FUNDAMENTALS
OF THE
THEORY OF
MOVEMENT PERCEPTION

BY

DR. ERNST MACH

Translated and Annotated

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Foreword to the Translated Edition

The value of this publication of Ernst Mach's work of 1875 on movement perception lies, first of all, in its scientific content and its useful applications to this day, even for space research, which would have delighted Mach. But the book also illuminates the kind of scientist-philosopher Mach was at that stage, and was to become in his later years.

During his doctoral work at the university in Vienna in the late 1850s, Mach had studied physics, mathematics, and philosophy, and then published on a wide range of primarily experimental subjects, from capillary phenomena to changes in musical pitch in coordinate systems in relative motion. His search for a specific field into which to throw his enormous energy led him to problems that exhibited a combination of physics, physiology, psychology of sensations, and psychophysics. It was a first indicator of his famous search for an Einheitswissenschaft, which in the words of the philosopher Max Schlick (1926), "arose from the wish to find a principal point of view to which he could cling in any research, one which he would not have to change when going from the field of physics to that of physiology or psychology. Such a firm point of view he reached by going back to what is given before all scientific research, namely, the world of sensations."

By 1860 he had become attracted to Gustav Fechner's pioneering ideas in *Elements of Psychophysics*, and for a while was also influenced by the work of the father of German physiology, Johannes Müller. Although Mach's innate skepticism and his own imaginative drive eventually caused him to question these authorities, he had become what Mach's biographer, John T. Blackmore, perceptively calls "an ontological phenomenalist who identified the external world with sensory impressions," and for that reason was more alert than most scientists to sensory novelties or peculiarities to which others pay only passing attention. Thus Mach suggested later in his *Popular Scientific Lectures* (1895, p. 272) that an important incentive to pursue his subsequent work on the effect of motion on the human body was the experience of accidentally observing a striking apparent inclination of the houses and trees as seen from a speeding railway carriage going around a curve.

Mach's search for an area in which he could excel in research on sense perception was, in his own opinion, also determined to some degree by the paucity of good experimental equipment available to him at the time. Thrown back largely on his own devices, he concentrated on his extraordinary mastery of observation. As he put it later, "Here, where I could observe my sensations, and against their environmental circumstances, I attained, as I believe, a natural Weltanschauung, freed from speculative, metaphysical ingredients" (Scientia 1910, p. 234). An example of his power of perception was one of his first observations to become famous, the discovery of the so-called Mach bands, a change in the perceived brightness under circumstances for which to this day there is still discussion concerning its physical basis—but which could well have been observed by others long before, if they had been alert and sensitive enough.

Soon after moving to his professorship at the University of Prague, he launched on a whole spectrum of research activities on topics directly accessible to the human senses—retinal stimuli, stereoscopy, auditory perception, optical experiments on interference and spectra, wave motion, and the use of photographic devices to study the propagation of sound waves by imaging the change of density of the medium through which they move, from which arose the famous "Mach number" and "Mach angle."

It is in this context of Mach's sensation-based research that we should read the first paragraph in his introduction to the work at hand, beginning with "There are unmistakable characteristic sensations which accompany active or passive movements of our body...." Indeed, the whole work is a hymn to the impression the human physiology registers under various, even extreme, changes of position or motion. While Mach builds on the individual contributions of such predecessors as Purkinje, Flourens, Goltz, and others, he aims, as he says in his Foreword, to produce "a complete overview of a chapter of physiology"—although also attempting to give a physical basis as far as possible (for example, the importance of angular acceleration rather than angular velocity in the sensation during the experience of rotation). Superficially the book may seem not organized along traditional lines, but one must keep in mind that he saw the aim of doing science itself as giving a "compendious representation of the actual." Thus, we encounter constantly new, simple, original devices and procedures throughout, and even the effects on animals are not forgotten. Reports on direct sensations are foremost, although most are qualitative rather than quantitative. Mathematics (which appears only briefly and is of the simple kind) and hypotheses are secondary. Thus one of the important conclusions in this book (p. 69) is stated quite straightforwardly: "It has been asserted and also disputed that a special muscle sense exists…. We therefore accept the muscle sense as a fact; something that can be observed, without bothering to explain it."

In many respects, these characteristics of his 1875 book point forward to his masterwork of 1883, known in its English translation as *The Science of Mechanics: A Critical and Historical Account of Its Development.* That book was on the reading list of practically every alert scientist for decades, including Albert Einstein, who noted in his autobiographical essay of 1949 that it was this book of Mach's which, as a youth, shook him out of the "dogmatic faith" of the previous approach to physics (Einstein, in Schilpp 1949, p. 21). Indeed, in one of his letters to Ernst Mach (17 August 1909), Einstein signed off with the phrase that he was Mach's “verehrender Schüler” (a student who venerates or reveres Mach).

Mach became world-renowned more through that book than through anything he did before or after. As his vast correspondence and the references to him in the literature of scientists prove, he amassed disciples for his science and his philosophy (even though he disavowed being a philosopher) throughout the world. These included such important figures in varied fields as Jacques Loeb and William James during his own lifetime, and Philipp Frank, P. W. Bridgman, and B. F. Skinner afterward. After the founding of the Nobel Prizes, Ernst Mach was repeatedly nominated in letters and petitions from distinguished scientists such as H. A. Lorentz, Ferdinand Braun, and Wilhelm Ostwald These nominations, even if unsuccessful in the end, do indicate Ernst Mach's standing among scientists at the time.

And yet, after the explosion of the new physics around the turn of the century, with one spectacular discovery or theory after another, Mach was left in the position of an Aussenseiter (to use the word in the title of the book edited by J. T. Blackmore and Klaus Hentschel, *Ernst Mach als Aussenseiter* [Vienna, 1985]), a person at the margin. His career, grounded in the splendid exploitation of sensations and the derogation of “hypotheses,” together with his self-confessed poor understanding of higher mathematics, at that point did put him then at a position outside the center of the new science. His greatest personal assets as an experimenter had become internalized by the community, and in a sense were now taken for granted.

To me, there is a certain poetic injustice about this reversal of fortunes, which the publication of this book may rectify to some degree. For what this work may lack in the kind of sophisticated mathematical-theoretical prowess which we associate with many of the giants of twentieth-century physics, it makes up by the careful accounts of the sophisticated experimentation involving the sensations of the human body. My own view is that this fact points to a particular source of “scientific intelligence” of which Ernst Mach was a primary exemplar, one which in fact is shared with other scientists before and since, but which curiously has practically been kept secret.

To explain what this secret is, I turn to a historical example. In 1902–4, the French mathematician Jacques Hadamard published a lengthy questionnaire (reprinted as Appendix I of his book *The Psychology of Invention in the Mathematical Field* [Princeton University Press, 1945]), under the title “In Inquiry into the Working Methods of Mathematicians.” This he submitted to his fellow scientists with a view to eliciting a typology of different aptitudes or, as we might now call them, intelligences, that helped them in their work. He included even such questions as whether they have ever worked in their sleep, or have found the answers to problems in dreams, or whether artistic and literary occupations hindered or helped in mathematical invention.

At the very end, the thirtieth question ran as follows: “It would be very helpful for the purpose of psychological investigation to know what internal or mental images, what kind of 'internal word' mathematicians make use of; whether they are motor, auditory, visual, or mixed, depending on the subject which they are studying.” Eventually, about 1944, Hadamard submitted this particular question also to Mach's erstwhile “student,” Albert Einstein, and the resulting “Testimonial from Professor Einstein” is published as Appendix II in Hadamard's book.

The two-page “testimonial” is well known among historians of science. In essence, the reply emphasizes that “the words or the language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be 'voluntarily' reproduced and combined.” He continues to explain that before he can arrive at the scientifically valuable “logically connected concepts” he engages in a “rather vague play with the above-mentioned elements” and then adds what is to us the most revealing point: *“The above-mentioned elements are, in my case, of visual and some of muscular type”* [emphasis added]. He also answered to the question about his “logical type” as being “visual and motor.” One part of this remarkable insight is fortified by a report from the psychologist and long-term friend of Einstein, Max Wertheimer, who reported that from 1916 on, he had questioned Einstein “in great detail about the concrete events in his thoughts.” Einstein replied: “These thoughts did not come in any verbal formulation. I very rarely think in words at all. A thought comes, and I might try to express it in words afterwards.” And Einstein added, “I have it in a kind of survey, in a way visually” (Wertheimer 1945, p. 184). It seems therefore that in addition to his other skills and intelligences, Einstein could, as it were, “feel” his way into the problem situation—not only, in the significant metaphor he often used, with a Fingerspitzengefühl—that helps to know whether one is on the right track in a complex research project--but in some more actually tangible way. I have occasionally heard from scientists about that same ability to feel in their bodies, in their muscles, the trajectory of an object under research. But of course this skill is never mentioned in textbooks or research papers, and is perhaps so rare among researchers as to remain slightly embarrassing to speak about. That ability seems to me also connected with Michael Polanyi's concept of the scientist's use of “tacit knowing,” as explained in his book *The Tacit Dimension* (1967).

Having read and heard of these evidences of the participation of some internal motor skills or kinesthetic intelligence during science research, and not having any sense of it myself, I have often wondered how such a concept could be demonstrated operationally. One insight came to me in the 1960s. I happened to be at a conference on the general topic of scientific creativity, where I encountered the psychologist and psychoanalyst George Klein. I asked him if he could throw any light on the matter, and his response was remarkable. He told me that, as it happened, he had persuaded Einstein in his late years to submit to a Rorschach test. As Dr. Klein described it, Einstein sat down before the opened book of Rorschach test images, staring at one of them for a long time; then, instead of speaking about his perception, Einstein slowly and silently rose from his seat, stretched out his arms, and waved them, like a giant bird. This stunning report gave me an inkling of what might be meant by having kinesthetic perception and allowing it to participate in a scientific query.

But to indicate that Einstein's (and Mach's) kinesthetic sensibilities are by no means unique, I draw on the clear description of the same guiding ability, provided by the great physicist and science statesman, I. I. Rabi, a Nobelist whose research on molecular beams and the magnetic resonance method was instrumental in bringing physics in the United States up to world-class level during the 1930s and 1940s. As his biographer John S. Rigden put it (in his book, *Rabi: Scientist and Citizen*, New York: Basic Books, Inc., 1987):

> “Rabi relied strongly on his intuition, which allowed him, in a manner of speaking, to put himself into the beam and, along with the other beam particles, experience the sudden jolts and subtle nudges as he streamed through the apparatus. As Polykarp Kusch has said, “He [Rabi] appears to ride around on the electrons within an atom or asks the question, 'If I were an electron, what would I do?' Possibly, through sheer force of character he gets the electron to do precisely that.”
>
> “So Rabi rode the sodium atom, first by clinging to an electron, then by sitting on its nucleus. He could feel the beam split decisively into two beamlets by the force of a strong magnetic field acting directly on the large magnetic moment of the sodium atom's outermost electron.” (p. 86)

Rigden then quotes Rabi directly from an interview concerning his crucial idea, in 1936, how to determine experimentally the sign of the magnetic moment of nuclei:

> “One day I was walking up the hill on Claremont Avenue and I was thinking about it [the sign of the nuclear magnetic moment] as kinesthetically with my body. Now, yes, I was thinking about this as follows: Here's the moment and it's wobbling around in the direction of the field and [to find] the sign was to find out in which sense it was wobbling. To do this, I have to add another field which goes with it or against it. This is the idea, just concretely. The whole resonance method goes back to this.” (p. 94)

To return to Ernst Mach's work at hand, on the subject of movement perception, I believe I can now understand a little better the kind of uncommon sensitivity to the phenomena Ernst Mach was investigating, often with his own body. So as we read in this work, let us keep his figure before our eyes, as he is standing on the rotating platform or sitting in the tilted chair mounted on a rotating frame, in every way participating in the events he describes as both subject and object, experiencing within himself kinesthetically this remarkable series of experiments.

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Preface to the Translated Edition

At the dawn of the 21st century, why would anyone translate a 19th century work on motion sensation by a physicist best known for his research on fluid mechanics? The answer is simply that Ernst Mach's experiments and insight into sensory mechanics and spatial orientation, though critical and amazingly clever, are largely ignored or unknown by the community developing models of multi-sensory interaction. They are as relevant now as they were in 1875, and they serve to remind physiologists of the importance of dynamics and of the need for clear unambiguous experiments in the elucidation of the possible sources of motion sensation. The work also holds an important place in the history of science, as it represents the introduction of quantitative models and theory into the descriptive realm of 19th-century experimental psychology.

Our own introduction to this material took place in 1972, when I was a visiting professor in Günter Baumgartner's neurology department in Zurich, helping Volker Henn to set up the monkey laboratory. Henn had just returned from New York where he worked with Bernard Cohen on single-unit recordings underlying eye movements in alert monkeys. We were interested in combining animal and human experiments relating visual and vestibular stimuli to eye movements and motion perception. When I showed Henn the draft of my chapter for Mountcastle's physiology text, it contained the usual historical reference to the erroneous 19th-century notion that the semicircular canals were stimulated by continuous flow of endolymph, and I blamed Mach, Breuer, and Crum Brown collectively for the misconception. Henn assured me, as usual with a twinkle in his eye, that Mach could not possibly have made such an error. Indeed, a careful reading of Mach's contributions to the Vienna Academy of Science showed that he indeed had it right. Mach showed that for a spinning subject the friction forces in the canal would bring the endolymph to a stop shortly after the canals reached constant angular velocity. Therefore, the decaying sensation of turning could not result from endolymph flow, but must instead reflect a detection of pressure within the organ.

Mach's 1875 book was never published in English translation. Henn was convinced of the importance of this work for contemporary researchers. Together we wrote a short summary of some of Mach's contributions in 1975 and Henn elaborated this work in 1984. Henn later persuaded me to work with him on an annotated translation of the entire book including hypertext capabilities. Volker Henn[1] died unexpectedly in December 1997, after most of this translation and its notes were completed. Fortunately, Hansjörg Scherberger, one of Henn's last postdoctoral students, stepped in to complete this work with me.

Although earlier research on vestibular physiology had established some of the important facts concerning the function of the labyrinth in spatial orientation, no general theory relating motion to its sensation existed at the time of Mach's writings. There was not even agreement about the location of the principal motion sensors. Flourens had described the results of lesions of the labyrinth on the head movements of pigeons, but provided no theory to explain the results. Goltz had surmised that the ampullae in the semicircular canal were responsible for detecting motion. Purkinje, meanwhile, had made important observations concerning vertigo and the dynamic response of motion sensation during and following prolonged turning. He correctly concluded that the organ of motion sensation was in the head, but erroneously assigned this function to a movement of part of the brain. In an allied field, Helmholtz had published his momentous work on physiological optics, which Mach greatly admired. But nothing existed in the way of physical theories for motion sensation when Mach's interest was stimulated. His research began with the fortuitous observation that, while riding around a curve on a train, the houses and trees appeared to be tilted. He brought the traditional rigorous approach of physics to the empirical and descriptive field of sensory physiology.

The application of his reductionist approach to science is clear in this work. He begins by identifying the functional requirements that sensors must serve. In this case, Mach requires sensors that detect angular and linear acceleration, rather than velocity, for all directions in space. He next argues why these sensors must be located in the head, since the axes of motion sensation move with the head. He further assembles the evidence in favor of the semicircular canals and the otolith organs serving this function, and shows how these sensors can meet the physical requirements. Finally, he presents a testable general theory of motion perception. He does not claim that the theory is definitive, but expresses the hope "that the results of my work will remain valuable, even if one does not make the connection to the hypothesis which I developed in the last chapter about the organ of motion perception."

One of the delights of this book is the description of the simple but elegant experiments that Mach used to eliminate alternative sources of motion sensation, such as pressure on the feet, redistribution of blood, or force on the head. He sought simple, parsimonious explanations for complex phenomena. In his pursuit of a theory that would encompass all of the various observations, he eschewed any explanation that required the introduction of non-observable entities. In a larger sense, this view is consistent with Mach's controversial philosophy of science, relying on observed facts rather than hypothetical "laws."

In this book Mach uses a somewhat rambling and narrative style that would be quite unacceptable according to current scientific standards. He combines his thought process with the weight of evidence to support his conclusions about the role of the semicircular canals and the otoliths in spatial orientation and motion sensation. In places his presentation seems almost a stream of consciousness, as he skips from one topic to another. Nevertheless he constantly seeks to remind the reader of the main point – the development of a theory of motion sensation based only upon observed input-output relationships and consistent with the laws of mechanics. For that purpose he also tries to teach some of the basic principles of mechanics to the physiologists of his day. In doing so he includes a number of illustrative examples to make his point, from Foucault pendulums to steam engines. Additionally, he offers a number of gratuitous comments about proper scientific methods and the shortcomings of some of the contemporary physiologists.

Mach was remarkable for the contributions he made in so many fields. In fluid mechanics his use of Schlieren photography to study shock waves and supersonic motion was recognized by attaching his name to the unit for the speed of sound in air. His work on visual psychophysics included the discovery of contrast enhancement at boundaries, now referred to as "Mach bands." Consistent with his positivism, Mach strenuously objected to the assumption of atoms as a necessary part of modern physics and disagreed with the theory of relativity. Albert Einstein, in his obituary in 1916, acknowledged Mach's great influence.

This translation is presented in a dual language format. The German text is preserved in order to provide direct access to the original font and layout. Brackets always delineate words or corrections added by the translators. This approach allowed us to deviate from the literal translation in favor of clarity by expressing Mach's ideas as he might have written them in English. Our numerous footnotes are intended both to explain Mach's text, including references to concepts and devices no longer known, and to put his ideas in the context of contemporary motion sensation research. Longer articles and related material are included only in the accompanying CD-ROM[2], which also contains the full text and links to all footnotes.

In the preparation of this translation we were assisted greatly by the members of the "Zurich Lab" that Henn headed at the University of Zurich, especially Caroline Saruhan, Markus Kotterer, Bernhard Hess, Domink Straumann, and Klaus Hess, Head of the Neurology Department. We are also grateful to Bruce Bridgeman, Lawrence Stark, Bernard Cohen, and Klaus Hepp for additional comments on the manuscript. The project was supported by the Betty and David Koetser Foundation for Brain Research, Zurich, the Apollo Program Chair of Astronautics at the Massachusetts Institute of Technology, and the National Space Biomedical Research Institute. Our historical research and access to Mach's papers and notebooks was made possible by the Ernst Mach Archive in Freiburg and the archive of the Deutsches Museum in Munich—in particular through the assistance of Margrit Prussat and Wilhelm Füssl—and the Burndy Library of the Dibner Institute for the History of Science and Technology at MIT. Marsha Warren assisted with copyediting and indexing the manuscript. The entire project was made possible by the guidance and encouragement of Michael Hennelly, formerly of Kluwer Academic/Plenum Publishers. Kathleen P. Lyons and Beth Kuhne of the publisher made valuable editing contributions.

Gerald Holton's learned foreword to this translation brings the story up to modern times, especially regarding Mach's influence on the next generation of physicists and his use of body introspection.

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Chapter Summaries

Introduction

(Pages 1–5) Mach briefly reviews the modest scientific literature on motion sensation. He states that, since motion can be clearly defined in physical terms, any treatment of it must start by defining physical parameters. He laments the lack of any coherent theory. Even Flourens, whose surgical destruction of single semicircular canals regularly led to violent motion disturbances in the pigeon, refrained from interpreting these results. Mach recalls how he first became interested in movement perception when he went around a curve in a railway car. He finally states that the principal facts on which he based his theory were known since 1824 (the experiments by Purkinje [Purkyně] and Flourens).

He attributes the lack of theory to an unwillingness to consider the motion sensation functional requirements independent of the possible mechanisms for its biological realization. He was aware of the fragmentary status of anatomical and physiological knowledge, and concludes that the physical treatment, i.e., the functional or logical description (in modern terms a model), will be unaffected by possible novel interpretations of the biological phenomena.

The Mechanical Foundations

(Pages 6–22) The basic principles of Newtonian mechanics are summarized. Mach introduces the principle of the conservation of areas, which is an antiquated way to explain the conservation of angular momentum. He goes on to discuss several examples of engineering apparatus to show that any movement in one direction will evoke a movement in an opposite direction, so that the center of gravity remains stationary. Spinning tops, centrifuges, electric motors, the Foucault pendulum, falling weights, and sailors running on a ship are all presented to illustrate the conservation of momentum. The chapter closes with speculation about the site of motion sensation.

The Phenomena Observed in Moving Men and Animals

(Pages 22–40) Mach explains that during motion only accelerations are sensed. He recounts the observation that houses and trees seem to lean when viewed from a train rounding a narrow curve. To conduct his research, he constructed a hand-driven three-axis human turntable. In a first series of experiments confined to angular motion, psychophysical responses are described for nine different studies including visual-vestibular interaction (pp. 25–28). A second series demonstrates sensations associated with the Coriolis effect (pp. 29–30). A third series shows the effects of linear acceleration (pp. 31–36), and measures thresholds. He discusses the relationship between vertical motion sensing and motion sickness. Further experiments combine angular and linear motion. He then turns to related animal experiments, rotating pigeons and rabbits, to observe postural disturbances. A short discussion follows that compares active to passive motion.

Flourens' Experiment

(Page 41–50) Flourens is extensively quoted concerning the experiments in which he lesioned single semicircular canals in animals and observed intense head instability in the planes of the affected canals. Mach wonders about the lack of theory. He refers to Goltz's interpretation of these experiments involving endolymph movement and pressure variation. Criticism of Flourens' experiments and of Goltz's interpretation, in particular those of Böttcher, are reviewed.

Phenomena Reminiscent of Flourens' Experiment

(Pages 51–54) The few human cases in the clinical literature reminiscent of Flourens' experiments are reviewed. Galvanic stimulation in human subjects and related electrical stimulation of fish are described.

Comparison of Movement Sensations with Other Sensations

(Pages 54–65) Mach describes experiments by Plateau to demonstrate that sensory organs seem to obey two common principles: (1) Aftereffects appear that are analogous to positive and negative after-images in the visual system and (2) adaptation occurs during continuing constant stimulation. Concerning visual experiments, several examples of optical illusions are presented to show that neither eye movements nor pupil variations are responsible for these phenomena.

Further Investigations of the Phenomena

(Pages 65–96) A series of further experiments is described to show that the sensory organ for motion detection most likely resides in the head. Mach systematically eliminates other sources of movement detection including connective tissue and bone, skin, muscles, blood, eyes, and the brain. An apparatus is constructed to investigate whether or not pressure under the feet plays a role. To investigate muscle load, a system of levers is fixed to the head with suspended buckets of water, which can be emptied quickly. To eliminate the influence of the spatial distribution of pressure, Mach placed subjects on a board above a kind of bathtub that can be raised so that the subject becomes buoyant in water without ever being moved. Visual vertigo and Breuer's extensions of Purkyně's experiments are reviewed. Mach describes visual-vestibular interaction including vection. He discusses the role that induced eye movements might play and concludes that nystagmus is a reflex elicited by acceleration. To prove the point he devises experiments in which eye movements can be dissociated from motion sensation. As all the experiments point toward the head as the seat for the organ to detect motion, Mach reviews the literature concerning possible explanations for these sensations. While in agreement with Purkyně that motion sensation takes place in the head, Mach disputes his view that the mechanical movement of the brain is the source of this sensation. Finally, he describes rotation experiments with the head partly or completely stationary in space, which support his claim that a sensory organ for motion sensation resides in the head.

Theory of the Phenomena

(Pages 97–124) The communications of Breuer and of Crum Brown, published at the same time and based on independent observations, are quoted extensively. Mach takes their findings and views them as support for his own theory. He concludes that the most likely organ that could detect angular and linear motion is the labyrinth, and discusses possible mechanisms. He performed experiments using an analog model of the canals to study the movement induced by angular acceleration, and demonstrated that the flow of endolymph was inadequate to explain the time course of motion sensation. He concludes that the adequate stimulus most likely is a pressure gradient across the cupula, which minimizes actual endolymph flow. Comparisons with other sensory organs show that the energy delivered by such a pressure gradient should be sufficient to induce a sensation for the accelerations associated with normal head movements. Mach then explains how the combined activity from the afferent nerves leads to a common perception of motion rather then a mosaic of separate sensations from each canal.

Conclusions

(Pages 124–126) Mach summarizes his theoretical and experimental results in eleven statements. The first ten relate to the dynamic nature of the sensation, the characteristics of the adequate stimulus, the location of the sense organ in the head, and the elimination of other possible origins of movement sensation. The eleventh statement postulates that the six oppositely paired semicircular canals constitute the organ of movement sensation. He emphasizes that the first ten statements are independent of the last, and will remain valid, whether or not later generations of physiologists can support his hypothesis that the labyrinth is the sensory organ of motion detection. Finally, to support his eleventh statement, he suggests further electrical stimulation and lesion experiments, which he wishes to leave to others with more appropriate knowledge and skills.

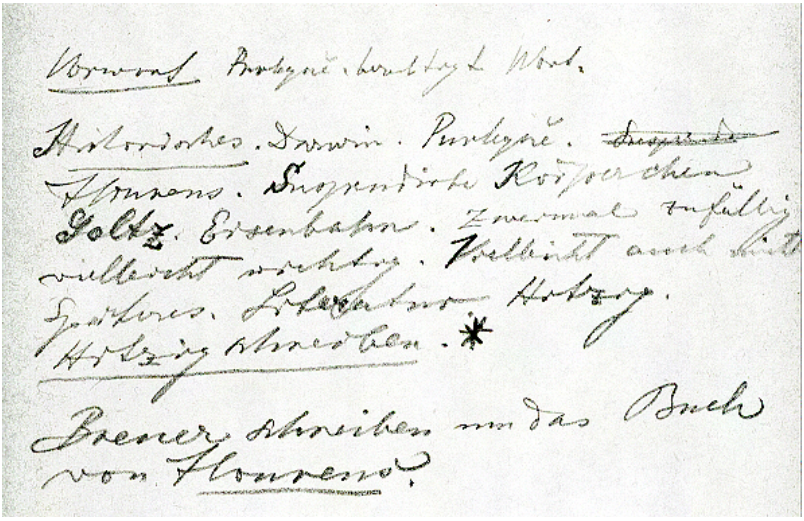

Figure A-4: Notes on references from Mach's Notebook of 1874: "Foreword – Purkyně. Historical: Darwin, Purkyně, Flourens, suspended particles, Goltz, Railroad, Doubly random might be important. Maybe with ... write to Hitzig*. Write to Breuer, asking for Flourens' book." (photograph courtesy of E. Mach Archive, Deutsches Museum, Munich)