Of frogs and men: the origins of psychophysiological time experiments, 1850–1865

Henning Schmidgen

Towards the end of the 1840s, Hermann von Helmholtz began to investigate experimentally the propagation of stimuli within nerves. Helmholtz's experiments on animals and human subjects opened a research field that in the following decades was intensively explored by neurophysiologists and experimental psychologists. Helmholtz's pioneering investigations justify the central place he occupies in accounts of the history of modern psychophysiology. Studying the concrete experimental settings and their local contexts shows how deeply the work of scholars such as Helmholtz is embedded in the history of culture and technology. In particular, the rapidly growing technologies of electromagnetism, which gave rise to telegraphy and electric clocks, facilitated the time measurements of 19th-century physiologists and psychologists.

On 15 January 1850, Hermann von Helmholtz (1821–1894) signed a short report and sent it off to the Physical Society and the Academy of Sciences in Berlin. Its first paragraph read:

> I have found that a measurable time passes when the stimulus exerted by a momentary electric current on the hip plexus (*Hüftgeflecht*) of a frog propagates itself to the nerves of the thigh and enters the calf muscle. In large frogs whose nerves were 50 to 60 millimetres long, and which I had kept at 2–6 degrees Celsius (whereas the temperature of the observation room was between 11 and 15 degrees), this length of time amounted to 0.0014 and 0.0020 of one second.[1]

Helmholtz and the velocity of nervous stimulation

Ever since the formation of the reflex concept in the 17th century, naturalists had been interested in the speed of the 'animal spirits' and the conduction velocity of the 'nervous principle'. With his investigations, Helmholtz entered the history of the experimental life sciences as the first scientist to make precise measurements of nervous action. In nerve-muscle preparations from the frog, Helmholtz measured a propagation velocity of stimuli between 25 and 43 meters per second[2].

Helmholtz's experiments were carried out in a world in which physiology (or 'organic physics'), telegraph technology and the military were closely interrelated. Three years before publishing the first volume of his path-breaking *Investigations on Animal Electricity* (1848), Emil Du Bois-Reymond (a friend and colleague of Helmholtz) had made concrete suggestions for measuring 'the speed of the muscle and nerve activity' at a meeting of the Physical Society[3]. Then in 1847, the journal of this society, *Advances of Physics*, printed the report of a young lieutenant in the Prussian artillery. Under the title 'On speed measurements', Werner Siemens, who later founded the well-known electricity group, offered an overview on the most recent methods for exactly determining the 'speed of bodies'. Almost all of the devices Siemens presented and explained relied on the application of electromagnetism. And whether it was Charles Wheatstone's chronoscope or the apparatus devised by Siemens himself, the main field for using these apparatus was military research. As Siemens put it, especially 'to the artillery it is of importance to know the speed of projectiles at various points of their trajectory.'[4] Furthermore, the military background of 'time microscopy' was not unfamiliar to Hemholtz. Between 1843 and 1848 he had received his training as squadron surgeon and military physician in Potsdam[5].

When measuring the propagation velocity of stimulations in nerves, Helmholtz initially used a method suggested by Claude Pouillet (1790–1868). As the French physician had reasoned, the degree of deflection of a galvanometer needle depended not only on the intensity of the electric current, but also on the time during which the current affected the needle. It thus should also have been possible to deduce the 'current time' from the deflection of the needle. Pouillet devised an electric circuit in which electric impulses of temporal precision could be produced by means of a rotating disk on which circumscribed contact surfaces were mounted. Given a constant electric current, the deflection of a galvonometer needle included in the circuit could be used to derive the

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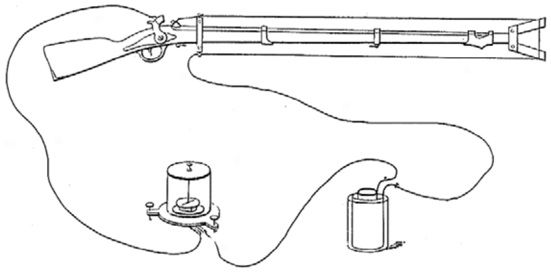


Figure 1. In the 19th century, most of the procedures to measure short time intervals were developed within the context of military research. Their primary use was measuring the velocity of projectiles at different points of their trajectories. With the advent of telegraph technology in the late-1830s, electromagnetism began to play an important role in this kind of precision measurement. The Figure shows the use of such a time measuring device in the context of ballistics. Its basic mechanism was suggested by the French physicist Claude Pouillet in 1844. The deflection of a galvanometer needle served to measure the time during which the current was active. In this set-up, firing the rifle opened the current which was closed again by the bullet cutting the wire at the rifle's muzzle. In the late-1840s, Hermann von Helmholtz adopted Pouillet's method for measuring the propagation speed in the nerves. Reproduced from Ref. 30.

time during which the current was active. Pouillet compared this procedure to the ballistic pendulum Benjamin Robbins had constructed some hundred years previously[6]. No wonder then that contemporary handbooks of electromagnetism displayed figures illustrating the use of Pouillet's method for ballistic purposes (Figure 1).

In his experiments on the propagation of nerve stimulations, Helmholtz adopted Pouillet's 'means to measure extremely short time intervals' for physiological use. Helmholtz devised two interconnected electric circuits, one to stimulate the nerve-muscle preparation, the other to measure the current time by means of a galvanometer. Both circuits could be closed in such a way that the preparation was electrically stimulated and the electric current was simultaneously sent through the galvanometer. When the muscle then started contracting, the current in the galvanometer circuit was immediately and permanently interrupted. From the deflection of the needle, Helmholtz could read off the time the muscle needed to contract after stimulation. Placing the electrode at different parts of the nerve-muscle preparation, the differences in the results obtained allowed him to calculate the propagation speed of the 'nervous impulse' (Figure 2).

This, however, was only the initial form of Helmholtz's experiments. In the extended investigations he carried out after his first report, Helmholtz adopted other methods for his time measurements, turning to graphical procedures. But when devising his famous 'frog myographion', he again relied on existing precision technologies – this time, the indicator tools used by steam engineers[7].

Helmholtz's psychological experiments

Amongst historians of biology, it is understood that Helmholtz's work on the propagation speed of nervous stimuli constitutes the beginning of a branch of research that, in the following years and decades, became known as 'nerve and muscle physics' and, in more recent times, has been labeled 'neurophysiology'. Scholars such as Gabriel Gustav Valentin and Albert von Bezold, Julius Bernstein and Étienne Jules Marey, and Keith Lucas and Edgar Douglas Adrian contributed significantly to this field. Less widely known is the fact that Helmholtz was interested in the time relations structured by the nervous systems of living beings not just from a *physiological* but also from a *psychological* point of view[8]. In fact, at the time at which he performed his studies on frogs, Helmholtz carried out similar experiments in human beings. Again, Helmholtz's aim was to measure the stimulation propagation in the sensory nerves.

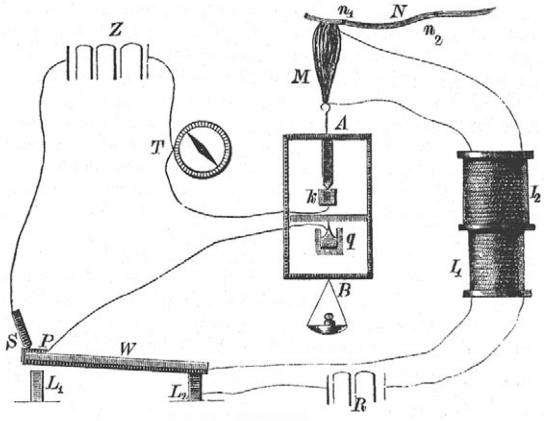
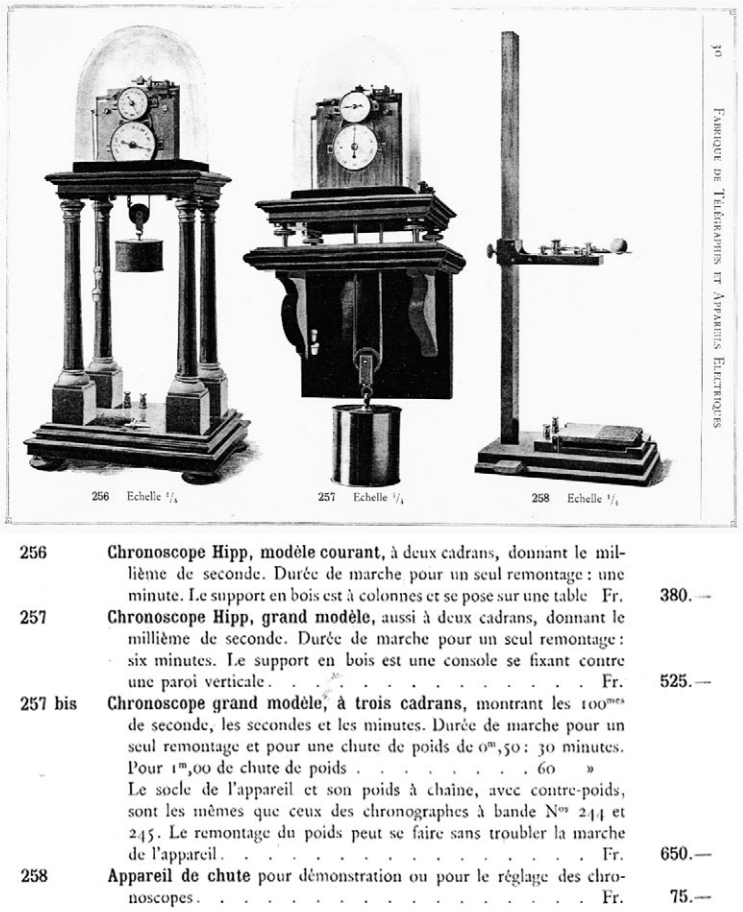


Figure 2. This contemporary reconstruction shows the use Helmholtz made of Pouillet's method for measuring the propagation speed of electric stimuli in the nerve. The set-up combined two electric circuits: one in which the battery, R, by passing through the induction spirales I_1 and I_2, could momentarily stimulate the nerve muscle preparation N/M; the other circuit connected the galvanometer T to the battery Z. The switch S/P allowed closure of both electric circuits at exactly the same time. The devices within the metallic frame A guaranteed that after the contraction of the frog muscle the time-measuring circuit was permanently interrupted. By placing the electrode at different points of the nerve (n_1, n_2), Helmholtz could deduce the time the nerve needed for the conduction of the stimulus. Reproduced from Ref. 31.

In comparison with his frog experiments, Helmholtz's work on humans presented special challenges. For obvious reasons, the experiments could not be conducted on preservable preparations separated from the rest of the organism. Helmholtz tried to circumvent this difficulty by measuring what today's psychologists would call 'simple reaction times'. In a communication to the Physical Society signed by Helmholtz on 15 December 1850, he reported on 'experiments on the propagation speed of stimuli in the sensory nerves of human beings', and described the basic structure of his experiments:

> In a human being, a very weak electric shock is applied to a limited space of skin. When he feels the shock, he is asked to carry out a specific movement with the hand or the teeth, interrupting the time measurement as soon as possible.[9]

When all parameters remained constant, Helmholtz found in the results of these experiments a 'surprising constancy'. As he reported to the Physical Society almost one year after his first paper, the results of repeated experiments in



256	**Chronoscope Hipp, modèle courant,** à deux cadrans, donnant le millième de seconde. Durée de marche pour un seul remontage : une minute. Le support en bois est à colonnes et se pose sur une table Fr.	380.—
257	**Chronoscope Hipp, grand modèle,** aussi à deux cadrans, donnant le millième de seconde. Durée de marche pour un seul remontage : six minutes. Le support en bois est une console se fixant contre une paroi verticale . . . . Fr.	525.—
257 bis	**Chronoscope grand modèle, à trois cadrans,** montrant les 100mes de seconde, les secondes et les minutes. Durée de marche pour un seul remontage et pour une chute de poids de 0m,50 : 30 minutes. Pour 1m,00 de chute de poids . . . . 60 » Le socle de l'appareil et son poids à chaîne, avec contre-poids, sont les mêmes que ceux des chronographes à bande Nos 244 et 245. Le remontage du poids peut se faire sans troubler la marche de l'appareil . . . . Fr.	650.—
258	**Appareil de chute** pour démonstration ou pour le réglage des chronoscopes . . . . Fr.	75.—

Figure 3. In 1861, the Neuchâtel-based astronomer Adolphe Hirsch was the first scholar to use a Hipp chronoscope for measuring the 'physiological time' of human beings. Following Hirsch's model, experimental psychologists began to make ample use of the Hipp chronoscope within their laboratories, especially between 1880 and 1900. In his seminal *Principles of Physiological Psychology* (1874), Wilhem Wundt recommended the Hipp chronoscope for carrying out psychological 'reaction experiments'. Reproduced from a Peyer and Farager trade catalogue, advertising the chronoscope in 1900. The advanced model retailed at 525 francs.

different subjects oscillated between a mean of 0.12 and 0.20 seconds. Within each series, however, there was only a 'probable error' of 0.003 seconds[10]. The relative homogeneity of measurements seemed to be a good precondition for deducing the duration of single aspects of the reaction process from the 'sums' of reaction times Helmholtz obtained. In other words, the Königsberg physiologist could start systematically to change single parameters of the experimental set up, holding the other parameters constant or at least assuming that they remained constant.

Before Helmholtz started these experiments, he had hypothesized distinct aspects or phases of the reaction process he observed. This was facilitated by the telegraphic metaphor used by Helmholtz and many of his contemporaries[11]. Thus, he explained that one part of the time between stimulation and reaction was consumed by the 'sending of the signal' (i.e. the stimulus) through the sensory nerves. Another portion of time (which Helmholtz assumed to be exactly as small or large as the first) was needed to transmit the 'message' through the motor nerves to the muscle. The remaining bit, Helmholtz concluded, was the time required 'in the brain for the processes of perceiving and willing'[9].

The concrete procedure Helmholtz then used was to stimulate the human body in different places (e.g. in the foot and the neck) and to derive the speed of the propagation of the stimulus within the sensory nerves from the differences in the results obtained. Helmholtz assumed 'that, as to their duration, the brain processes of perceiving and willing do not depend essentially from the position of the skin part that was hit'. In this perspective, it seemed to be plausible that the stimulation of different skin regions of the human body only altered 'the first link' of the reaction chain (i.e. the propagation in the sensory nerves)[9].

The results Helmholtz obtained showed that the propagation of stimulations in the human sensory nerves were approximately twice as fast as those in the frog. As he explained in his communication to the Physical Society, the difference between the time needed to react to a stimulation of the big toe and the time needed to react to a stimulation of the sacrum suggested a stimulation speed of 62.1 meters per second. Comparing the reactions to finger stimulations with those to stimulations of the neck gave a result of 61.0 meters per second[12]. Helmholtz concluded that in humans, the 'message of an impression' propagates itself 'to the brain with a speed of circa 60 Meter (180 feet) [per second] and does not differ noticeably at various times.'[9] Helmholtz also reasoned that the time needed 'by the brain for the processes of perceiving and willing' was 0.1 seconds.

He had to admit, however, that his experiments with humans involved a factor apt to threaten the required constancy of all others, namely the attention of the subject under experimentation. 'Slight feelings of sickness' and 'fatigue' of the experimental subject could significantly disturb the precision measurements, as well as distractions of all kinds: 'If at the time of perceiving the signal the thoughts are occupied with something else, and if the mind has to recall to itself what kind of movement one must carry out, it [the reaction] takes much more time.' At this point, Helmholtz had definitely reached psychological ground[13].

Adolphe Hirsch and the Hipp chronoscope

With his transition from frogs to human beings and the introduction of the variation and subtraction method, Helmholtz opened a research field that for a while was explored by individual researchers coming from different subject areas. As is well-known, it was only in the late-1870s that scholars such as Wilhelm Wundt in Leipzig, Alfred Binet in Paris and Edward B. Scripture at Yale University started to consolidate and expand this field at both the institutional and disciplinary level, contributing to a growing 'physiological' or 'experimental psychology'.

Besides the German ophthalmologist Rudolph Schelske[14], the German–Swiss astronomer Adolphe Hirsch, director of the State observatory at Neuchâtel, was one of the first individuals after Helmholtz to publish a study on the speed of 'nervous conduction'. The background for Hirsch's investigation was scientific and at the same time technological and economical. In 1858, the Neuchâtel observatory was founded with the explicit aim of providing the clock makers in the Jura Mountains with precise measurements of time. As a well-trained astronomer, Hirsch was aware that individual observation errors affected the registering of star passages that were required for astronomical time determinations. Since the early 19th century, astronomers had become increasingly aware that individual differences between observers could result in significant measurement errors. But Hirsch was not just interested in the problem of the so-called 'personal equation'. Ever since his student days in Heidelberg, where he had studied with the famous naturalist Friedrich Gustav Henle (1809–1885) amongst others, Hirsch had also been fascinated with physiology. With Emil Du Bois-Reymond, whose father came from Neuchâtel, Hirsch maintained an intense correspondence often focusing on physiological questions.

In his 1862 publication on the topic, Hirsch renamed the 'sum' Helmholtz had spoken of with respect to the time 'between the stimulation and the beginning of the movement' as 'physiological time'[15], a term Wilhelm Wundt would adopt when publishing the first textbook on the emerging discipline of psychology, *Principles of Physiological Psychology* (1874)[16]. Of even more consequence for the history of experimental psychology was Hirsch's use of an instrument that was far easier to handle than the Pouillet method used by Helmholtz: the Hipp chronoscope (Figure 3). Hirsch had borrowed this precision time-measuring device personally from the instrument maker Matthäus Hipp (1813–1893).

In the early 1860s, Hipp, the former director of the Federal Telegraph Institution in Bern, had moved to Neuchâtel, where he founded his own private telegraph factory (Figure 4). Hipp had equipped the Neuchâtel observatory with all the telegraphic apparatus Hirsch needed for communicating time signals to the clock makers' workshops in the Jura Mountains and to the telegraph office in Neuchâtel. Starting in June 1860, all the telegraph offices in Switzerland received the time signal from Hirsch's observatory, thus establishing a vast landscape of distributed standard time[17].

As early as the late-1840s, the Hipp chronoscope had been presented to the public. This 'time seer' was an electromagnetically controlled mechanical clock that could measure short time intervals with a precision of up to 1/1000 of a second. Hipp's instrument was based on Wheatstone's chronoscope, and like Wheatstone, Hipp thought that his chronoscope was potentially of major interest to the military. In 1849, the chronoscope was presented as an instrument 'to measure the time of falling bodies and for experiments on the velocity of shotgun bullets.'[18] However, it was the first of the suggested uses that actually played a role in applying the chronoscope during the 1850s. Physicists such as Friedrich Reusch and Wilhelm Eisenlohr used the Hipp chronoscope to verify Galileo's laws of falling bodies[19].

When Hirsch published his *Chronoscopic Experiments on the Speed of Sensory Perception and the Nerve-Conduction* in 1862, he stressed that research on the propagation speed of stimuli within the nerves of living organisms was, properly speaking, the task of the physiologist. Following the model given by Helmholtz, Hirsch carried out his own experiments on the topic, with human beings as test subjects. One of them was Hipp, the others mostly members of the Neuchâtel Society of Naturalists. Hirsch stimulated different regions of the body with electricity. Just like Helmholtz, he wanted to derive the speed of the 'nerve conduction' from the time differences that he measured. However, the results Hirsch obtained differed significantly from those of Helmholtz. From his experiments, he concluded that 'the conduction speed in the sensory nerves is circa 34 meters per second.'[20] That was roughly half the speed that Helmholtz had found. According to Hirsch, human beings reacted as slowly as frogs.

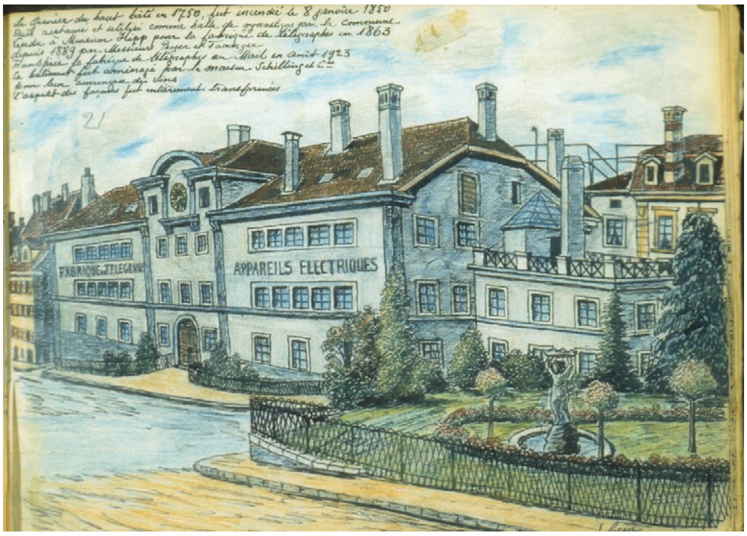


Figure 4. This drawing shows the Neuchâtel telegraph factory founded by Matthäus Hipp in 1862. Hipp constructed many of the chronoscopes used by time-measuring physiologists and psychologists in the late-19th century. Hipp's main business was the production of telegraphic apparatus and electric clocks. In the late-1850s, Hipp provided the telegraphic installations for the Neuchâtel observatory, allowing its director, Hirsch, to send precise time signals to the workshops of the clock makers in the nearby Jura Mountains. In 1860, all the telegraph offices of Switzerland received daily time signals from the Neuchâtel observatory. Shortly afterwards, Hipp installed an electric clock system in the city of Neuchâtel, serving to distribute observatory time throughout the public buildings and places of the city. Similar clock systems were delivered by Hipp to Zurich, Rome and other cities. Reproduced from a drawing (ca. 1929/1930) from the sketchbook of the Swiss artist Léopold Gern, Museum of Art and History, City of Neuchâtel.

Despite the initial publication of Hirsch's study in French and in the obscure *Bulletin* of the Neuchâtel Society of Naturalists, it soon began to attract the attention of physiologists. In 1865, a German version of Hirsch's paper was published in Moleschott's journal *Investigations into the Biology of Men and Animals*[21]. This version of Hirsch's article had a decisive impact on further studies of 'physiological time' and also on the use of the chronoscope in this context. When Wundt published his *Principles of Physiological Psychology* more than ten years later, he quoted Hirsch's article from the *Investigations* and strongly recommended the chronoscope for the purposes of physiological and psychological chronometry, because this instrument 'allows one to read off immediately the absolute value of time.'[22] In the following years, Hipp's instrument was present in nearly all of the emerging psychology laboratories throughout Europe and the USA. In 1902, the successor to Hipp's

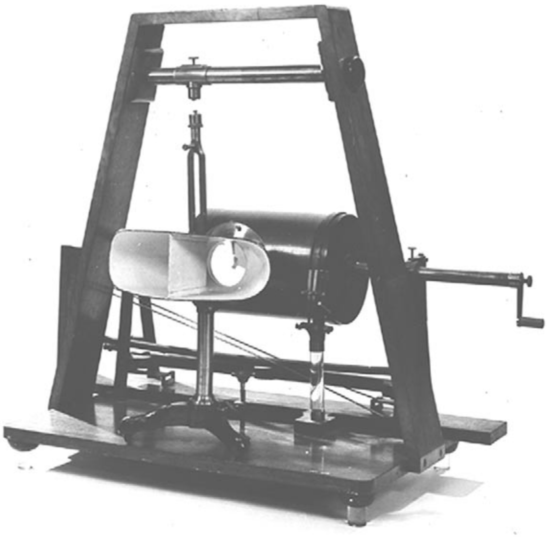


Figure 5. By means of this instrument, the Utrecht physiologist Franciscus Cornelius Donders attempted to measure the 'physiological time' of psychological processes. Presented by Donders as a 'noematachograph' (literally, a speed-of-thought writer) in 1867, this device was based on a Scott phonautograph as modified by Rudolph Koenig. The phonautograph allowed graphic recording of human speech (used in Donders' time experiments as both stimulus and reaction) and simultaneous registering of a time curve drawn by the vibrations of a tuning fork. The 'noematachograph' allowed electric sparks to be used as visual and/or acoustic stimuli and weak electric shocks as tactile stimuli. The reactions to these different stimuli could be recorded by shouting into the funnel of the instrument or by pressing a telegraph key hooked on its electric circuit (not shown). Reproduced, with permission, from University Museum Utrecht.

firm, the Peyer and Favarger company in Neuchâtel, advertised the chronoscope, underscoring the fact that it had already been sold to more than 65 scientific institutions all over the world, including Berlin, Leipzig, Paris, Cambridge, Ann Arbor, Philadelphia and Moscow[23].

Donders and de Jaager on the speed of thought

Shortly after Hirsch's publication, two physiologists confirmed the results of his experiments. In 1865, Franciscus Cornelius Donders (1818–1889), professor of physiology at Utrecht University, started to work on physiological time, in close cooperation with his student, Johan Jacob de Jaager. Their aim was to reproduce Helmholtz's experiments in human beings. In addition, both physiologists were explicitly interested in the psychological aspects of the time relations given in the human brain and nervous system. Similar to Helmholtz and Hirsch, Donders and de Jaager initially applied electromagnetism for the purpose of precision time measurements. The result of their studies was that the conduction velocity in the sensory nerves of various subjects averaged between 26.00 and 26.09 meters per second. Again, that was roughly half the speed that Helmholtz had measured[24].

During the course of their joint experiments, however, Donders became more and more sceptical about the precision of the electromagnetic recording device they used. In a manuscript, Donders described what in his eyes was the fundamental problem of this method: 'If the current intensity changes, the results also change.'[25] As long as the energy for their instruments was derived from 'galvanic elements' that were difficult to standardize, constancy of current intensity was indeed a problem that occupied time-measuring physiologists and psychologists.

Looking for other, non-electric time-measuring devices, Donders noticed the phonautograph of Léon Scott. This instrument was initially constructed to graphically record human speech. In the early 1860s, the Parisian instrument maker Rudolph Koenig supplied the phonautograph with a time-measuring device. Because Koenig was able to determine exactly how many vibrations a tuning fork made per second, he applied it as a time marker. Side by side with traces of human speech, the modified phonautograph could thus record a time curve. Koenig's apparatus allowed Donders to use human utterances as both stimuli and reactions (Figure 5). And in Donders' eyes, speech was a much more 'natural' stimulus than electricity. In addition, speech was psychologically more interesting, because it was deemed to be directly connected to specifically human activities.

In their basic form, Donders' experiments, carried out with the modified phonautograph, followed Helmholtz's variation and subtraction method. But Donders shifted the variation method of Helmholtz from physiological to explicitly psychological terrain. In a first series of experiments, he measured the time of reactions to simple verbal stimuli such as 'ki'. The experimental subject was simply asked to respond by repeating 'ki' as quickly as he or she could. In a second series of experiments, Donders confronted his subjects with an arbitrary succession of syllables 'ki', 'ka', 'ko', etc. Here, the test subject was asked to respond only when he or she had heard 'ki'. Comparing the results of the two series, Donders claimed to have obtained the time needed for a basic psychological process (i.e. the identification of 'ki'), or as Donders put it, 'the decision of a dilemma'. The average time Donders measured for this choice reaction was 0.056 seconds[26].

Epilogue

On 26 February 1864, Emil Du Bois-Reymond wrote a letter to his Neuchâtel friend Adolphe Hirsch. In it, Du Bois-Reymond described Helmholtz's attitude toward the diverging results in measuring the propagation speed of stimuli in the sensory nerves of human beings. Because the results given by other experimenters were almost always half of Helmholtz's own results, Helmholtz 'arrived at the presumption that during the complicated calculation from which his number emerged he had dropped the divisor 2 at some point.' Du Bois-Reymond added that Helmholtz wanted to replicate his experiments in order to convince himself 'that he is not feeling and acting twice as quick as other human creatures.'[27]

Helmholtz came back to his work on psychophysiological time only after moving to Heidelberg University. In a first series of experiments, carried out with his student Nicloai Baxt in the late-1860s, Helmholtz arrived at results that were close to those of Hirsch and Donders. The average speed he now found was 33.9005 meters per second[28]. Could Helmholtz really have committed a calculation error? When Helmholtz made further experiments, he was confronted with another surprising phenomenon. In spite of improved measuring devices, he had to face the fact that in 'mid summer 1869…much larger values' surfaced on a completely regular basis. Now the average was 64.5611 meters per second[29]. Apparently, the changing room temperature and, as a consequence, the slight changes in body temperature, exerted a considerable influence on the experimental results. Lowering the temperature of body limbs by means of ice, Helmholtz and Baxt made experiments that confirmed this hypothesis[30]. What had initially presented itself as a possible calculation error thus turned out to be a new research topic.

This episode is not purely anecdotal. Through his experiments from the early 1850s, Helmholtz had opened a field of research that was eagerly explored by physiological psychologists of the 19th century and cognitive scientists of the 20th century. However, the experiments carried out in this field remained susceptible to disturbances. Whereas timing devices were steadily improved, the changing attention of experimental subjects continued to threaten the reliability of psychophysiological time experiments. Scholars managed to measure the velocity of impulse conduction in the peripheral nerves with increasing precision, but it remained hard to investigate the dynamics of central processes as long as time was the only parameter. In fact, Helmholtz's ingenious variation and subtraction method had turned the brain into some sort of black box. Only with the advent of 'real time'-scanning technologies [e.g. electro-encephalography (EEG) and positron emission tomography (PET)], did it become possible to bring some more light into that dark chamber from which, day by day, our thinking, feeling and doing emerges.

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