Balance Function Assessment and Management

Third Edition

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PREFACE

On behalf of the editors and authors, we would like to welcome you to the third edition of *Balance Function Assessment and Management*. Notable updates to this edition include the first chapter that reviews "An Historical Perspective of the Perception of Vertigo and Dizziness and Vestibular Medicine." We have also included new chapters on the topics of "Vestibular Balance Therapy for Children" (Chapter 19) and "The Aging Vestibular System: Implications for Rehabilitation" (Chapter 25). Further, this edition includes a chapter on "Challenging Cases" (Chapter 27) and we end this textbook with four appendices covering "Pathophysiological Signs and Symptoms of Dizziness," "Coding and Billing," "Interprofessional Education and Practice," and "Specialty Rotational Vestibular Assessments." In response to the comments from readers of the second edition, we have reduced the length of the textbook by making it more concise.

Finally, the reader will note that this third edition has been edited by six nationally and internationally known clinical scientists in the area of dizziness, vertigo, and chronic unsteadiness. . These editors include Kamran Barin, PhD, Robert F. Burkard, PhD, Kristen Janky, AuD, PhD, and Devin L. McCaslin, PhD. We are grateful for the participation of these talented individuals in the planning, development, and realization of this third edition. It has been our objective from the first edition of *Balance Function Assessment and Management* to produce a textbook for both the student and the practitioner that treats comprehensively the assessment and management of dizziness. To the extent that we have achieved this goal, you, the reader, will be the judge.

Gary P. Jacobson, PhD Neil T. Shepard, PhD

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1

An Historical Perspective of the Perception of Vertigo, Dizziness, and Vestibular Medicine

Christopher K. Zalewski

HISTORICAL BEGINNINGS AND COMMONPLACE MISDIRECTION

Most medical histories can, at some point in time, always be brought back to Aristotle. Along with Hippocrates of Kos (c. 460–370 BC; Figure 1–1), Plato (c. 428/7 or 424/3–348/7 BC; Figure 1–2), and Socrates (c. 470–399 BC; Figure 1–3), Aristotle (c. 384–322 BC; Figure 1–4) was arguably one of the greatest philosophers and early scientists in history. He was not only the first to introduce the scientific study of all the human senses, he also provided the first written account of vertigo in 330 BC (Ross, 1927).

> Why is it that to those who are very drunk everything seems to revolve in a circle, and as soon as the wine takes a hold of them they cannot see objects at a distance? . . . [O]bjects near at hand are not seen in their proper places, but appear to revolve in a circle. (p. 892a)

And although the philosophical pondering of alcohol-induced dizziness does have its medical and vestibular merit, the actual attribution for the discovery of the physiologic link between the vestibular system and vertigo would not occur for almost another two centuries. The historical recount of this elusive discovery is, in many ways, similar to other medical discoveries. It is one that is shrouded with misdirection and debate, as well as highlighted with triumph and tragedy.

For some historical discoveries, storied misdirection is not uncommon during a time period when written accounts were sparse and interpretation of science was more philosophical than fact. One of the most poignant misdirections is that of Charles Darwin's legacy. Although Charles Robert Darwin (c. 1809–1882) is universally recognized as the Father of Evolution and Natural Selection, largely due to his published work *On the Origin of Species* in 1859, public acknowledgment is seldom given to Alfred Russel Wallace (c. 1823–1913), who was instrumental in the independent conceptualization and propagation of the original framework for the theory of natural selection in his papers "On the Law which has Regulated the Introduction of New Species" (1855) and "On the Tendencies of Varieties to Depart Indefinitely From the Original Type" (1858), the latter paper being directly sent to Darwin by Wallace himself. Interestingly, the overshadowing of Alfred Russel Wallace by Charles Darwin was not the first time controversy surrounded the crediting of the Darwin namesake for introducing and revolutionizing a groundbreaking

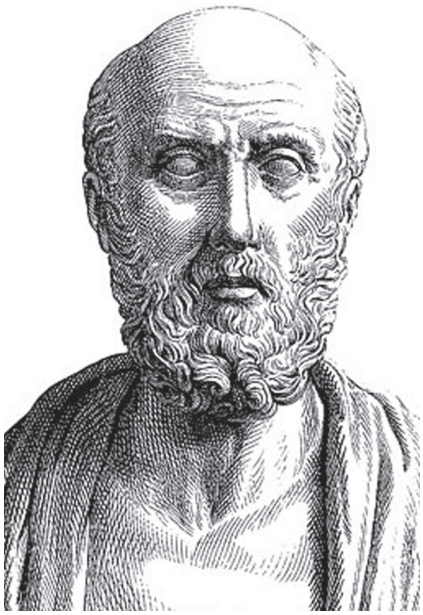

Figure 1–1. Hippocrates of Kos (460–370 BC).

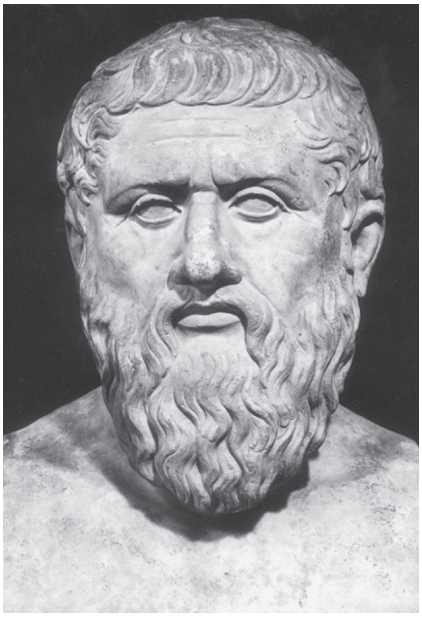

Figure 1–2. Plato (428/7 or 424/3–348/7 BC).

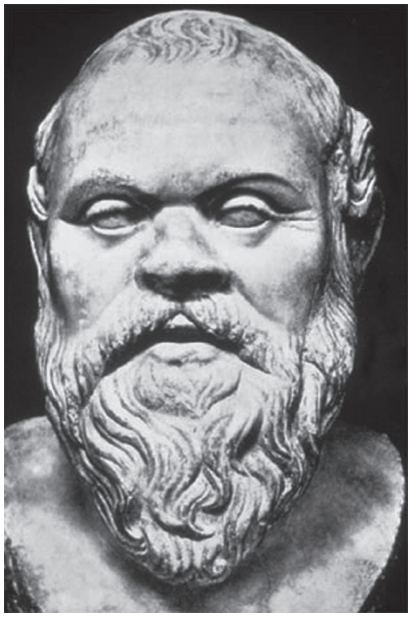

Figure 1–3. Socrates (470–399 BC).

Figure 1–4. Aristotle (384–322 BC).

scientific theory. Charles's grandfather, Erasmus Darwin, is often given credit for the earliest work on the origins of vertigo and nystagmus, rather than a young scientist by the name of William Charles Wells.

WILLIAM CHARLES WELLS AND ERASMUS DARWIN: THE DUELING "VESTIBULAR PHILOSOPHERS"

William Charles Wells was a scientist for whom the story surrounding the discovery of the vestibular sixth sense begins. Some 65 years before Charles Darwin published *On the Origin of Species*, Charles Darwin's grandfather, Erasmus Darwin (c. 1731–1802; Figure 1–5), in collaboration with Robert Waring Darwin (c. 1766–1848), the father of Charles Darwin, published a section entitled "Of Vertigo" in *Zoonomia; or, The Laws of Organic Life (Vol I)* in 1794. This work nearly erased Charles Wells's sentinel work on the discovery of the relationship between vertigo and nystagmus. As such, *Zoonomia*'s account of life, medicine, and early theories of evolution, including rudimentary ideas of vertigo and dizziness, is the reason that initial descriptions of vertigo are often attributed to Erasmus Darwin. It is Erasmus Darwin's contributions to medicine, nature, and life that are highly acknowledged as one of the pinnacles of human physiology and thought. His four editions of the two volumes of *Zoonomia* have been recognized as among the most comprehensive and foundational works from which theories of modern medicine and philosophy have originated. As such, Darwin's recognition for theories on dizziness and

Figure 1–5. Erasmus Darwin (1731–1802).

Figure 1–6. Thomas Willis (1621–1675).

Figure 1–7. Julien Offray de la Mettrie (1709–1751).

vertigo in *Zoonomia* all but dismissed the literary work published a mere two years earlier by Charles Wells, an essay that (correctly) refuted the current belief surrounding the sensation of vertigo at the time.

From Visual Vertigo to Visual After-Images: The Emergence of the Sixth Sense

At the turn of the eighteenth century, Darwin's published views on vertigo and dizziness continued to propagate the well-accepted notion at the time, that vertigo and dizziness were a disturbance of "visual processing." The idea of "visual vertigo" was first offered by Thomas Willis (c. 1621–1675; Figure 1–6) in 1661 in his publication *De Anima Brutorum quae Hominis Vitals ac Sentitiva Exercitationes Duae* [The Beasts and the Man's Life: 2 Exercises]. Here, Willis suggested that vertigo occurred solely from a disturbance of vision due to animal spirits in the central nervous system. Later in 1737, Julien Offray de la Mettrie (c. 1709–1751; Figure 1–7) supported this notion in his work *Traité du Vertige* [Treaty of Vertigo], but stated that vertigo was *physiological* rather than a consequence of animal or humorous spirits. This idea of "visual vertigo" was further supported and refined by William Porterfield (c. 1696–1771) in the same year (1737). However, Porterfield affirmed that visual vertigo was specifically *not* associated with eye movements (i.e., nystagmus), but rather occurred due to aberrant visual *neural processing* of images. This concept of "phantom" neural visual processing was similar to phantom leg syndrome, a concept that was familiar to Porterfield, whose leg was amputated in his youth.

The suspected origin of "visual vertigo" was held for another 65 to 70 years. It was not until 1792 that Charles Wells suggested that the sensation of vertigo was actually due to eye movement that could easily be elicited following head (body) rotation. In his

Essays upon Single Vision with Two Eyes: Together with Experiments and Observations on Several Other Subjects in Optics, Wells published what is now known to be the first account detailing the association between vertigo and eye movement (i.e., nystagmus of vestibular origin). In this report, Wells was the first to describe both the fast and the slow phase of eye movement during nystagmus. Although Charles Wells did not specify what internal organs were responsible for the production of this "nystagmus," with the use of after-images, Wells was the first to provide irrefutable evidence systematically linking the pattern of eye movements to the direction of perceived vertigo (Wade, 2003). Most notably, Charles Wells published this essay in 1792, which was two years *prior* to the publication of Erasmus Darwin's *first* edition of *Zoonomia; or, The Laws of Organic Life (Vol. I)*. However, in their publication, Erasmus and Robert Darwin detailed the characteristics of vertigo and continued to support Porterfield's earlier, and erroneous, notion that "visual vertigo" was specifically *not* associated with eye movements. Unfortunately, Wells's association with eye movement and post-rotational vertigo as a landmark discovery in vestibular science went largely unnoticed—so much so that Charles Wells himself would essentially drift into historical oblivion for this discovery.[1]

The Erasmus Wells Debate

One hundred and thirty-one years after Thomas Willis first introduced the concept of "visual vertigo," and a little more than two centuries since Aristotle first introduced the five senses, the notion that there could be a sixth sense, one of motion perception, was brought to scientific light. But who was rightfully due the scientific discovery? Although Charles Wells's sophisticated experiments on post-rotational vertigo and nystagmus were seemingly irrefutable, they were also essentially unknown, and ostensibly almost deliberately unrecognized. This was likely due to the fact that Erasmus Darwin's world-renowned publication of *Zoonomia* was essentially medical and philosophical law at the time. Additionally, since the majority of scientific writings were in the German language, Erasmus Darwin clearly had the advantage, as *Zoonomia* was translated into German, while Charles Wells's *Essays upon Single Vision with Two Eyes* was only published in English (Wade, 2003). Moreover, his essay appeared in *vision* literature, a far cry from that of neurology, or "vestibular" research (if such a medical classification had existed then). It was also unclear whether Wells's work was poorly represented in the German translation of *Zoonomia* or Erasmus Darwin himself did not fully understand Wells's work, or both. Or perhaps it was because the word "vertigo" was not even in the title of Wells's essay. The topic of vertigo was, in fact, one of the "*Several Other Subjects in Optics*" that was addressed in the title of Wells's 144-page essay, buried between pages 85 and 105.

Several sources have suggested that Charles Wells also struggled against his own exasperation. Despite his kindness and warmth of heart he was easily offended (Wade & Tatler, 2005). As such, Wells was at times irascible, even describing himself as "naturally irritable" in his own memoir (Wade, 2003). Whether or not these traits projected Wells as an obstinate and indignant person, it is clear that such qualities would have undoubtedly affected his reputation within the scientific community. In this regard, one could easily detect such indignation in two rejoinders Wells published in *The Gentleman's Magazine* in September and October of 1794, only three or four months after the first volume of *Zoonomia* was published. Wells's quick dispute of Darwin's comments on visual vertigo was, if nothing else, highly detailed and concise. In each letter, Wells provided a rather pointed rebuttal that articulated a clear and concise scientific counter argument to each of Darwin's apparent logical statements supporting "visual vertigo." Among Wells's points was the notion that vertigo could occur in complete darkness, that is, in the absence of any visual *processing* (Wade, 2003). However, it was Wells's use of optical after-images that provided the indisputable scientific evidence supporting a *physiologic* link between eye movements and vertigo, thus finally putting to rest the notion of "visual vertigo." Though Wells did not provide a theory as to the origin of the production of these eye movements (i.e., "vestibular" nystagmus), his work did lay the scientific foundation for others to begin considering this question.

The Gentleman's Magazine *Refutes*

Wells's two responses to Darwin's theory of visual vertigo in *Zoonomia* were highly publicized at the time, as *The Gentleman's Magazine* was well regarded. However, the magazine was not widely read by scientists outside of Britain (Wade & Tatler, 2005). Regardless of

[1]The phrase "drift into historical oblivion" is a play on words, respectfully evoking the title of Nicholas Wade's book *Destined for Distinguished Oblivion* (see the Epilogue).

the magazine's limited readership, Wells's rejoinders in *The Gentleman's Magazine* had gained both scientific attention and popularity. As such, Erasmus Darwin briefly acknowledged Wells's alternative theories on vertigo and nystagmus in his third edition of *Zoonomia*, which was published in 1801 (i.e., almost 10 years following the initial publication of Wells's *Essays upon Single Vision with Two Eyes.* Unfortunately, Darwin's position on visual vertigo changed little in the third edition. It was not until Darwin's final fourth edition of *Zoonomia* that Erasmus and Robert Darwin would finally acknowledge, although begrudgingly, Charles Wells's scientific contributions linking eye movements (nystagmus) to the perception of vertigo (Wade, 2003). Amazingly, however, they continued to support the theory of visual vertigo, thus continuing to dismiss Wells's conclusions.

Most notably, it was Wells's second letter to *The Gentleman's Magazine*, detailing the post-rotation nystagmus response that possibly offered the best evidence to suggest his work was the *first* foundational work on *vestibular* research.[2] Specifically, it was Wells's succinct description of the involuntary post-rotational nystagmus in his second retort, which detailed the apparent motion of the environment after cessation of rotation (Wade, 2003). The apparent rotation of the environment was dependent not only on the direction of subject rotation, but also on the direction of involuntary eye movement. Furthermore, the direction of the rotation of the environment switched directions in accordance with the change in the direction of head rotation (Wade, 2003). Finally, Wells also detailed the suppression of nystagmus with concentrated vision (i.e., vestibulo-ocular reflex [VOR] suppression), as well as the perception of vertigo and documentation of after-image eye movement in darkness. Collectively, Wells's observations on vertigo and nystagmus are the first and foremost definitions of what we now know today to be the properties of clinical vestibular nystagmus. However, despite Wells's scientific evidence supporting the association between vertigo and eye movements, the use of rotation for the diagnosis of vertigo and investigation of vestibular function would continue to remain absent in neurology clinics for over a century. In fact, it would take another 100 years until Róbert Bárány (c. 1876–1936) applied these "rotational" properties clinically.

It is interesting that the published feud between Wells and Darwin in *The Gentleman's Magazine* may have been the primary reason for the eventual crediting of Charles Wells's work on vertigo and nystagmus. The detailed responses by Wells allowed for the public expansion of his theories and the devolution of "visual vertigo."

BRIDGING THE GAP: THE PHYSIOLOGIC LINK BETWEEN THE VESTIBULAR SYSTEM AND VERTIGO

The notion of linking head rotation to nystagmus (and vertigo) was a novel finding at the time, and suggesting that the semicircular canals were the origin for this nystagmus might have been the most logical step in the scientific process. However at the turn of the eighteenth century, an erroneous notion still persisted. There was a continued belief by many that the "Cretan Labyrinthos," as Aelius Galen (c. 129–200/216 AD; Figure 1–8) had elegantly named the vestibular labyrinth, was responsible for *auditory localization*. After all, the anatomy of the labyrinth easily supported the contention that the semicircular canals were aligned for optimal sound localization (and amplification as Du Verney had suggested in 1683; Figure 1–9). Unfortunately, at the time of Wells and Darwin, the scientific bridge between the vestibular labyrinth, head rotation, nystagmus, and vertigo had yet to be made, and

Figure 1–8. Aelius Galen (129–200/216).

[2]Despite Wells's work in vestibular research, it is often Jan Evangelista Purkyně (c. 1787–1869) and Jean Pierre Flourens (c. 1794–1867) who are frequently credited with and subsequently often referred to as the "Fathers of Vestibular Science"—but more to come on this later.

Figure 1–9. Joseph Guichard Du Verney (1648–1730).

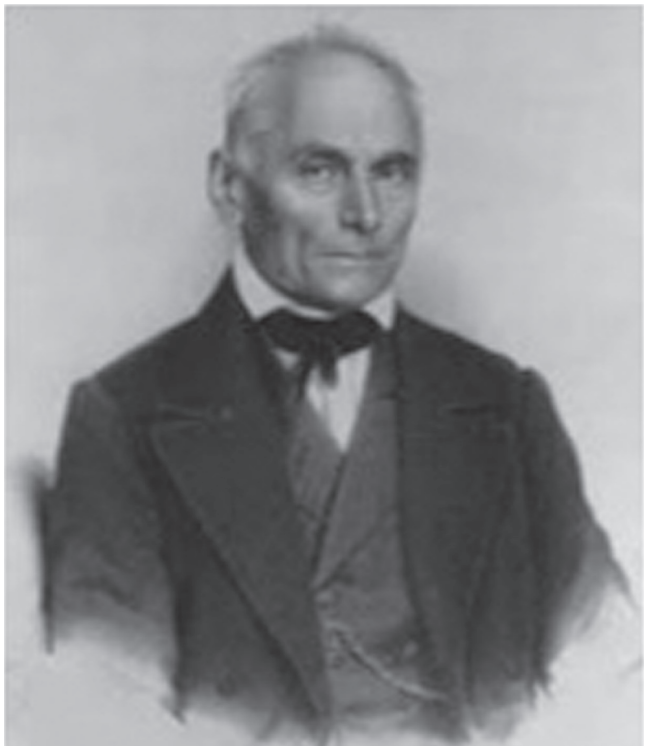

Figure 1–10. Jan Evangelista Purkyně (1787–1869).

because of this, it was unclear whether even Wells's work actually had any direct impact on the work of two well-known vestibular scientists (Purkyně and Flourens), who made these final connections.

Purkyně and Flourens

Jan Evangelista Purkyně (Figure 1–10) and Jean Pierre Flourens (Figure 1–11) were two world-renowned physician scientists, both performing work in vertigo and motion perception. Purkyně in particular was highly regarded and extremely well known, as one merely had to address a letter to "Purkyně, Europe" and it would be delivered successfully (Baloh, 2002). Along with other scientists at the time, such as Ernst Josef Mach (c. 1838–1916), Josef Breuer (c. 1842–1925), and Alexander Crum-Brown (c. 1838–1922), the discovery of the link between the vestibular system, vertigo, and eye movements advanced quickly. Unfortunately for Wells, neither Purkyně nor Flourens spoke fluent English (Wade, 2003). As such, neither one ever referenced Wells's work on vertigo and nystagmus. Most of the vestibular *research* at the turn of the century came from either Germany or France, with German often being the language of choice. Darwin's *Zoonomia* was widely cited and available in German, which *was* familiar to both Purkyně and Flourens (evidenced by the fact that they both often cited *Zoonomia*) (Wade & Tatler, 2005). Both scientists continued to disregard Wells's evidence on post-rotational vertigo and nystagmus, and

Figure 1–11. Jean Pierre Flourens (1794–1867).

continued to promote their own beliefs.[3] For example, Purkyně continued to promote the idea that vertigo occurred in response to the independent rotation of the cerebellum. Moreover, it was likely Erasmus Darwin's work on rotation (not Wells's work) that may have swayed Purkyně to abandon this idea and move toward accepting a link between the vestibular system and vertigo. In fact, on more than one occasion Purkyně assigned *sole* credit to Darwin for his investigation of vertigo and the physiologic background of this phenomenon (Wade, 2003). This notion further supported Purkyně's apparent unfamiliarity with Wells's work on vertigo and nystagmus. This was reinforced by the fact that Purkyně himself is often credited with being the *first* to make the association between eye movements and rotation (Wade, 2003). In fact, most of the work related to vertigo and its physiologic and subjective bases often begins with citing Purkyně and Flourens's work, which is clearly evident in Coleman Griffith's highly regarded, well-known, and often-cited historical perspective *An Historical Survey of Vestibular Equilibration*, published in 1922. Griffith begins his historical survey with Purkyně and Flourens' work on vestibular physiology, which may explain why most literature often cites Purkyně and Flourens as the "Fathers of Vestibular Science."

. . . And Then There Were Six

The characterization of the original Aristotelian five senses went unchallenged for nearly two thousand years. It was Charles Wells's 1792 treatise that provided the first indisputable evidence that supported the link between the patterns of eye movements in relation to the direction of post-rotary vertigo. However, two decades would linger on this evidential theory, until scientific discovery would take another giant leap forward. Scientific evidence would soon be provided by Purkyně and Flourens in the early nineteenth century that would significantly propel forward Wells's evidence. Interestingly, Purkyně and Flourens would provide this evidence independently from one another, as both were actually unknown to one another during this time (Bárány 1916, Laureate Lecture).

At the turn of the nineteenth century, both physician-scientists independently published their reports on vertigo and rotation, as well as semicircular canal function. Purkyně's early publication in 1820, *Beiträge zur näheren Kenntniß des Schwindels aus heautognostischen Daten*, continued to expand on the *symptomatic* link between the vertiginous behavior of objects in the visual field and rotation (Griffith, 1922). However, it was Flourens' landmark work published in 1824, *Recherches expérimentales sur les propriétés et les fonctions du système nerveux dans les animaux vertébrés*, that linked definitively discrete *physiologic* disturbances in the visual system when the semicircular canals of pigeons were stimulated. Flourens would publish three more landmark articles from 1824 through 1842 on the physiologic link between the visual system and the semicircular canals: (1) *Experiences sur les canaux semicirculaires de l'oreille dans les oiseaux* (1830), (2) *Experiences sur les canaux semicirculaires de l'oreille dans les mammifères* (1830), and (3) *Recherches expérimentales sur les propriétés et les fonctions du système nerveux dans les animaux vertébrés* (1842) (this 1842 report having the same title as his initial publication in 1824) (Griffith, 1922). It was Purkyně's and Flourens' experiments and writings from 1820 through 1842 that provided the scientific evidence that confirmed the physiologic link between the vestibular system and vertigo.

In particular, Flourens' work in 1824 all but single-handedly transformed the long-held belief, that the vestibular system was responsible for sound localization, into the more scientifically accepted belief that the vestibular system was actually responsible for motion perception (and vertigo, when aberrantly stimulated). It was Flourens' research involving the extirpation of semicircular canals in pigeons which provided the irrefutable evidence for the vestibular system's role in the perception of motion, thus heralding the elusive sixth sense. In the words of Róbert Bárány during his Nobel Prize acceptance speech (Bárány, 1916, Laureate Lecture):

> Flourens thought that it would be possible to get an insight into the function of the semi-circular canal apparatus by destroying it. In fact, these experiments which were undertaken with pigeons, rabbits and other animals produced quite remarkable, constant and previously unknown disturbances. For instance, if the horizontal semi-circular canal was destroyed in a pigeon, it went on turning horizontally in a circle.

[3]While neither Purkyně nor Flourens ever referenced Wells's work on vertigo and nystagmus, it remains curious that both scientists *continued* to neglect Wells's contributions to vertigo and nystagmus, even after he was briefly acknowledged by Erasmus Darwin in the third edition of *Zoonomia* in 1801 (Wade & Tatler, 2005), which was 23 years prior to their landmark manuscript identifying the physiologic link between vertigo, nystagmus, and the vestibular system.

> If a vertical semi-circular canal was destroyed, the pigeon turned somersaults. Flourens has described the phenomena extremely well. But he did not give an explanation. In particular, he did not have the faintest idea that the animals were suffering from vertigo. You can see from this how easily one can pass by within an inch of the truth.

The concept of a sixth sense struggled for nearly two thousand years after Aristotle first described the five principle human senses. Therefore, it was not surprising that the concept was not accepted universally by scientists at the time. This skepticism included Jan Evangelista Purkyně, who *continued* to remain somewhat hesitant in acknowledging all the available scientific evidence at the time (Wade, 2003), largely because his work continued to focus on the *symptomatology* of the vertiginous response, rather than the neural *physiology*.

ROTATION IN THE EARLY NINETEENTH CENTURY AND DISCOVERIES OF VESTIBULAR PHYSIOLOGY . . . AND NEVER THE TWO DISCIPLINES SHALL MEET

A majority of the work investigating vertigo and rotation in the first quarter of the nineteenth century was, interestingly, *not* focused on that of scientific exploration of dizziness but rather the clinical treatment for the mentally insane. Despite the growing interest in the use of rotation and the written accounts supporting the "new" theory physiologically linking eye movements and vertigo, the use of rotation in the early nineteenth century was most commonly found in psychiatric asylums.

Secondary to Erasmus Darwin's publication of *Zoonomia*, the application of rotation quickly became a prominent therapeutic technique during the early nineteenth century for psychiatric disorders. In 1801, Erasmus Darwin introduced his "rotating couch" (Wade, 2003) as a means of inducing intentionally provoked vertigo and subsequent slumber in psychiatric patients. The idea of "medicinal slumber" was well accepted at the time and motivated many in the field of mental health care to prescribe such medically induced slumber for the treatment of psychiatric disorders in the early 1800s (Cohen & Raphan, 2004). Well-known psychiatrists Joseph Mason Cox, of Fishponds Private Lunatic Asylum, and William Saunders Hallaran (c. 1765–1825), a physician superintendent at the County and City of Cork Lunatic Asylum, even developed their own "circulating swings," for which they are probably best remembered. The success of "Hallaran's Circulating Swing" in 1818 (Breathnach, 2010) was adopted by many at the time and, in particular, by Anton Ludwig Ernst Horn (c. 1774–1848), of the Charité-Hospital in Berlin, Germany. Horn eventually developed his own, ceiling-suspended, 13-foot rotating bed, which was capable of spinning 120 revolutions per minute (Belofsky, 2013) and producing up to four or five times the force of gravity (Harsch, 2006). Horn's "psychiatric centrifuge" was also well accepted and widely used between 1814 and 1818 for the treatment of mental disorders. He reported success for the use of his "psychiatric centrifuge" in patients with hysteria (Harsch, 2006). Medicinal slumber continued through the late nineteenth century, including use of a human centrifuge in 1898 by Dr. F. R. von Wenusch to investigate the therapeutic potential of acceleration (White, 1964). However, the transition of using rotation for the treatment of psychiatric disease to the diagnosis of vertigo and dizziness would not occur until the vestibular system's role was firmly redefined, both physiologically and clinically, from that of audition to one of motion perception.

From Rotation of the Mentally Ill to Vestibular Physiology Discoveries

Despite the absence in the use of rotation for the *clinical* diagnosis and treatment of vertigo and dizziness throughout the 1800s, there were significant *research* advancements being made in the scientific understanding of vestibular physiology in the later quarter of the nineteenth century. Most notably, Ernst Josef Mach (Figure 1–12), Alexander Crum-Brown (Figure 1–13), and Josef Breuer (Figure 1–14) proposed the "hydrodynamic theory of semicircular canal function" between 1874 and 1875. Ernst Josef Mach published *Grundlinien der Lehre von den Bewegungsempfindungen* in 1875, Crum-Brown published *On the Sense of Rotation and the Anatomy and Physiology of the Semicircular Canals of the Internal Ear* in 1874, and most noteworthy, Josef Breuer published "Über die Funktion der Bogengänge des Ohrlabyrinthes" in 1874 and "Beiträge zur Lehre vom statischen Sinne" in 1875. Although all were instrumental in the development of the hydrodynamic theory, Josef Breuer's role was particularly significant in its development (Baloh, 2017). In fact, Josef Breuer would be one of the most prolific vestibular physiologists in the latter quarter of the nineteenth century, publishing

Figure 1–12. Ernst Josef Mach (1838–1916).

Figure 1–13. Alexander Crum Brown (1838–1922).

more than 200 articles on the topic of vestibular physiology in his lifetime (Baloh, 2017).

The introduction of the hydrodynamic theory of semicircular canal function was staggering at the time. It was a great leap forward in the understanding of vestibular physiology, and the theory still remains prominent to this day. It is interesting that Mach, Breuer, and Crum-Brown independently arrived at similar conclusions but from different perspectives. The independent research from each scientist was truly brilliant, and eloquently recounted by Róbert Bárány during his 1914 Nobel Prize acceptance speech.

It is also worth noting that, during the time of these discoveries, Alexander Crum-Brown also devised methods for measuring thresholds for detecting body movements on a rotating stool. He determined that the thresholds were lowest when the head was positioned so that one of the semicircular canals was in the plane of rotation, a precursor to Ewald's laws of semicircular canal function.

During this time period, Ernst Josef Mach also published scientific reports investigating the nature of otolith responses as well as the first reports indicating that the semicircular canals responded to *acceleration*, not velocity (Cohen & Raphan, 2004). Between 1874 and 1875, Ernst Mach constructed a rotational chair that was mounted in a rotatable frame and examined the perception of the visual vertical during static tilt as well as the visual aftereffects of body rotation. Mach performed such studies after observing the vertical tilting of telegraph poles when rounding an inappropriately banked curve on a train (Cohen & Raphan, 2004). For his work on subjective visual vertical, some consider Ernst Mach the "Father of Otolith Function Testing." Despite this otological notoriety, Ernst Josef Mach, being an Austrian physicist and philosopher, is probably better known for Mach's principle, which was a precursor to Einstein's Theory of General Relativity.

Figure 1–14. Josef Breuer (1842–1925).