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Ernst Mach's Piano and the Making of a Psychophysical Imaginarium

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> . . . we have to complete observed facts by analogy.
>
> —Mach (1886, p. 13)

In the summer of 2018, I revisited Professor Mach. It had been over a decade since I'd made my way up the wide stairs and down the halls of the Deutsches Museum in Munich to the light-filled reading room of the museum's archives. This time, I passed Hermann von Helmholtz's Steinway piano on the stair landing. The archives had also acquired more of Ernst Mach's unpublished writings. I was eager to examine these, and I found re-engaging with the materials I had studied so carefully before to be something like visiting an old friend. Here were Mach's careful drawings of the inner ear bones. There was his quickly jotted recipe for risotto Milanese.

In the ten years since I had completed that project on nineteenth-century psychoacoustics and music, the history of science scholarship has crystallised its engagement with how things, phenomena, and concepts become objects of enquiry. Scholars frame this as how scientific objects come into being (Rheinberger and Fruton 1997; Daston 2000; Landecker 2007). In my own research, I'm interested in the phenomena that occur prior to the scientist's engagement with objects of enquiry. That is, I'm curious about the sensory perceptual processes that in turn frame the scientist's approach to and eventual understanding of scientific objects. The investigative object's coming into being is the culmination of an earlier crystallisation of the investigator's individual sensory perceptual framework.

I begin with the assumption that hearing is historical. That is, not only have sounds changed over time, but how individuals have heard them, what elements they found to be meaningful, and so on, have also changed over time. From there, we can begin to think about how the scientific ideas about hearing are both a clue to their developers' – the scientists' – own hearing and how they also altered their ways of hearing. I think we can presume – or at least I do – that, for the scientists, the process of studying sound and the sensory perception of it not only created new knowledge, but also altered the scientists' very perceptual frameworks. They altered their own bodies. Then, as

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they conveyed their scientific ideas, assumptions, and practices, the scientists made similar sensory perceptual frameworks possible in those around them and after them. Indeed, it was Mach that initially drew me to psychoacoustics. It was Mach's writings that first and firmly cemented my understanding of the profound implications of such a psychophysical world view for the practice of science, both as an individual and as a species. In this chapter, I document how Mach solidified his early interest in psychophysics, expanded its principles both as an experimental instrument and as a philosophical world view, and mobilised a very specific understanding of psychophysical parallelism and analogies to develop new ideas and articulate them to others.

A Psychophysical Imaginarium

Most generally, we understand an imaginarium to be a (not necessarily physical) space dedicated to the cultivation of ideas. Mach's psychophysical imaginarium was such a space in a layered, threefold way. It was, from the 1860s onward, an experimental programme. It was also, by the 1880s, a monistic world view that framed his thinking about scientific questions (to be potentially answered through psychophysical study). And finally, Mach's psychophysical imaginarium was a stage in a longer, evolutionary arc of humanity's understanding of the world. Mach toggled between these uses of his psychophysical imaginarium as needed to creative and fruitful ends. He also developed techniques to facilitate parallel imaginaria in others, such as readers and lecture audiences.

Mach began his 1863 *Vorträge über Psychophysik* with a swan dive into the ongoing preoccupation of the scientific community with experimental and representational precision (Holmes and Olesko 1995). The concern, among the sciences outside physics especially, was articulating the messiness of life processes as general, mathematical laws. Mach suggested, however, that fussing over which sciences were inherently exact and which were not was wrongheaded. The distinction could only be made during developmental stages, implying that all sciences worked towards exactitude and universality. Indeed, he claimed, psychology (the science of psychical phenomena) as well as psychophysics (the science of the interrelation of physical and psychical phenomena) were well on their way to becoming fully exact doctrines. To illustrate as much, Mach devoted the three lectures of *Vorträge über Psychophysik* to the history and current research of psychophysics, framed most fundamentally as a tension between individual sensory experiences and universal laws (Mach 1863, pp. 4–5).[1]

[1] Tellingly, Mach made the provocative claim here that physics was nothing more than applied mechanics and linked the observations of astronomers to Adolphe Quetelet's statistical distribution of individual difference.

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Let's return to Mach's understanding of psychophysics. In the third and longest lecture in his 1863 *Vorträge über Psychophysik*, Mach defined the task of psychophysics to be the determination of the exact relationship between physical stimulus and psychical sensation by means of experience, observation, and experiment (Mach 1863, p. 12). The measurement of the stimulus was straightforwardly mechanical. The measurement of the sensation was, Mach continued, more difficult. But it had been done by others in the form of just-noticeable-difference measurements, most notably by his friends and colleagues Ernst Heinrich Weber and Gustav Fechner. In the 1830s and 1840s, Weber had performed a series of experiments on the sensation of touch, incrementally changing the difference between weights placed, while visually obscured by a piece of cardboard, in an experimental subject's hands, documenting whether the subject correctly noticed the difference (Weber 1834, 1846). He performed a similar set of experiments with temperature difference, as well as measurements of the variation in touch sensitivity across the body.

Fechner had struggled through these decades to reconcile his extreme empiricism with his phenomenalism (Heidelberger 2004, pp. 73–74). He was critical of strictly materialist science as too reductive, limited to an individual's own consciousness (Fechner 1851, pp. 1–14, 289–293). He instead proposed a system in which individual consciousness was connected to an immortal, all-knowing consciousness. What he termed 'day view' (*die Tagesansicht*) science consisted of a direct realism in which physical appearances existed objectively but were also interconnected with a higher consciousness (Fechner 1879/1994). In this world, physical and psychical experiences were merely two different perspectives of the same event, both of which were real. In October of 1850, Fechner was struck with what he described as an epiphany that Weber's experiments on touch sensitivity demonstrated what he had suspected was a correspondence between an arithmetic series of psychical intensities and a geometrical series of physical intensities. In his two-part 1860 publication *Elemente der Psychophysik*, Fechner presented this psychophysical monism in mathematical form, now called the Fechner–Weber law. The stimulus x was related to the sensation y as follows: $y = a\log(x/b)$, where a and b were constants (Fechner 1860b, p. 13). This was not necessarily a resolution to the mind–body problem, so much as a treatment of the functional relationship between the psychical and the physical.

After deriving it, Mach explained that Fechner's mathematical expression could be applied to measure a variety of sensory experiences (Mach 1863, p. 17). Mach briefly described several examples, ranging from light intensity to the sensation of tone pitch to the sense of time, as well as some subsidiary principles of Fechner's law. He then devoted the remainder of the discussion to exploring the psychophysical differences between the eye and ear. Initially, Mach believed these would be similar, parallel sensory organs. Turning to the recent work of Fechner, Helmholtz, and Wilhelm Wundt, it became clear that

while both adhered to the Fechner–Weber law, the organs functioned quite differently to perceive light, colour, space, pitch, and volume. Mach appears to have especially admired that Fechner was able to carry out all of his psychophysical examinations without making any assumptions about the nature of the psychical nor the actual processes that connected stimulus and sensation. He was able to, Mach implied, stick to the 'facts of experience' (*Thatsachen der Erfahrung*), and so precision and therefore progress in science carried on (Mach 1863, p. 39).

Mach then asked, if the physical and psychical were so closely related, how should one think about their connection? Fechner understood physical stimulation and psychical sensation to be two different points of view regarding the same experience. Perhaps, Mach continued, this parallelism explains how the observer of a brain sees an event as an electric current, but for the owner of the brain, an event is the colour green (Mach 1863, p. 40). As Fechner described, the view of a sphere changes whether one is on the convex outside or concave inside. Mach found this to be a tidy way to cope with conflicting appearances/observations, such as wave versus particle explanations for the dispersal of light. From here, Mach pivoted to attack the conception of atoms generally. He pointed out that physicists found it quite difficult to imagine atoms – as they were then understood – as centres of force. What, other than nothing, could be at the centre? And what did it mean for one centre of force to be acting on another? 'Let us confess it!' Mach continued, 'nothing of the externality of the atom' could be reasonably extracted (Mach 1863, p. 41).[2] This is Mach's earliest articulated phenomenalist, anti-atomist position.[3] It was a direct consequence of his initial engagement with psychophysics.

For Mach, the psychophysical framework was the only way for the sciences of physics, physiology, and psychology to progress, for they were inextricably connected. Furthermore, psychophysics meant that exact research did not need to be abandoned as one ventured beyond the 'realm of the plainly sensible' (*das Gebiet des Handgreiflichen*). This must in part explain his immediate enthusiasm for Fechner's work.[4] Mach later described this period

[2] '*Auch Physiker haben schon die Schwierigkeit gefühlt, sich die Atome materiell vorzustellen, und einige betrachten daher die Atome als blosse Kraftcentra. Doch ist ein Kraftcentrum für sich eigentlich nichts. Und was heisst es wohl, wenn man sagt, ein Kraftcentrum wirke auf ein anderes? Gestehen wir es kurz! Wir können dem Atom vernünftiger Weise keinerlei Aussenseite abgewinnen, sollen wir aber überhaupt etwas denken, so müssen wir demselben eine Innenseite beilegen, eine Innerlichkeit einigermassen analog unserer eigene Seele*' (Mach 1863, p. 41).

[3] Other scholars have traced Mach's engagement with atomism to his 1896 *Die Prinzipien der Wärmelehre historische-kritisch entwickelt* (Brush 1968).

[4] Fechner completed the first volume of *Elemente der Psychophysik* at the end of 1859 and the second volume during the following summer. Mach's lectures embracing and elaborating on the philosophical implications of a psychophysical world view dated to 1863.

as one during which his views were quite unstable. He described how, as a teenager, he was struck by the superfluity of the Kantian 'thing in itself', and soon after, on a bright summer day, he became aware of the world, his own ego/soul included, appearing as a single shimmering, coherent mass of sensations. For Mach's own research in the 1860s, 'alternating study of the physics and physiology of the senses, and through historico-physical studies', a psychophysical approach was the only way forward (Mach 1886, p. 21).[5] Two decades later, in his *Beiträge zum Analyse der Empfindungen*, Mach defended his past approach, explaining that he sought only to adopt a point of view in physics that was consistent across other domains of science.[6]

He had by then, however, developed his own, more specialised guiding principle for the study of the sensations: the *principle of the complete parallelism of the psychical and physical* (Mach 1886, p. 28). Between 1860 and 1880, Mach moved past Fechner's conception that the psychical and physical were two sides of the same reality – the inside and outside of a sphere. For Mach, this shared reality was predicated on a duality, whereas his view was one of unity (Mach 1891). He jettisoned the distinction 'between things and sensations, between outer and inner, between the material and spiritual world' (Mach 1886, p. 12). The world could instead be understood, Mach explained, to be made up entirely of elements, such as colours, sounds, and pressures. These elements could be described functionally as sensations or as physical properties, but scientific study had to break out of habitual stereotyped conceptions of a dualistic world. Mach offered his readers an illustration of the psychophysical experience/observation of himself observing across sensory modalities from different points of view and circumstance (Figure 1.1).

Admittedly, moving across the false borders dividing the psychical from the physical became more difficult when observing individuals other than oneself or non-humans or the influence of one's own body on one's sensations. Here, Mach explained that observed facts 'must be supplemented by analogy' (*eine beobachtete Thatsache durch Analogie ergänzen*) (Mach 1886, p. 13).[7] If psychophysics was the experimental programme best suited to exploring Mach's monistic understanding of the world, analogy was one of the critical tools for the practice of psychophysics. Despite their status as not observed

[5] He had just completed an examination of the controversy between Christian Doppler and Joseph Petzval and was able to demonstrate the effect of changed colour or tone as the observer changes position in relation to the source of the wave (Mach 1861).

[6] Atomism did not, he emphasised, meet this requirement – not in 1863, nor in 1886 (Mach 1886, p. 21).

[7] Mach had several different understandings of analogy. Some of these are addressed elsewhere in this volume. Here, I address only this narrow conception of analogies as non-facts that contribute to the practice of science.

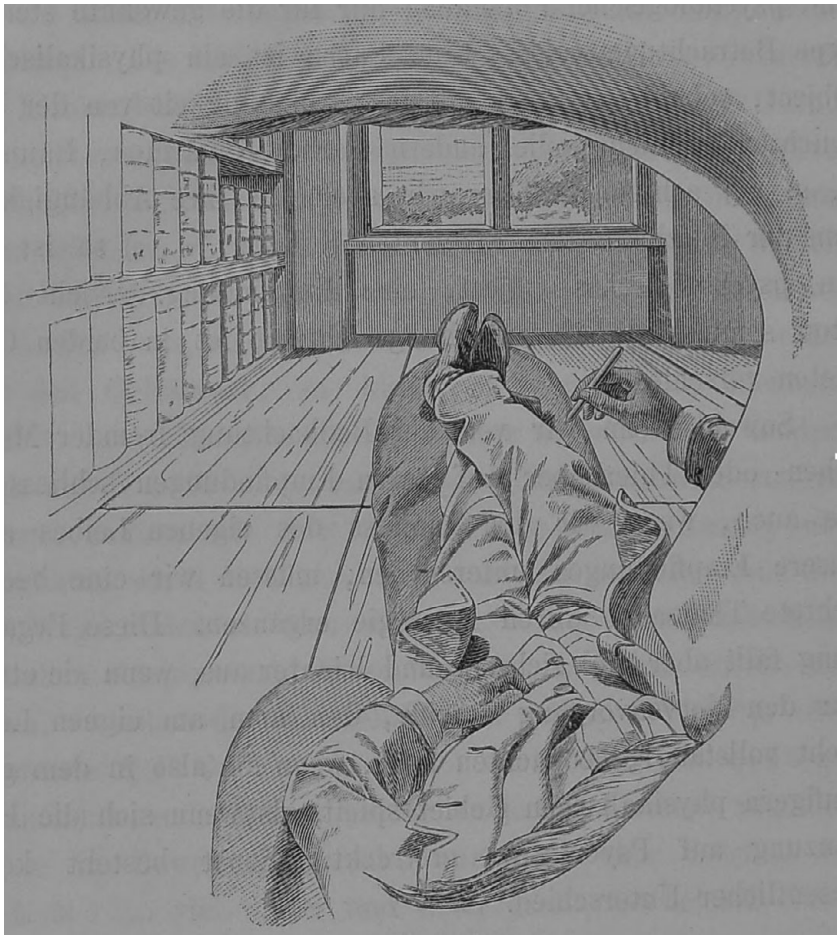

Figure 1.1 Mach reclined on his sofa with his right eye closed, observing himself observing (Mach 1886, p. 14)

facts, analogies held epistemological power. To sum up, the psychophysical imaginarium as experimental programme made epistemic use of a principle of psychical and physical parallelism and analogy as supplement.

Mach's Vienna

The monistic position Mach asserted in 1886 followed two decades of psychophysical experimentation. I deliberately employ the word 'followed' here in the strictly chronological sense. It is the historian's task to document

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the swirl of intellectual and cultural resources that Mach drew upon in the development of his own ideas, but it is also possible for the historian to overreach and posit direct, causal connections. Perhaps we can line up some analogies though? Mach himself described his intellectual position to be unstable in the 1860s, so let's begin there. What was he up to then?

Mach was in Vienna in 1863, working with Josef Popper-Lynkeus of the Vienna Physical Institute on a series of experiments on sound sensation. Mach also met Eduard Kulke that summer, both having been drawn into a lively discussion on the nature of musical tones at the Café Griensteidl (Mach 1906, pp. x–xi). The two men remained close friends, meeting up almost daily until Mach moved to Graz and then corresponding regularly until Kulke's death in 1897. Kulke had trained in mathematics and physics, but he built a career writing short stories, plays, and music criticism. Much of his fiction was devoted to portraying the folk life of Moravian–Jewish villages – ghetto tales of a sort. Mach noted that Kulke's Judaism had limited his academic advancement, and he spoke admiringly of his friend's courage to defy the 'raw anti-Semitism' he frequently encountered in the performing arts world of *fin-de-siècle* Vienna (Mach 1906, pp. x–xiii).

The deeply entwined nature of music and politics (and raw anti-Semitism) are best exemplified by Richard Wagner's essay 'Das Judenthum in der Musik'. Wagner revised this in 1869 to attack the music critic Eduard Hanslick, who had criticised the Viennese performance of *Lohengrin*, and he claimed that Hanslick's concealed Judaism rendered his writings anti-German. Several music scholars have argued that Wagner intended the character of Sixtus Beckmesser, who embodied several contemporary Jewish stereotypes, in his 1868 *Die Meistersinger von Nürnberg* opera to be a caricature of Hanslick.[8] These cruel episodes must be situated in several larger trends in the European music world, including a growing engagement with non-Western music, an interest in the music of 'internal others' and folk music, as well as the so-called War of the Romantics (Bohlman 2000; Born and Hesmondhalgh 2000; Radano et al. 2000). The allegiances in this war fell along stylistic and philosophical lines. The Leipzig-based composers Johannes Brahms and Robert and Clara Schumann, the violinist Joseph Joachim, and the critic Hanslick repeatedly clashed with the Wagner-led *Neudetusche Schule*.

Kulke loved Wagnerian opera, and he surrounded himself with such Wagnerians as Franz Liszt, Hans von Bülow, Peter Cornelius, and Anton Bruckner. Kulke described his passion for Wagner's music as an 'aesthetic heresy' (*ästhetische Ketzerei*) prompted by the opening chords of the *Tannhäuser* opera. When others mocked him for finding Wagner's music

[8] There was an ongoing debate on this matter among German studies and music scholars through the 1990s, but it seems to have been definitively resolved by Thomas Grey (Grey 2002, 2008, 2009).

beautiful – even pointing out that it was not acoustically possible for his harmonies to be beautiful – Kulke maintained that it was beautiful to him (Kulke 1906, pp. vii–viii). His individual, subjective experiences of music were valid.

Mach had at this time just completed an effort to physically then physiologically explain the role of attention in individuals' subjective experiences of sound. This phenomenon was and continues to be termed 'accommodation in hearing'. An example: the opening chords of the overture of Wagner's *Tannhäuser* began with the woodwind section. As the instruments wound through their mysterious melody, a listener could focus on, say, the clarinets and hear their melody distinct from the other instruments. Focusing instead on the bassoons in the same passage, the listener would experience something else. The listener could deliberately toggle their attention from instrument to instrument or take in the ensemble as a whole, thereby altering their individual aural experience of the performance. Applying Gustav Kirchhoff's theory of equal absorption and transmission to the eardrum, Mach placed a rubber tube in an experimental subject's ear. He then sang softly while moving the other end of the tube back and forth past his own ear. While Mach believed he had demonstrated a kymographic model of the hearing organ, the observations did not offer insight into the mechanism of accommodation (Hui 2013).

In the summer of 1863, with Popper-Lynkeus and his students, Mach attempted a new experimental approach to study accommodation in hearing, this time with a vibrating tuning fork held in his teeth, along with one end of a rubber tube in one of his ears and the other in an assistant's ear (Mach 1865). Mach would alter his attention, focusing first on the tuning fork's fundamental tone, then the overtones. For Mach, the focus of his attention was strong and distinct. The assistant, however, heard no change as Mach redirected his attention. Over the next decade, Mach mapped out the topography of the middle ear to better understand the senses of balance and acceleration. In 1871, he began a series of experiments with Johann Kessel on cadaver ears (Mach 1872b; Mach and Kessel 1872, 1874; Kessel 1874). The elaborate experimental set-up included the middle ear of a cadaver, weights, pulleys, a Lissajous vibration microscope, and a tuning fork. Mach and Kessel were able to demonstrate that changed tension on the tensor tympani muscle altered the transmission of sound through the ossicles (ear bones), but this was only the mechanical/physiological component of the accommodation phenomenon. An attempt to perform a similar series of experiments on a living person with the assistance of an 'ear mirror' did not replicate their previous results. Accommodation in hearing was a psychophysical phenomenon; it could not be understood in the 'realm of the plainly sensible' only. Mach would spend the next decade mobilising both parallelism and analogy to investigate it.

Psychophysical Parallelism and Epistemic Analogies

As I turn to Mach's unpublished writings now – his laboratory notebooks, lecture notes, and correspondence – I want to run a little fast and loose with Mach's understanding of the role of parallelism and analogy in experimental science. Briefly, in what follows, I will present the more formal entries of experimental programmes, recorded observations, and lecture notes against the less formal marginalia and loose-leaf inserts. These latter often took the form of brief lists of seemingly unrelated objects, concepts, and names. Christoph Hoffmann has shown how Mach's research notebooks cannot simply be read as 'passive reflections of experimental operations or cognitive processes' (Hoffman 2003, p. 183). Rather, these notebooks – Mach's act of writing in them – were epistemological tools. As techniques of science, Hoffmann argues, Mach's writings must be analysed within a knowledge production framework (Hoffman 2003, pp. 183–184). I push Hoffmann's central thesis a bit further. I argue that Mach's unpublished writings – lab notebooks, lecture notes, and correspondence – were the medium through which Mach cultivated his psychophysical imaginarium. Or, at least, we can use these writings to trace, through his use of analogy, some of the inflection points in the development of his psychophysical world view.

Mach's lab notebooks are especially rich resources for illuminating his knowledge-making frameworks, as Hoffman has noted. Mach frequently wrote out research questions, returned to several pages in a row to cross out material, and even wrote down exclamations of frustration; truly a boon for the historian attempting to reconstruct Mach's intellectual craft. In his lab notebooks from the 1870s, the same period in which he was examining accommodation in hearing and lecturing on psychoacoustics, Mach's jottings indicate that he was struggling to understand the movements of the middle ear bones as sound was transmitted through them. These were the accommodation experiments using a Lissajous microscope on a cadaver's ear.[9] Mach sketched out the stroboscopic images and tried to reconcile them with the rotation of the stirrup bone. He noted that the tensor tympani and stapedius muscles reduced this rotation. Then, at the top of the next page, Mach jotted, 'I cannot convince myself of that? Where am I mistaken?' (Mach 1870). In the subsequent lab notebook, after a series of crossed-out derivations, Mach sketched out several images of rotation angles. Then he began investigating the effects of sirens and pipes on the ear muscles. The next pages include sketches of abstract experimental preparations for the series of tests Mach performed with rubber tubes and sounding instruments. We can see that he

[9] It is admittedly a little tricky to confirm dates in these materials, but Mach references the accommodation of the stirrup bone near the end of this notebook. The subsequent notebook is dated 1871.

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considered using rubber muscles in addition to the experiments performed on human subjects.

Additional drawings of rotation angles, schematics of the middle ear, diagrams of rubber tube preparations, interference waves, and references to Helmholtz, Georg Ohm, André-Marie Ampère, Wundt, Charles Darwin, and Ernst Haeckel populate five more lab notebooks. This chapter is not the place to work out the step-by-step process of Mach's thinking. Rather, I want to show here that the knotty problem of explaining accommodation in hearing dominated Mach's experimental programme. He returned to it again and again over the next decade, each time with a different experimental approach. It became clear to Mach that accommodation in hearing could not be understood via physics or physiology alone. In that sense, it was an emblematic case for the application of the psychophysical parallelism he would propose in a concrete form in 1886.

We can see Mach practicing it himself, however, by as early as 1871 in his university lectures. Mach divided a medium-sized black notebook into preparatory notes for two courses of Experimental Physics, one dated to the summer of 1871 and the other to the winter of 1871/1872. The summer course mostly covered optics. The winter course began with mechanics and then moved to oscillators and acoustics. These are neatly written, with derivations and numbered examples of standing waves and so on. At one point in this notebook, seven loose sheets of paper are tucked between the pages. Most of them consists of lists. Here is one (Mach 1871b):

Middle-tones
Tuning-fork research
Piano
Bodies of greater absorption (damping?)
Airspace. Attenuation
Resonators. 1 large pipe.
Tone colour
Cortical Fibres
Sound plates with resonance-tubes
Interference tubes . . . execution via the middle tones
Speed of sound
Application on the forehead
Research on the track

A bit later in the course, Mach discussed Ernst Chladni's vibrating plates and Félix Savart's work on vibrating rods. Following a tidy diagram of longitudinal waves through a vibrating rod, there is another list (Mach 1871b):

Tuning fork research
Tone colour. Partial tones alone.
Superposition

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Spectral analysis analogue. Noise
Resonance tones
König's apparatus Reed pipes?
Harmonic and unharmonic partial tones of body
Coexistence of the same
Dependence of tone colour of this drawing*
Independence of tone colour of phase difference
Analogy of spectral analysis . . . Noise.
Resonators *
Organ pipes * open, covered
König's Flame apparatus * vowels

And then on the following page, accompanied by a musical staff with a series of notes labelled with vowel sounds, there is the following (Mach 1871b):

Vowels. Tone colour of the same
König's research (Zenger)*
Artistic representation of vowels with electric tuning forks.
Independence of tone colour of phase difference
Piano research. Very enlightening.
On the other hand it remains a mystery how one is able to sing the same ~~Ton~~ Vowel of an entire scale.

On another slip of paper that followed a few pages later was the following bracketed list (Mach 1871b):

Partial tones of sound
tone colour
relationship
melody
harmony
ear theory
Euler
Lipps
v. Oettingen

In each of these, we see a seeming jumble of experimental instruments and configurations (tuning forks, resonators, sound plates, a piano, and application on the forehead), physical concepts (attenuation, the speed of sound, resonance, and the theories of Euler, Theodor Lipps, and Arthur von Oettingen), physiological systems (cortical organ and fibres), and musical concepts (tone colour, melody, and harmony). Compared to his laboratory notebooks, which hew closely to physics and physiology, Mach's lecture notes are more wide-ranging. I think we can read this relative freedom of movement between realms – from experimental instruments, to scientific concepts, to musical

phenomena, and so on – as a two-step process: first, we can read his formal lecture notes as outlines to constrain his thinking and help him stick to a curriculum of sorts; but second, we should read the inserted lists as additional thoughts and reminders to himself to also talk about his ongoing piano research and so on. These lists were analogies. They functioned to supplement, quite literally, the shortcomings of precise science in explaining the sensory perception of sound. He was already thinking broadly, moving from the acoustics of wave interference to tone colour and then melody and then the structure of the ear, shifting from physics to musical aesthetics to sensory perception.

Acknowledging that the source record is more circumstantial than explicit, I would like to suggest that it was the exercise of articulating his ideas to others – students, friends, and the public – that fuelled the fullest expression of his psychophysical world view. That is, scaling out from his laboratory notebooks to his lecture notes to his correspondence to his public lectures, Mach became more bold in the practice and articulation of his monism. Here is one more example, from his correspondence with the music critic Kulke. Through the 1870s, their correspondence returned again and again to the question of an evolutionary theory of musical aesthetics. In 1872, Mach asked Kulke if he believed it possible for listeners in the present to hear what the ancient Greeks had heard. Was it simply a matter of attention (Mach 1872a)? Kulke was at this time working on a Darwinian theory of melody, *Über die Umbildung der Melodie: Ein Beitrag zur Entwickelungslehre*, which was eventually published in 1884 (Kulke 1884; Hui 2014). Mach, we know, was working on an experimental study of accommodation in hearing that was psychophysical in its parallelism, use of analogy, and, ultimately, phenomenology. In an undated letter to Kulke, likely between 1876 and 1878, well before the publication of *Analyse der Empfindungen*, Mach included a sketch that anticipated the famous illustration in that book (see Figure 1.2). It should be noted that, in this iteration, the figure whose perspective the viewer experienced was nursing a coffee and a cigarette; not, as the later image showed, drawing itself and/or the world. Still, it was instructive: 'How to execute the self-perception of "I"'. To underscore my earlier point, for Mach it was the act of articulating his work on accommodation in hearing to others that facilitated increasingly expansive psychophysical positions.

Mach's Piano

I have argued elsewhere that music was a proxy scientific language for Mach, describing it as 'a consequence of his constant and uninhibited engagement with the music world' (Hui 2014, p. 174). Revisiting Mach, and thinking more carefully about the role of parallelism and analogy in his psychophysical experimental programme, I think I can make a more direct claim that

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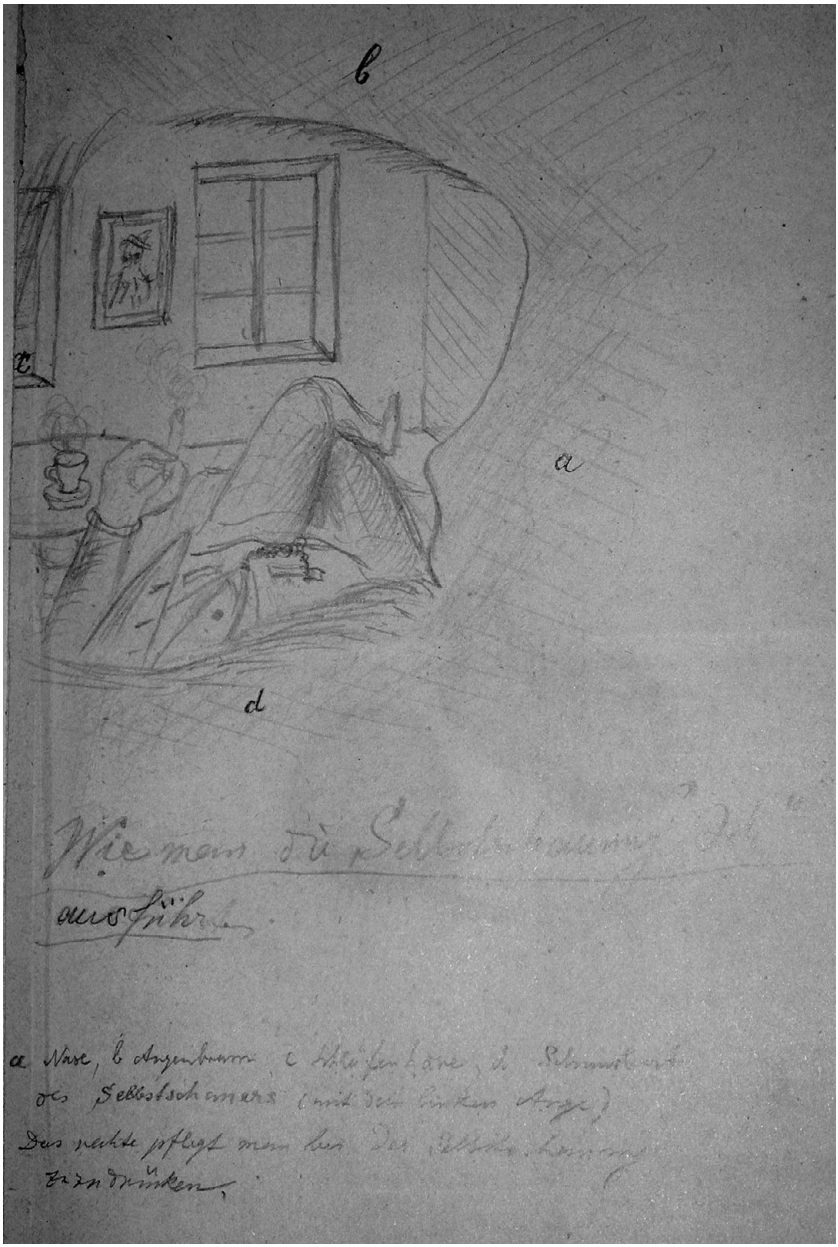

Figure 1.2 Ernst Mach, undated letter to Eduard Kulke (letter no.24, from between 1876 and 1878).
Ernst Mach Papers, Dibner Library of the History of Science and Technology, Smithsonian Institution Special Collections, Washington, DC

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Mach's use of music was a by-product of his friendship with musicians. I think we can comfortably understand this use of music to be a deliberate choice by Mach. This was exactly the toggling between realms (from physical to psychological, etc.) that he claimed was necessary for the sciences to move forward (versus atomism, which was stuck in a single realm).

I promised a piano, so let's talk about Mach's piano. Mach had a Bösendorfer grand and was friends with the Bösendorfer family, who were based in Vienna. The 'Bösendorfer sound' was known for its richness and clarity.[10] It was a more brilliant sound than, for example, Steinway pianos, and many preferred this tone colour. This brighter voicing was a consequence of the solid spruce rim, which was jointed together rather than being bent veneer. The entire box of the piano resonated, which threw more upper harmonics into sympathetic vibration when the instrument's keys were struck. The acoustics and aesthetics of Mach's piano should be kept in mind as we think about how he used it in scientific settings both as analogy and experimental instrument.

In 1866, Mach reworked Hermann von Helmholtz's 1863 opus *Die Lehre von den Tonempfindungen* for musicians as *Einleitung in die Helmholtz'sche Musiktheorie: Populär für Musiker dargestellt* (Mach 1866). That is, he eliminated Helmholtz's detailed descriptions of experiments and mathematics and minimised the discussion of physics. Mach disagreed with Helmholtz's understanding of the role of attention in sound sensation as strictly psychological, but otherwise summarised Helmholtz's points in a straightforward way. He embraced Helmholtz's use of the piano as an analogy for the mechanics of the ear. In this text and in popular lectures he gave the year before (1865), Mach described the following scenario to illustrate sympathetic vibration (Mach 1864a, 1864b). Two pianos were placed next to each other, with the dampers lifted on one of them (by pressing on the sostenuto pedal). When a key was struck on the damped piano, the same note rang on the undamped piano. Sounded chords on the damped piano similarly activated the same notes on the undamped instrument. According to Mach, the undamped piano was performing a spectral analysis of sound, separating the sounded tones into individual component parts (Mach 1864a, pp. 23–25).

This was essentially how Helmholtz – and Johannes Müller before him – mobilised this ear-as-piano analogy.[11] Mach expanded on it, however, to also explain accommodation in hearing. In 'Die Erklärung der Harmonie', he described an example of the phenomenon (and possibly performed it during

[10] Bösendorfer pianos are also known for their 92- and 97-key models. These were added to the company's series around 1909.

[11] Helmholtz had drawn on Müller's use of the piano as a model for sympathetic vibration. Julia Kursell offers an extensive discussion of the epistemological power of the piano model for Helmholtz (Kursell 2018).

the public lecture) in which a piano sounded two different chords in succession, voiced the same so that all tones were of the same loudness. Then, before the two chords were played again, the listener was directed to focus their attention on just the root tones of each chord or just the upper tones. Because the root tones were the same for both chords, the listener focusing on just the root tones would experience the sounded chords differently from if they were focusing on just the upper tones, which changed between the two chords. This piano demonstration (real or virtual) facilitated the experience of accommodation in hearing for Mach's audience. Through careful training, Mach continued, a listener could refine their spectral analyser and differentiate even a single tone into its constituent fundamental tone and harmonic overtones (Mach 1864b, p. 37). Drawing on Helmholtz, Mach noted that these overtones contributed to tone colour (timbre) and consonance, and they were ultimately the root of Western musical harmony. Accommodation informed the spectral analysis process. So here we slide into Mach's very specific understanding of the role of analogy as supplement to observed facts.

But the role of attention in altering the individual's experience of sound was also an observed fact. Mach demonstrated accommodation in hearing again and again in lectures and his writings so readers could recreate it in their mind's ear. Mach's piano returns here. The accommodation chord demonstration (he also did a series of demonstrations inverting and reversing melodies to demonstrate the lack of spatial symmetry in sound), especially Mach's claim that one could train one's body to experience the phenomenon in a more pronounced way, would have been additionally amplified by the Bösendorfer sound (Mach 1864a). Of course, it is unlikely that Mach used his Bösendorfer piano for his public demonstrations. It is possible, though, that he used it to work out his thoughts alone, in the laboratory, or even in his lecture courses (it is unknown where he kept his piano). Again, the bright Bösendorfer sound was a consequence of the design and voicing that allowed for more upper harmonics to be sounded. A listener concentrating on discerning harmonics in a sounded tone would be more likely to hear them on a Bösendorfer than a Steinway, Pleyel, or Erard. By asking his readers or listeners to imagine specific psychophysical experiences, Mach established the broad outlines of a new way of thinking about subjectivity. By walking his audience through these experiences step by step with a piano, Mach facilitated for them a psychophysical imaginarium.

Conclusion

In 1872, Mach published *Die Geschichte und die Wurzel des Satzes von der Erhaltung der Arbeit*, and in it a full articulation of his position that ideas were bound to specific times and places. It was also in 1872 that Mach asked Kulke whether they could still hear what the ancient Greeks heard. This was not a

question of whether the sounds of the world changed over time, but whether the perception of these sounds did, for Mach was deep in his studies of how an individual's perception of sound could change moment by moment as they altered their attention. If accommodation in hearing was psychophysical, then it was also historical and historicist. Recall that Mach described his researches in the 1860s as 'alternating study of the physics and physiology of the senses, and through historico-physical studies'. I venture that Mach's early studies of accommodation in hearing were foundational for his later historical epistemology. In describing and explaining the phenomenon of accommodation in hearing, Mach also prompted it in his readers and listeners. Mach moved between realms, from acoustics to physiology to mathematics to musical notation to sound itself, enacting the parallelism he called for. He extended his own feedback loop of psychophysical framework to psychophysical imaginarium to others – to me, and perhaps to you, too.

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