cortical fiber be thrown into vibration. The large number of cortical fibers—one per piano string—allowed for accommodation and thus an appreciation of music. A listener could, for example, pick out the melodic lines of a Bach fugue. Or she could distinguish separate tones of simultaneous impressions (*Eindrücke*), not just a harmonious chord but any combination of tones, by directing her attention.[43]

Mach elaborated on the role of attention in an individual's experience of music in "Die Erklärung der Harmonie," using the chord demonstration discussed above. An individual would hear the harmonic sequence of the two chords differently depending on which tones—the roots of the chord, which changed, or the upper tones, which remained unchanged—she directed her attention toward. The art of music composition, Mach asserted, therefore lay in guiding the listener's attention. There was also an art of hearing, he continued, which was not the gift of every person.[44] Only through extensive practice could one develop the ability to further differentiate a single tone into its fundamental tone and harmonic overtones.[45] Attention combined with the accommodation mechanism allowed the individual to distinguish harmonic overtones, which, according to Helmholtz, were the root of Western harmony. Mach's work

[40] Mach presented this example in his 1865 lecture "Die Erklärung der Harmonie," reprinted in *Zwei populäre Vorlesungen über musikalische Akustik* (Graz, 1865), 18–31, and in his article of the same year, "Bemerkungen über die Accommodation des Ohres" (cit. n. 2).

[41] According to Mach, groups of sonorous bodies behaved similarly—individual tones within the group only sounded when their particular note (*sein Eigenton*) was struck. Mach gave other illustrations of his point: a dog's response to "Phylax," his name, and utter indifference to such other heroic names as "Hercules" or "Plato," or the unified throb of two hearts in love. Mach, "Über die Cortischen Fasern des Ohres," reprinted in *Zwei populäre Vorlesungen* (cit. n. 40), 10–1.

[42] Ibid., 27.

[43] Ibid., 28.

[44] Mach, "Erklärung der Harmonie" (cit. n. 40), 37.

[45] In a clear reference to Helmholtz's work on tone sensation, Mach explained that these overtones played an important part in the formation of musical timbre as well as the consonance of sound. Mach developed a fuller, generally celebratory, discussion of Helmholtz's theories in his *Einleitung in die Helmholtz'sche Musiktheorie* (cit. n. 30).

suggested that Western musical aesthetics both shaped and were the product of the accommodation mechanism in hearing.

The pervasive use of musical examples and arguments in Mach's investigations of accommodation in hearing suggests that he made the three following assumptions: First, he assumed that music was a valid avenue through which to understand the sensation of sound because music and sound were equivalent or at least closely related. Second, he assumed that his audience was well versed in music theory and had extensive musical experience—enough to follow and be convinced by the musical passages written on the page. Third, Mach's frequent use of musical examples also assumed the validity of his audience's individual experience of music. An experience of the accommodation phenomenon could only be subjective. By attempting to root sound sensation in accommodation, Mach tied it to the attention of the individual and his or her experience. Individual attention was of course part of individual aesthetics, and specific to local time and space. It was historicist, at least for a single individual.

MACH'S HISTORICITY OF HEARING AND THE EPISTEMOLOGICAL CONSEQUENCES

Let us turn now to some of the consequences of Mach's use of music, and by association his musical aesthetics, in his studies of accommodation in hearing, and how these consequences might relate to his increasingly evolutionary worldview. Although Mach had read Darwin's *Origin of the Species* soon after its publication in 1859 and later integrated many elements of it into his theory of "economy of thought," his conception of evolution was very much rooted in Lamarckian inheritance of acquired traits, as was typical at the time. It was Lamarck's secondary law of inherited acquired traits that gained a new popularity—in isolation from his full program—during the latter half of the nineteenth century.[46] Darwinian and Lamarckian conceptions of evolution were often tangled at the end of the nineteenth century. Individuals who described themselves as Darwinians—or have since been described as Darwinians, like Herbert Spencer—frequently gave Lamarckian inheritance equal if not greater weight in their evolutionary perspectives. Mach was no different.

Further, Mach embraced Ewald Hering's work on the inheritance of memory. It was Hering's elaboration on Lamarckian inheritance to include Gustav Fechner's psychophysics that motivated Mach to expand his understanding of evolutionary inheritance to include psychological traits as well.[47] Hering argued that the inheritance of acquired traits included not only physical traits but psychical ones as well—after all, they were the same, according to Fechner.[48] Memory, Hering claimed, was an

[46] Peter Bowler explains that neo-Lamarckism was a diverse movement, varied both geographically and disciplinarily but unified by a perception of the shortcomings of the Darwinian evolutionary mechanism of natural selection. Neo-Lamarckians appreciated that the inheritance of acquired traits was directed, so that there was no issue of unfit individuals being lost in the fitness struggle. In this sense neo-Lamarckism was appealing because it was moral; organisms were not at the mercy of their environment and could retain control over their own destiny. Bowler, *Evolution: The History of an Idea*, 3rd ed. (Berkeley, Calif., 2003), 236–8.

[47] Hering presented his lecture "On Memory as a General Function of Organized Matter" before the Imperial Academy of Sciences in Vienna on 30 May 1870. Reprinted in Samuel Butler, ed., *Unconscious Memory*, 2nd ed. (New York, 1911), 80–3.

[48] In his 1860 text *Elemente der Psychophysik*, Fechner presented a monistic understanding of the world in which psychical and physical experiences were two different perspectives on the same event, two sides of the same reality. He offered the example of a circle differing depending on whether one stood inside or outside of it. According to Fechner, it was impossible, when standing on the plane of

inherited germ that was the unifying force of consciousness, powering the development of individual beings, and therefore the universal function of organized matter. This view of memory implied that "the development of one of the more highly organized animals represents a continuous series of organized recollections concerning the past development of the great chain of living forms."[49]

Mach similarly saw both physical and psychical traits as being transmitted through generations. In an 1875 article, "Bemerkung über die Function der Ohrmuschel," Mach explained how Darwin's discussion in *Descent of Man* of a statue of Puck in which he was given the pinna (the tips of the outer ear) of an animal prompted Mach to an understanding that the outer ear acted as a resonator for higher notes in humans as in animals.[50] Certainly animals gained advantage from fine determination of the direction of sound and changes of timbre—the crackle of grass or leaves—and some of the residual traces of this function likely still remained in humans for similar reasons.[51] The ability to distinguish subtle sonic differences as well as invoke organized recollections for the sake of survival persisted in the ears of listeners at the end of the nineteenth century.

Mach had combined this evolutionary understanding of sensory perception with aesthetics from very early on. In an 1867 lecture, "Why Has Man Two Eyes?" Mach first addressed the question as one of survival in which the two eyes were required for depth perception. But his discussion soon turned to a survey of the different visual aesthetic traditions of ancient cultures. Mach explained that if you "change man's eye . . . you change his conception of the world. We have observed the truth of this fact among our nearest kin, the Egyptians, the Chinese, the lake-dweller."[52] Evolving physiology—the changing of the sight organ itself—explained the variety of visual aesthetic traditions across time and place.

In 1871, while he was particularly engrossed in his search for the accommodation mechanism in hearing, Mach presented his belief that repetition of sensory stimulation was the key to "agreeableness."[53] Symmetry was the most agreeable stimulus because it conditioned repeated sensations, most noticeable in the visually pleasing effect of regular figures, especially straight vertical and horizontal lines.[54]

Continuing, Mach explained that human appreciation for symmetry was deeply rooted in the physiology of the sensory perception organ.[55] He claimed that human

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the circle, to simultaneously experience both the convex and concave sides. Fechner, *Elemente der Psychophysik*, vol. 1 (1860; repr., Amsterdam, 1864), 2–3.

[49] Hering, "On Memory as a General Function of Organized Matter" (cit. n. 47), 83.

[50] Mach, "Bemerkung über die Function der Ohrmuschel," *Archiv für Ohrenheilkunde* 9 (1875): 72–6.

[51] Ibid., 76.

[52] Mach, "Why Has Man Two Eyes?" in *Popular Scientific Lectures*, trans. Thomas McCormack (Chicago, 1898), 66–88, on 82.

[53] Mach, "Ueber die physikalische Bedeutung der Gesetze der Symmetrie," *Lotos* 21 (1871): 139–47.

[54] Attempting to locate symmetry in sound sensation, Mach performed experiments in which he played a series of moving notes and chords on a piano while looking in a mirror, then with the sheet music reflected vertically and then horizontally in the mirror. Melodies became unrecognizable and the chords, when mirrored, were reversed (the series of major key intervals, when reflected across a horizontal axis, sounded like a series of minor key intervals and vice versa). Because sound sensation was temporal, rather than spatial, like visual sensation, Mach concluded that there was no symmetry in the sonic realm other than an intellectual one in the transposition from a major to a minor key in the Western harmonic system. Ibid., 145–7.

[55] This was, Mach explained, why visual symmetry was still appreciated by those who had, for example, lost an eye. Ibid., 144.

beings' notions of beauty could very well be different if their physiology were different. With that, Mach then further asserted that conceptions of beauty could be modified by culture, "which stamps its unmistakable traces on the human body."[56] The idea of eternal beauty was thus mistaken; had not, in the recent past, all musical beauty been restricted to a five-toned scale?

So aesthetics were psychophysical. And an individual's aesthetics were subject to Hering/Lamarckian inheritance. It is likely that Mach understood this inherited knowledge to be quite broadly defined, extending to both the psychophysics of sensation and aesthetics. In an 1872 letter to Kulke, Mach asked if the people of their country could presently hear what the Greeks had heard and the Slavs still hear. And could the answer lie in attention (*Aufmerksamkeit*) only? He mused that a developmental history of melody, harmony, and rhythm would be very interesting.[57] In a later letter, Mach asked why the Germans and the Slavic people phrased their melodies differently. Kulke replied that the question was a historical one.[58] It was also, Kulke continued, an issue of aesthetics and a further application of Darwinian evolution to the arts. For both Mach and Kulke, musical aesthetics were subject to variation and inheritance, much like physiological attributes.[59]

By 1885 the discussion of the accommodation mechanism of sound sensation had all but disappeared from Mach's writings. He never did find it. But, between his psychophysical studies and his ongoing dialogue with Kulke, Mach's historicist understanding of both sound sensation and musical aesthetics was fully formed. In *Die Analyse der Empfindungen*, Mach asked how the development of modern music and the sudden appearance of great musical talent—genius, he claimed, seemingly appeared in a single generation rather than through the slow accumulation of ancestors' efforts—contributed to the survival of the species. Why did humans possess such fine discrimination of pitch, sense of intervals, and sensitivity to acoustic coloring that so far exceeded necessity or even usefulness? After all, according to Mach, music "satisfie[d] no practical need and for the most part depict[ed] nothing." He concluded that individuals developed their discriminating sensation of tone—of pitch, of harmony—much as they developed their visual ability to distinguish lines, "as a sort of collateral product of [their] training, a sense for the agreeable combination of lines."[60] By 1885, the ability to create and appreciate music was for Mach a byproduct of evolution:

> To deny the influence of pedigree on psychical dispositions would be as unreasonable as to reduce everything to it, as is done, whether from narrow-mindedness or dishonesty, by

[56] Ibid.

[57] Mach to Eduard Kulke, 30 May 1872, no. 4, Ernst Mach Papers, Dibner Library of the History of Science and Technology, Smithsonian Institute Special Collections, Washington, D.C.

[58] Eduard Kulke to Mach, 26 Oct. 1872, Ernst Mach Nachlass, Deutsches Museum Archives, Munich.

[59] Fifty years later, folklorist and composer Béla Bartók maintained a similarly imprecise but also similarly evolutionary and psychophysiological position, explaining that "peasant music is the outcome of changes wrought by a natural unconscious; it is impulsively created by a community of men who have had no schooling; it is as much a natural product as are the various forms of animal and vegetable life." Bartók, *The Hungarian Folk Song*, ed. Benjamin Suchoff, trans. M. D. Calvocoressi (Albany, N.Y., 1981), 3.

[60] Mach, *Analysis of the Sensations and the Relation of the Physical to the Psychical*, trans. C. M. Williams (New York, 1959), 307–8. Originally published as *Beiträge zur Analyse der Empfingdungen* (Jena, 1886).

> modern fanatics on the question of race. Surely everyone knows from his own experience what rich psychical acquisitions he owes to his cultural environment, to the influence of long vanished generations, and to his contemporaries. The factors of development do not suddenly become inoperative in post-embryonic life.[61]

For a while Mach viewed musical aesthetics as an alternative entry point to investigating sound sensation, because culture "stamps its unmistakable traces on the human body." This is evidenced in his decades-long use of music to explore the psychophysics of accommodation in hearing. But once he determined that sound sensation was, not just for the individual, but for the human species as a whole, historically and culturally contingent, the mechanism of accommodation in hearing became irrelevant and he ended his pursuits.

These early psychophysical investigations of sound sensation of course had philosophical consequences for Mach; namely, an increasingly phenomenological and positivist approach to the world.[62] In *Die Analyse der Empfindungen*, Mach described how the superfluity of the Kantian "thing in itself" abruptly dawned on him: "On a bright summer day in the open air, the world with my ego suddenly appeared to me as *one* coherent mass of sensations."[63] This realization fueled his belief that one should approach the world as if it were made up entirely of elements of sensation—reality, appearances, and one's self in the world all one buzzing mass. Man did not surrender as an individual into nature, but rather, was already part of it. When one conceived of the world, as Mach did, as a single coherent mass of sensations, the individual was one perspective within a complete psychophysical whole. Fechner had eliminated the causal connection between the physical and the psychical, replacing it with mathematical dependence only. With his development of psychophysical monism, Mach dispensed with Fechner's two-sided nature in favor of complete unification.

[61] Ibid., 309. In this last sentence Mach was making an oblique reference to the work of his former student, the Viennese music critic and comparative musicologist Richard Wallaschek, *Anfänge der Tonkunst* (Leipzig, 1903).

[62] A historiographical note: I have aimed to push the origins of Mach's historicism back to 1863, the year in which he first met Kulke and Kulke's dilemma, and the year in which he first began his search for the accommodation mechanism of sound sensation. Already in 1867 Mach was thinking of the sense organs as well as visual aesthetics within an evolutionary, historicist framework. Certainly by 1871 he was. If any doubt remains about the early date of 1863, it should be noted that Mach himself described his work since 1863 as "historico-physical investigations." Mach, *Analysis of the Sensations* (cit. n. 60), 30.

[63] Ibid.; translator's emphasis. The passage in the original German reads: "An einem heitern Sommertage im Freien erschien mir einmal die Welt sammt meinem Ich als eine zusammenhängende Masse von Empfindungen." Mach, *Die Analyse der Empfindungen und das Verhältnis des Physischen zum Psychischen*, 4th ed. (Jena, 1903), 24. The operative verb here, *erscheinen*, is usually translated as "to seem" or "to appear" but it can also be translated as "to strike." All of these suggest an inseparability of nature and the experiences of the mind that likely sounds familiar to scholars of pragmatism and William James's radical empiricism. Indeed, James and Mach had known each other since the 1870s, corresponded extensively, and pored over each other's work. Historian Gerald Horton has carefully documented the extent of the two men's intellectual exchange, emphasizing the significant impression Mach's writings made on James. Judith Ryan has further argued that it was the 1886 edition of Mach's *Analyse der Empfindungen* that was the missing intellectual link between the evolving versions (the 1884 manuscript versus the 1890 chapter in *Principles of Psychology*) of James's essay "The Stream of Thought." Horton, "Ernst Mach and the Fortunes of Positivism in America," *Isis* 83, no. 1 (1992): 27–60; Ryan, "American Pragmatism, Viennese Psychology," *Raritan* 8 (1989): 45–55.

MAX PLANCK'S ACCOMMODATION EXPERIMENTS

Mach might have been the first to admit that these phenomenological consequences of his psychophysical work were not inevitable. A study of accommodation in hearing did not necessarily a positivist make. Let us turn now to the accommodation study of the Berlin physicist Max Planck.[64] To be sure, Planck's investigation was not nearly as extensive as Mach's, nor did Planck actively place himself at the intersection of the music and natural science worlds. But he was no less steeped in a rich world of music. He played several instruments and was a frequent concert attendee. Planck was also well versed in the sound-sensation writings of his Berlin colleagues Hermann von Helmholtz and Carl Stumpf. And—connecting additional threads between music and experimental studies of sound sensation—Planck attended several evenings of music at the Helmholtz household, where he heard the violinist Joseph Joachim perform his *Hungarian Dances* as well as Marianne Brandt and Rudolf Oberhauser sing selections from Wagner's *Walküre*.[65]

Soon after Planck's assignment to the Berlin Institute for Theoretical Physics in the early 1890s, the institute received a large harmonium designed by Carl Eitz, built for the Prussian state government by the Schiedmayer piano factory in Stuttgart. Eitz, originally from Halberstadt, taught primary school in Eisbaden until his retirement in 1911, but was better known as a music pedagogue and acoustician.[66] Halberstadt's most famous musical resident at this time was the town organ, completed by organ builder Nicholas Faber in 1361. The third manual of the Halberstadt organ contained the earliest form of a keyboard of seven keys in succession within which an additional five were arranged in groups of three and two—the arrangement predominantly seen on keyboard instruments today. Harry Partch would later describe the Halberstadt organ as the apple in Eden.[67] Eitz developed various scientific instruments, including an apparatus that rendered sound waves visible, as well as a number of musical instruments. Of these, most notable was a harmonium with 104 pure tones per octave. He developed a *Tonwort* solmization method for training students to sing according to just intonation, which was later implemented in the Bavarian school system.[68] An early exploration of quarter tones, the system employed 31 separate syllabic note names for each diatonic, chromatic, and enharmonic degree of the untempered scale. He later further extended this system to support the harmonium that had been developed two decades earlier by R. H. M. Bosanquet, with 53 mathematically pure tones per octave.[69]

[64] Planck is best known for his research on black-body radiation in which he extended the principles of mechanics (employing Ludwig Boltzmann's definition of entropy in a gas) to radiation, in turn establishing some of the initial groundwork for quantum physics.

[65] Planck, "Persönliche Erinnerungen aus alten Zeiten," in *Vorträge und Erinnerungen von Max Planck*, 5th ed. (Stuttgart, 1949), 7.

[66] Halberstadt is currently home to the ASLSP/John-Cage-Orgel-Kunst-Projekt in which, beginning in 2000, John Cage's piece "As Slow as Possible" is being performed very slowly over 639 years in the church of St. Burchardi.

[67] Partch, *Genesis of a Music* (cit. n. 3), 373–4. Partch also, incidentally, mentioned Eitz's harmonium (ibid., 438).

[68] Eitz, *Das mathematisch-reine Tonsystem* (Leipzig, 1891).

[69] Bosanquet's "generalized keyboard harmonium" was first presented at the Musical Association in London in May of 1875. *Grove Music Online*, s.v. "Eitz method," by Bernarr Rainbow, 15 Oct. 2011, http://www.oxfordmusiconline.com/.

Planck was tasked with examining the Eitz harmonium's untempered scale. Eitz's instrument consisted of four and a half octaves, beginning with F and ending with the C three octaves above. Each octave contained 104 tones (the keyboard familiar to most readers has 13 tones per octave). Planck published a summary of this investigation in 1893, "Ein neues Harmonium in natürlicher Stimmung nach dem System C. Eitz," noting that the instrument was relatively easy to play with a little practice.[70]

In the course of studying Eitz's instrument Planck became quite interested in the role of the untempered, "natural" scale in modern, unaccompanied vocal music. He tested both himself as well as a number of vocalists and players of string instruments (instruments without fixed tuning systems), comparing aesthetic impressions of both tempered and untempered scales, with the goal of determining the extent to which the untempered scale played any practical role in contemporary music making. Planck claimed to find, somewhat to his surprise, that the tempered scale was far more pleasing. Continuing, he explained that even in the harmonic major triad, the natural third sounded feeble and inexpressive when compared with the tempered third.[71] He ascribed this unanticipated preference for tempered tuning "to a habituation through years and generations," because "before J. S. Bach, the tempered scale had not been universally known at all."[72]

In his 1893 article "Die natürliche Stimmung in der modernen Vokalmusik," published in the musicology journal *Vierteljahrsschrift für Musikwissenschaft*, Planck argued that accommodation in hearing may very well have been at the root of this preference for temperament.[73] He explained that the relaxed, inattentive ear, hearing a major triad in which the third was pure but the fifth was slightly tempered, would have the impression of consonance. Only with proper and careful attention would the listener determine the fifth to be tempered. Planck explained that even the early nineteenth-century acoustician Ernst Friedrich Florens Chladni had noted something similar, that an interval only ever so slightly off from pure could be heard as pure.[74]

So Planck believed that accommodation in hearing did not simply bring out the tones focused on more distinctly, but actually altered the impression of their tuning. Accommodation for Planck meant that the listener heard different sounds. Taking Mach's chord example from the beginning of this article, if the demonstration had been performed on an equal-tempered piano, the listener, when instructed to simply listen to the chords (the first time the progression was played), would have, according to Planck, heard them as just tuned. The second and third times through the chord progression, when asked to focus his or her attention on the high and low pitches, the listener would have heard the chords as equal-tempered. Perhaps we can borrow the nineteenth-century distinction that listening was active and hearing was passive for

[70] The 104 tones are determined by the formula $2^p 3^q 5^r$, if p, q, and r are close for any positive or negative integers or zero sets. The syntonic comma (81:80), the Pythagorean comma (approximately 74:73), and the schism (about 887:886) can be given on the instrument by an interval that is still too large by about 301:300, almost the natural seventh (7:4). Planck, "Ein neues Harmonium in natürlicher Stimmung nach dem System C. Eitz," *Fortschritte der Physik* 49 (1895): 557–8.

[71] Planck, *Max Planck: Vorträge, Reden, Erinnerungen* (Berlin, 2001), 61.

[72] Ibid.; translation mine.

[73] Planck, "Die natürliche Stimmung in der modernen Vokalmusik," *Vierteljahrsschrift für Musikwissenschaft* 9 (1893): 418–40. The article was republished the following year as a pamphlet by Breitkopf and Härtel (Leipzig). I must extend a special thank-you to Erwin Hiebert for bringing this article to my attention nearly a decade ago upon hearing of my interest in Mach's studies of accommodation.

[74] Ibid., 422.

further clarification: for Planck, listeners listened in natural tuning and heard in equal temperament.

Planck's understanding of accommodation—that it altered the sound heard—bore similarities to what Stumpf termed "music consciousness" (*Musikbewusstsein*). Highly skilled, musically trained listeners, Stumpf explained, would hear impure intervals as pure out of musical habit, biased by their music consciousness.[75] Helmholtz had previously made a similar claim, though about the sound generated by highly skilled musicians rather than the sound heard.[76] Helmholtz argued that pure intervals, with their coincident overtones, were heard as more consonant and that this was the reason that the very best musicians naturally migrated to pure intervals. He also saw this as further evidence of the superiority of untempered tuning systems (the natural tuning Planck referred to).

Planck, thirty years later, to his admitted surprise, found the opposite: both listeners and musicians migrated to tempered intervals.[77] Now, Planck did not link this accommodative ability to musical skill. In fact, he thought that it was for the most part involuntary.[78] Explaining that a sustained sounded interval would, over time, become smaller, smoother, and softer, with a correlated sense of decreasing tension, Planck implied that the phenomenon was psychophysical.[79] It was not, however, a timeless effect. Planck explained that the fact that temperament was the aural resting state (that focus and accommodation were required to hear pure, natural intervals, which would then slip back to tempered intervals when the listener relaxed) showed the "habituation of our ear to tempered tuning" as a consequence of its predominance.[80]

Planck suspected that this phenomenon of accommodation in hearing—and the corresponding phenomenon in which individuals would, when relaxed and unfocused, hear in tempered tuning—was linked to various effects in Western musical composition. It contributed, he believed, to the power of the leading tone, the fermata, and the compositional return to the tonic key, all of which were dependent on the subtle and sustained aftereffects created by the habituation of a listener constantly exposed to equal temperament.[81] Accommodation amplified musical aesthetics.

In pursuit of experimental support of this theory beyond studies of his own ear with the Eitz harmonium, Planck took advantage of the abundance of musical groups in

[75] Stumpf introduced this concept (he also used the term "music-infected consciousness"—*musik-infizierten Bewusstsein*) in the course of a fierce debate in the early 1890s with Wilhelm Wundt and Wundt's student Carl Lorenz over tone-differentiation data collected by Lorenz from both musically trained and musically untrained experimental subjects. See Alexandra Hui, "The Bias of Music Consciousness: The Aesthetics of Listening, in the Laboratory and on the City Streets of Fin-de-Siècle Berlin and Vienna," *Journal for the History of the Behavioral Sciences* 28, no. 3 (2012): 236–50.

[76] According to Helmholtz, it was impossible to detect "any false consonances" in the music performed by the very best instrumentalists (on bowed and wind instruments, where the intonation can be controlled by the players themselves) because they naturally played in just intonation and they "know how to stop the tones they want to hear, and hence do not submit to the rules of an imperfect school." Hermann von Helmholtz, *On the Sensations of Tone as a Physiological Basis for the Theory of Music*, 4th ed., trans. from the 4th German ed. (London, 1877), 324–5.

[77] Samples of the passages Planck tested, in both equal temperament and just intonation, can be heard in audio 2 (300KB; MP3) and audio 3 (300KB; MP3) in the electronic version of this article. Both samples were recorded by Peter Pesic using Finale music-notation software, Santa Fe, N.M., 2012. Special thanks to Alexei Pesic and William Sethares.

[78] Planck, "Natürliche Stimmung in der modernen Vokalmusik" (cit. n. 73), 423.

[79] Ibid., 424, 431–2.

[80] Ibid., 425.

[81] Ibid., 425–6.

Berlin. His studies of various a cappella choirs arrived at similar conclusions: with only a few exceptions, singing was unambiguously tempered.[82] He asked the choirs to perform a series of sequences of sustained chords that would sound distinctly different when sung in natural tuning, with pure intervals, than when sung tempered. Even the very best choirs slid into tempered tuning and could only sustain pure intervals with repeated practice and focused attention. Modern vocal music, Planck concluded, was performed almost without exception in tempered form. This sliding was, of course, not due to poor singing or laziness but to instinct buttressed by accommodation.[83]

PLANCK'S HISTORICITY OF HEARING AND THE EPISTEMOLOGICAL CONSEQUENCES

So, was Helmholtz wrong? Did the musically trained passively hear and generate tempered intervals rather than pure ones? Planck made no attempt to explain his contradictory findings other than to note his astonishment. And also to suggest that perhaps accommodation in hearing was similar to other stimuli that affect sensory perception, and correspondingly, aesthetics, in subtle ways.[84] Helmholtz had performed his *Tonempfindungen* research three decades prior. Perhaps the Berliners' ears had changed.[85]

Indeed, the implication of Planck's conclusions was that the hearing organ was remarkably sensitive and malleable. Though tempered tuning had only recently been introduced on a large scale, Planck's studies of accommodation in hearing suggested that, unless pushed to do otherwise, not only did listeners hear tempered intervals but musicians generated tempered intervals. Through habituation, Berliners' ears (or at least Planck's and those of members of the Royal College of Music) had become accustomed to both creating and receiving tempered tones in only a few generations—a very Lamarckian time scale.

It is worth noting that Planck did not mobilize his findings toward a discussion of Western musical aesthetics. He ventured that tempered hearing and accommodation might explain the power of some musical features, but he stopped there. Certainly Planck did not, as Helmholtz did, see and lament the expansion of equal temperament as the harbinger of poorly performed and poorly composed music.

Let us now attempt to situate Planck's concept of sound sensation within his broader understanding of the world. Planck had understood his task as a scientist, from the very beginning of his career, to be the pursuit of a unified conception of all the forces of nature. The interconnection of laws of mechanics, conservation, least action, quantum physics, and relativity drew on more general Wilhelmian values em-

[82] He worked mostly with the Royal College of Music in Berlin, under the direction of Adolf Schulze. Ibid., 430–1.

[83] Ibid., 434–7, 439–40.

[84] Ibid., 430.

[85] One could also point here to Stumpf's *Musikbewusstsein* debate with Wundt and his student Lorenz. Stumpf argued that the musically trained overwhelmingly heard pure intervals, in contrast to the untrained—essentially the exact opposite findings from Planck. If Stumpf's claims were based only on Lorenz's data, then perhaps the Leipzig musicians heard differently from the vocalists of Berlin that Planck worked with. If Stumpf's claims were, however, rooted in some of his earlier *Tonpsychologie* research in Berlin, then he and Planck may very well have employed the same musicians.

phasizing an ideal of unity among political, cultural, and intellectual life.[86] At the beginning of the twentieth century, Planck began to articulate an epistemological framework made up of no less than three worlds: the world of the human senses, the real world, and the world of physics. This latter world, because it was advanced by the finite human mind, was subject to change in relation to the other two worlds.

The world of physics sought to determine the laws connecting the world of sense with the real world. Planck described a historicity in this program, explaining that depending on the stability of physics at a particular time, one worldview would dominate.[87] There had been overall, however, a steady march of the physics world toward the real world. As the world of physics had moved away from the world of sense, according to Planck, it had lost much of its former anthropomorphic character and become progressively more abstract.[88] Planck advocated an ultimate—though admittedly unattainable—dual goal of complete domination of the world of sense and total understanding of the real world by physics. It was therefore the duty of scientists to continue to purge all anthropomorphic elements and no longer admit "any concepts based in any way upon human mensuration."[89]

Planck's conception of sound sensation fit into this widening space between the world of physics and the sense world based on human mensuration. For one, this increasing distance reinforced Planck's framework by revealing the deceptiveness of the senses—a single listener could hear the same interval differently depending on her use of accommodation, and a vocalist could only maintain a pure interval with careful and sustained concentration. In his 1908 Leiden lecture "Die Einheit des physikalischen Weltbildes" (The unity of the physical universe), when surveying the progress of physics away from the sense world, Planck explained that the fields of physical acoustics, optics, and thermodynamics had all eliminated their dependence on the immediate perceptions of the senses.[90] Though accommodation in hearing could, with effort, overcome the tempered hearing acquired through habitual exposure to the recent explosion of equal temperament, the use of frequency and wavelength to measure sound waves eliminated the human element and was certainly more reliable.[91]

Further, the implication of Planck's studies of accommodation among vocalists underscored his position that the sense world and the real world were indeed separate. If passive hearing could shift significantly in just a few generations due to material and aesthetic shifts in the music world with the spread of equal temperament

[86] John Heilbron, *The Dilemmas of an Upright Man: Max Planck and the Fortunes of German Science* (Berkeley, Calif., 1996), 4.

[87] Planck offered the examples of the second half of the nineteenth century, during which the physical world was very stable and many believed that a complete understanding of the real world was within reach, and conversely, the interwar period, a time of change and instability in physics, when many turned to positivism. Planck, *Das Weltbild der neuen Physik* (Leipzig, 1931), trans. W. H. Johnston as *The Universe in the Light of Modern Physics*, 2nd ed. (London, 1937), 12–3.

[88] Planck, *Universe in the Light of Modern Physics* (cit. n. 87), 14–5.

[89] Ibid., 49.

[90] Planck, "Die Einheit des physikalischen Weltbildes" (lecture, University of Leiden, 9 Dec. 1908), trans. R. Jones and D. H. Williams as "The Unity of the Physical Universe," in *A Survey of Physical Theory: Max Planck* (London, 1993), 1–25.

[91] Such sentiments and efforts to eliminate human judgment from acoustics continued through the twentieth century, as seen in the rebuffing of Sheridan Speeth's psychoacoustic approach to international nuclear arms control, discussed by Axel Volmar in this volume.

(that is, very much as a result of human activity), and yet a listener could, with accommodation, toggle between tuning systems in her sensory perception of sound, certainly the sense world and the real world were not one and the same. For Planck, physicists could know more than just the world of direct experience. This conception of physics as oscillating between the worlds of sense and reality but also asymptotically approaching unity with the real world is a rather delightful solution that allowed Planck room to historicize scientific thought while maintaining an antipositivist stance.

Much has been written by historians of science on the epistemological clash between Planck and Mach, and going into too much detail here would distract from the larger points of this article.[92] It should be noted, though, that Planck was deeply disturbed by the popularity of Mach's phenomenology and believed it to be a threat to exact science. Mach's system, according to Planck, was not science and "evade[d] the most convenient criterion of all scientific research—the finding of a *fixed* world picture independent of the variation of time and people." The goal of science, Planck continued, was not the adaptation of our ideas to our perceptions, but rather, "the complete liberation of the physical picture from the individuality of the separate intellects."[93] Planck attacked Mach's phenomenology as misguided self-alienation when applied to the sciences and ended his 1908 Leiden lecture by decrying Mach as a false prophet.

CONCLUSION

I would like to conclude with a brief discussion of the work of Harry Partch, the early twentieth-century American composer and musical-instrument maker, perhaps best known for his monophonic system based on a forty-three-note octave. To perform his monophonic pieces, he built the Ptolemy harmonium.[94] In contrast to Bosanquet's or Eitz's harmonium (he mentioned Bosanquet's in his 1949 text *Genesis of a Music*), which were built as acoustic and music-theoretical instruments, Partch explained that his harmonium was built for a composer and his musical creations. Extending the aspirations of Arnold Schönberg, Alexander Scriabin, and Henry Cowell to expand the triad basis of tonality, Partch's Ptolemy ended the double tyranny of temperament and the diatonic scale.[95]

I include Partch here for two reasons. First, as the earliest composer to seriously

[92] The most thorough treatment is Heilbron's *Dilemmas of an Upright Man* (cit. n. 86), but see also Lawrence Badash, "The Completeness of Nineteenth-Century Science," *Isis* 63, no. 1 (1972): 48–58; John Blackmore, "Ernst Mach Leaves 'The Church of Physics,'" *British Journal for the Philosophy of Science* 40, no. 4 (1989): 519–40; Steve Fuller, "Retrieving the Point of the Realism-Instrumentalism Debate," *Proceedings of the Biennial Meeting of the Philosophy of Science Association* 1994, vol. 1: *Contributed Papers*, 200–8; Nadia Robotti and Massimiliano Badino, "Max Planck and the 'Constants of Nature,'" *Annals of Science* 58 (2001): 137–62; and Richard Staley, "On the Co-creation of Classical and Modern Physics," *Isis* 96, no. 4 (2005): 530–58.

[93] Planck, "Unity of the Physical Universe" (cit. n. 90), 38–9.

[94] Partch explained that whereas the basis of tonality in the contemporary music system was the triad chord (composed of a fundament, the third, and the fifth interval), his monophonic system continued past the fifth through the eleventh overtone in fourteen of its tonalities and through the ninth overtone in the other ten. Partch, "A New Instrument," in *Enclosure 3: Harry Partch*, ed. Philip Blackburn (St. Paul, Minn., 1997), 49. The article was originally published in *Musical Opinion* (1935): 764–5.

[95] Ibid.

pursue microtonal music, right down to the development of his own microtonal musical instruments, Partch drew on the psychophysical studies of sound sensation of the nineteenth century. Indeed, he described his discovery of an English translation of Helmholtz's *Tonempfindungen* at the Sacramento public library as "the key for which I had been searching."[96] Helmholtz's discussion of the various tuning systems of Western music encouraged Partch to abandon equal temperament.

I also see Partch as a resolution of the contrasts between Planck and Mach. His realization of the historicity of tuning systems liberated him to develop both a new tuning system and new instruments with which to perform music composed in this new system. As a consequence his music sounded new; for most of us, a piece composed in the forty-three-tone scale will include tones and intervals never before heard. One could say that Partch wanted to break the habituation to tempered tuning discovered by Planck. His criticism of musicological training and pedagogy was that it rehashed old compositional styles, techniques, and sounds. Recall Planck's assertion that listeners' ears must have changed through habituation over time to hear—when unaccommodated—tempered rather than pure intervals because "before J. S. Bach, the tempered scale had not been at all universally known." Partch quipped in response: "There is, thank God, a large segment of our population that never heard of J. S. Bach."[97]

In the early 1920s, Partch had become increasingly dissatisfied with the limits of traditional music training. In particular, he was troubled by the emphasis on technique and skill in playing an instrument and, correspondingly, the belief that polished technique was the equivalent to good performing. Further, Partch was frustrated by the popular assumption that the present represented progress in comparison to the past. By 1928 he had drafted his monophonic principles, which were based on his belief that the individual's spoken words were the most potent and intimate tonal ingredients available and therefore "the juice of a given identity in the tonal world."[98]

Following his intuitive break with the aesthetic expectations of the Western tonal system, Partch then set about justifying his innovative sounds through critical and historical analysis. In *Genesis of a Music: An Account of a Creative Work, Its Roots, and Its Fulfillments*, he documented four thousand years of music history in terms of a shift, with noteworthy exceptions, away from "instinctive Corporeal attitudes" to "an Abstract character."[99] The antiphonal singing that replaced the Chinese and Greek chant traditions liberated music from language and forced the listener to think of music itself as conveying meaning. By the eighteenth century, music had transcended language, space, moment, and the human body (musical morality in fact denied the human body) as the mass expression of pure form. Certainly there were

[96] Quoted in Jules Joseph, "Harry Partch Uses 43 Tone Scale to Preserve Natural Word Rhythm," *University of Wisconsin–Madison Daily Cardinal*, 30 Jan. 1945. Cited in Bob Gilmore, *Harry Partch: A Biography* (New Haven, Conn., 1998), 48.

[97] Partch, *Enclosure 3* (cit. n. 94), 93.

[98] Partch, *Genesis of a Music* (cit. n. 3), 5–6, quotation on 7.

[99] Partch offered sung or chanted stories, poems recited or intoned, early seventeenth-century Florentine dramas, and music intended for dances in which a story or situation is described as examples of corporeality. Abstract character could be seen in such musical forms as "songs with words that are intended not to convey meaning but simply to set the mood of the music; songs or dramas with words that do not convey meaning because of the style of composition; . . . all purely instrumental music." Ibid., 9.

recent exceptions—Modest Mussorgsky, Arnold Schönberg—but for the most part, contemporary conductors, performers, and composers were all conditioned by the "steam-pressure exploitation of mediocrity."[100]

Not that Partch wanted to return to an ancient corporeal music. Certainly the phrases of the past were not timeless in their meaning, or they would be abstractions. Partch's monophonic music was instead a new individual expression. But it was also "frankly and extremely Corporeal," seeking the intimacy of one voice and one instrument.[101] Monophonic music was liberated from the shackles of habituation and conditioning through its explicit prioritization of the individual's expression and experience of sound. It had meaning (if only to the individual) precisely because it was so firmly subjective.

* * *

One of the larger goals of this article has been to examine why and how music was appropriated for psychophysical studies of sound sensation and the consequences of this appropriation. I have shown that for Mach, deeply steeped in the music world, the use of music and musical instruments in his search for the mechanism of accommodation in hearing was a natural and uncomplicated impulse. Planck studied an a cappella choir to resolve questions raised by what had begun as an investigation of the acoustics of microtones. Both men turned to music to better understand psychophysical phenomena without hesitation or self-conscious defense.

The use of music to explore psychophysical phenomena required both men to accept the validity of individual, subjective experiences of sound. Or, when sound was music, to accept the validity of individual, subjective musical tastes. This they also appeared to do without hesitation, indicating a confidence in their own musical tastes—a further indication of their comfort in the world of music.

Both Mach and Planck were unsuccessful in achieving their initial respective goals of locating the accommodation mechanism and establishing the root of natural tuning in modern vocal music. Instead they were only able to reconcile the subjective experience of accommodation in hearing with more universal claims about musical aesthetics by conceiving of hearing itself as changeable, historical. If an individual's experience of sound was psychophysically bound to the individual's musical milieu, then not only were her musical tastes changeable but so were her ears. It was precisely at this time that Western musical aesthetics were also changing radically. The sonic upheaval fueled by changing tuning systems and the introduction of non-Western music reinforced Mach's and Planck's shared belief in the historicity of hearing.

The central role of subjectivity in accommodation in hearing revealed by both Mach's and Planck's studies buttressed and, in Mach's case, directly contributed to their opposing epistemological positions. Mach was eventually able to reconcile psychophysical laws of sound sensation with historically and culturally contingent musical aesthetics by rejecting the universality of sound-sensation processes and coming to the belief that hearing itself was historical.

Planck's work on accommodation, though far less extensive than Mach's, also essentially came to the conclusion that hearing was historical. For Planck, the ear

[100] Ibid., 60.
[101] Ibid., 61.

could, through habitual exposure, begin to hear in different tuning systems. And yet they mobilized their findings to different ends: Mach to show that knowledge itself was historical and that the only reality was that indicated by sensations; Planck to argue that knowledge was only exact and valuable when it moved away from the world of sensation toward a separate reality.

Partch presents a third path. His monophonic music unified the subjectivity of creating sound with the subjectivity of sensing sound. For Partch, music was not the means of finding answers to psychophysical questions. Music was the answer.