THE
HUMAN MOTOR

Energy, Fatigue,
and the Origins of Modernity

ANSON RABINBACH

BasicBooks
A Division of HarperCollins*Publishers*

CHAPTER FIVE

The Laws of the Human Motor

The human body has been compared, insofar as the source of movement is concerned, with a machine that functions by means of heat. We know that no machine ever creates energy. The most perfect motors can do no more than transform heat into movement.

—Fernand Lagrange
Physiologie des Exercises du Corps

SOCIAL HELMHOLTZIANISM

BY the 1890s the achievements of German physics and physiology, as well as Marey's investigations of the human and animal machine, produced a program for investigating the physiology of labor power. The techniques pioneered by Marey, together with the efforts of a small, international avant-garde of European physicians and physiologists, were enlisted in the search for precise laws of muscles, nerves, and the deployment of energy in the human organism at work. Marey's laboratory served as both a training institute and a clearing house for the new energeticist science.

These physiologists translated the ideas of energetics into a program of social modernity that conceived of the working body as a system of economies of force and as the focal point for new techniques that could eliminate social conflict while ensuring productivity. Firm believers in the achievements of materialist physiology, and dedicated to social progress, these pioneers of the science of work were for the most part liberal republicans and in some cases socialists. They saw industrial physiology as the intersection of social policy and medicine. For these progressive *savants* "social hygiene" could be served by the new ideas of biological materialism and by the triumphs of the laboratory. Their hopes were predicated on a neutral and benevolent state that would implement their achievements and ensure the rational application of scientific solutions to the "social question."

"Social Helmholtzianism" thus created an image of work entirely unconnected to milieu, class, or political interests. It presented the body of the worker as a universal, degendered motor, whose specific and nonenergetic needs could be bracketed. Energy conservation became a social doctrine. The author of a major treatise on the physiology of work, André Liesse observed that "the human being . . . always remains a machine, but that machine directs itself, within the limits of the environment in which it performs, and the faculties it employs. It is, if we permit ourselves the expression, a self-propelling machine, powered by itself, with the aid of nutrition, the source of its energy and the will to conservation."[1] Armand Imbert, a Montpellier physiologist, an assiduous researcher of fatigue and a dedicated reformer sympathetic to the workers' movement, elaborated some of its most cherished ideals in his 1902 synthesis, *Mode de fonctionnement économique de l'organisme.* "It is a fascinating idea," wrote Imbert, "to think that our organism, as a machine which produces work, is constructed according to a general model and presents a mode of functioning in which every wasteful, or even less powerful expenditure of energy, is avoided."[2] Imbert's characterization underscores the productivist utilitarianism of the new science of the working body. Its goal was to discover efficient expenditures of labor power, to find "the degree of energy economy which we unconsciously realize in the functioning of our organism as a motor."[3]

By the later 1890s the problem of fatigue was identified as the paramount manifestation of the body's limits to produce work. Fatigue, European scientists and social reformers concluded, was a greater threat to the future of a modern industrialized nation than either rapacious capital or the atavistic worker lacking in discipline and time sense. "Any considerable amount of work," Imbert noted, "measured in duration or in terms of quantity in relation to a unit of time, involves fatigue, and it is in reality because of the preoccupation with reducing fatigue, that we regulate our functions."[4] The so-called natural desire to avoid work did not lead to an unproductive laborer; it was the body, undermined by excessive, irregular, poorly organized, and exhausting work. Consequently, a rational solution to the labor problem could be found in physiology, not politics. Labor power was seen as a purely physiological issue, a single instance of the more general problem of energy conservation and its transformation into work.

The new science of labor made possible the search for the quantitative laws of the muscles, the nerves, and the deployment of energy within the human organism. Though the physiology of work could not be an exact science, it nevertheless "confirmed and explained the basic law of all physical processes, the 'law of the least effort.'"[5] The *law of the least effort* (sometimes called the law of "least action"), to which Helmholtz devoted several theoretical studies in the mid-1880s, posited that masses in motion always exert the least amount of work in passing from potential to kinetic energy. Helmholtz claimed that this principle could be demonstrated in a variety of specific cases, including electromagnetic conversions.[6] The idea that nature essentially found the shortest means to achieve its ends could, the physiologists of work concluded, also permit the discovery of the most suitable external conditions for efficiently using those forces employed in labor. Moreover, the physiologists applied this idea to the body: "Following the principle of the conservation of energy, which has been indisputably verified on the muscles, the heat given off, and the mechanical work produced, will be found to be equivalent; that which the human motor gains, on the one hand, it loses on the other."[7]

For the pioneers of the new science of the laboring body, social Helmholtzianism envisioned a labor force that did not have to be inculcated with eternal truths about the importance of will, the sin of idleness, or the value of work: Moral exhortations, the idealization of the "true worker," and the reflections of political economists on the needs of the worker were obsolete. Instead, the physiology of labor power offered a neutral approach free of social conflict: in the future the industrial workplace would be modeled on the technology it served.

The emergence of a physiological approach to labor coincided with important changes in work during Europe's second industrial revolution. If the first industrial revolution was essentially a revolution in steam-driven technology, textile production, and the railroad, the second was a revolution of electric power, of steel and chemical production, and of the rise of industries producing heavy machinery. European industrial production soared after 1895: the industrial enterprise expanded accordingly, with increasing emphasis on planning, administration, and design of the plant.[8] By the end of the nineteenth century the patterns of industrial discipline typical of the first half of the century (paternalism, familialism, surveillance) also changed markedly. With a huge workforce, rapid turnover, and immigration, ideas of industrial edification were either obsolete or took a back seat to issues of time, work norms, and wages. The "new factory" of the second industrial revolution was rapidly eliminating craft production and was employing an unskilled workforce in a setting where new technologies increasingly determined the nature of work and the organization of the workplace. The moral discipline of work, which middle-class reformers attempted to inculcate among earlier generations of industrial laborers, was giving way to the discipline of the workplace, to conflicts over the tempo of work, and the risks of mechanized industry. Unions were increasingly challenging management over work norms and the right to determine them.[9] In an era when work was measured by time and motion rather than by desire or will, the prospect of a purely technical or scientific solution to what Michelle Perrot has called the "crisis of discipline" was particularly welcome.[10]

For this reason the apparent scientific neutrality of the medicalized discourse on labor power appealed to progressive reformers on both sides of the Rhine. Efforts to regulate scientifically the tempo of labor coincided with the first attempts by the governments to regulate labor conflict and create a "scientific labor policy." For the proponents of the new science of work, the efficiency of the human organism provided reformers with a "higher law" than the vicissitudes of class conflict and authoritarian labor policies. Nevertheless, only after the science of labor power had established itself as an acknowledged source of expertise, or social knowledge, did it intervene significantly in the political arena. As we shall see, industrial accident legislation, the length of the working day, the duration of military service, and the economics of the national deployment of the labor force were all eventually judged by the standards of research in fatigue.

We can distinguish three phases in the early development of the European science of work: (1) a theoretical development in the study of the economies of energy, heat, motion, and fatigue in the body (1867–1900); (2) the growth of a laboratory science of work and the collection of data on modern industrial work (1900–1910); and (3) the first interventions in the workplace and efforts to influence state policy on questions such as length of the working day and the causes of industrial accidents. This latter period also witnessed the first challenges posed by the American system of industrial management devised by F. W. Taylor. In each of these phases scientists attempted to reduce labor to a purely instrumental, or technical act, which lent itself to the rigors of physiological experiment and social science. Although in this chapter we will be concerned with the initial phase from the 1880s to roughly 1900, the economics of energy remains a motif of the science of the working body.

MUSCULAR THERMODYNAMICS

The central problem confronting the nineteenth-century physiologists who adopted the thermodynamic model of the human motor was the production of animal heat and the physiological processes that consumed and replenished the body's energy supply. The historian of biology William Coleman has emphasized that "during the nineteenth century, the overall chemical and physical relationships of the respiratory process—which subsume the question of organic heat production—were brought into close agreement with the principle of the conservation of energy."[11] The effort to demonstrate the principle that equivalent amounts of energy produce equivalent amounts of mechanical work—that the consumption and the expenditure of energy were equivalent—became a recurrent theme of late nineteenth-century physiology. In Germany and France, physiologists attempted to prove that Julius Robert Mayer had been right to claim in the 1840s, though without substantiation, that "the organism in its overall measurable relations with the external world—that world serving as source and drain for the organism's energy supply—was an energy conversion device, a machine no less than those scrutinized by mechanics and thermodynamics."[12]

After 1850 muscle physiology was a fertile ground for applying energy conservation to physiology.[13] As early as 1845 Mayer wrote that "the muscle is a tool, by means of which the transformation of force is effected, but it is not the substance which is transformed into the performance produced."[14] Mayer showed how oxidation was the ultimate source of energy for the organism's capacity to do mechanical work.[15] And Helmholtz, in one of his earliest essays, stated that research on animal metabolism confirmed that the materials supplied to the body by respiration and digestion "provide the entire sum of vital warmth during the successive stages of their combination."[16]

However, the question of how the muscles converted heat to work remained a source of persistent controversy. By the late 1840s developments in muscle physiology shifted to the "electro-motor" power of muscle tissue discovered by the Italian physiologist Carlo Matteucci and by Du Bois-Reymond. The latter's *Untersuchungen über thierische Elektricität* (1848) was a mechanist manifesto and a strongly worded polemic against vitalism.[17] In the 1850s Helmholtz's famous experiments measuring the duration of muscle spasms demonstrated that "the course of these inner transformations remained exactly the same, even when the muscle performed under different external conditions of load."[18] Marey's myograph (1867) also enhanced the popularity of studies of the intensity of muscle contraction under various conditions, providing some of the earliest tracings of muscle fatigue.[19]

In the second half of the century, German physiologists remained in the forefront to demonstrate the relevance of energy conservation to muscle physiology.[20] Adolf Fick, an early pioneer of muscle physiology, confirmed that the comparison between the action of the muscle and the steam engine was "apt and instructive [since] in both cases we are concerned with the effects of chemical forces through which the motion of certain masses and also heat are created."[21] Concerned with the chemical changes in a muscle as a consequence of fatigue, Fick also scrupulously investigated the chemistry of "muscle substance" during work: "The fact that chemical changes in the muscles take place is already indicated by certain general phenomena which are easy to observe on one's own body. Everyone knows that when a group of muscles works very energetically for a time, this does not continue with the same force despite the impulses of the will. This phenomenon, which is well known by the name of fatigue, proves irrefutably that the muscle undergoes an inner transformation through its work."[22]

Initially Fick closely followed the chemist Justus von Liebig's view that the decomposition of nitrogenous substances, especially protein, was the chief source of the muscle's work, a theory abandoned only in the last quarter of the century. Paralleling energy conservation, Fick claimed that the work of the muscles revealed that "the sum of potential and moving energy of the system is always of constant size, which cannot be altered by any positive or negative work of any force within the system."[23] Experimenting on themselves during a strenuous climb of the Faulhorn (literally lazy mount), Fick and his collaborator, the chemist Johannes Wislicenus, found that the protein used up in the effort was only a small fraction of the total calories consumed. These and other experiments confirmed that the analogy of the human motor could be applied to the physiology of nutrition as well: "A machine is built of iron. Yet, in work this iron is hardly consumed in significant quantity, while the burning of coal provided the work."[24] Coal represents, of course, carbohydrates, while the iron, or protein, was necessary in only limited amounts.

Fick's discovery, as well as the experimental work of a London chemist Edward Frankland, revealed that muscle protein (as Liebig had held) could not alone account for the work performed, though attention soon focused on the importance of intermediary metabolic processes, especially the metabolic exchange of foodstuffs and nutriments.[25] Carl von Voit, professor of physiology in Munich, who studied and collaborated with Liebig, undertook some interesting empirical studies of the food consumption habits of Bavarians during the 1870s. But von Voit's most famous work, with his co-worker Max von Pettenkofer, were attempts to measure the content of both gaseous and solid wastes, the energy-equivalents of food intake. In a series of well-known experiments conducted on dogs, Voit demonstrated that the animals converted nitrogenous substances into energy, but found that the dog's urea or fecal substance could not alone account for the production of heat. Using a respiration chamber—an apparatus that could control food intake as well as end-products and waste over time—they ascertained that the total daily input of carbon, hydrogen, nitrogen, and oxygen was present in the body's excretions and exhaled gases. Voit and Pettenkofer also made the important discovery that oxygen utilization differed according to the food consumed, influencing the body's efficiency. Although he refuted Liebig's theory of protein as the primary source of muscular energy, Voit's effort to discover an accurate and universally applicable measure of the value of foodstuffs in relation to energy output was hampered by his reliance on a traditional framework of the chemical theory of metabolic "substances," or *Stoffwechsel.* A mathematically reliable system of equivalence between the amount of potential energy ingested in the form of nutriments and the amount of energy produced, remained elusive.[26]

A more conclusive answer was provided by one of Voit's students, Ludwig Max Rubner, who jettisoned the idea of chemical substances and used calories to calculate the energetic content of each nutriment (fats, protein, starch) required to produce an equivalent amount of energy. Despite Voit's resistance, Rubner's theory of the substitutability of foodstuffs was ultimately confirmed, leading in 1894 to his establishing of the exact caloric values of all nutritive substances. Rubner had finally solved the problem of energetic equivalents, or *Kraftwechsel,* in human physiology:

> Calculation of the energy content of nutritional materials henceforth provides us with a legitimate expression of their capacity to provide for specific needs of the cells. Useful energy is a measure of their value, transformed energy a measure of the biological energy created. These are the foundations of an energetic conception of warm-blooded life.[27]

Rubner's experiments with a calorimeter (1889) assured the triumph of *Kraftwechsel* over *Stoffwechsel,* offering conclusive proof of the organism as a "heat machine."[28] After 1891, when Rubner became professor of hygiene in Berlin, he greatly expanded his "hygienic" approach to physiology, working not merely as an advisor to the military, but popularizing his ideas in a series of works on hygiene and nutrition.[29]

ELASTICITY AND EFFICIENCY: AUGUSTE CHAUVEAU

The view that the human machine possessed a superlative efficiency was a key precept of the energeticist physiology. The German physiologist Emmanuel Munk observed that the human motor was "the most complete dynamic machine" as compared with the "machine" proper, which wastes nine-tenths of its heat in the conversion to force, whereas the body uses 40 percent of its chemical materials in the production of work.[30] The source of the body's greater efficiency was the "law of the least effort"—the internal economy of the conversion process within the organism.

In his 1867 course at the Collège de France, Marey also argued that "the chemical actions which take place in the organism are the cause of the production of heat in animals," and consequently "the animal organism is no different from our machines except by its more advantageous efficiency."[31]Demonstrative proof of the human machine's greater efficiency was the contribution of Marey's co-worker, Auguste Chauveau, whose prodigious work in the 1880s resulted in the "law of the least effort" in physiology. For Chauveau, "the contracted muscle is the result of a special and absolutely perfect elasticity of the muscles . . . adapted to the functional purposes envisaged and anticipated by muscular work."[32] His experiments on the flexors of the forearm demonstrated the "unconscious, but constant effort to reduce the total expenditure of energy to a minimum." The principle of efficiency is contained in the economy of work performed by muscles, Chauveau claimed, so that in its design and execution, the human motor always chooses "the most economic course."[33] Chauveau therefore concluded that a "mechanical optimum" *(optimum mécanique)* might be obtained if certain loads and speeds could be calculated for each kind of physical labor.[34]

These initial efforts to produce a thermodynamics of the working body did not always meet with universal acclaim. In France, the growing challenge of German physiological mechanism produced considerable controversy over how far the analogy of the motor could be pursued. Defenders of Claude Bernard's view that biology was sovereign in its own domain were skeptical, as were some physiologists sympathetic to materialism, like Gustave-Adolphe Hirn, who acknowledged the primacy of energy in explaining the universe but who remained dubious of Marey and Chauveau's overliteral use of the metaphor of the machine.

Hirn cautioned that the metaphor was being pushed too far: "The phenomena of energy does not in reality correspond to the reality of things, as the acts of an automata do not correspond to those of a living being."[35] He admonished the mechanists for their zeal, claiming that "the living motor was neither a thermal nor a caloric motor."[36] Nevertheless, defenders of the metaphor continued to assert, as did Chauveau, that "vital properties are nothing other than the aptitude to transform . . . *potential energy* or *forces of tension* . . . into a special mode of actualized energy."[37] And the leading defender of physiological materialism in France, Charles Richet, contended that even mental activity could be understood as a transformation of force, producing a chorus of rebuttals by those whose Cartesian sensibilities were profoundly injured by his refusal to accept the dualism of mind and body.[38] One writer argued that the increase in "crimes of blood" during rising temperatures proved that body heat or "external temperature was one of the elements that determined the forms of thought."[39]

Despite these controversies, by the 1890s the physiology of human and animal energetics established a more sophisticated understanding of the human motor's efficiency at work. Both Marey and Chauveau believed that the crucial elements in the science of work that emerged from their research included (1) the conversion of energy and the measurement of the chemical forces that undergo "metamorphosis" in work; (2) the problem of "physiological time," for example, in measuring the duration of an impulse sent from the nerves to the muscles; (3) the elasticity of the muscles and the phenomena of shock; (4) the problem of fatigue; and (5) the analysis of time and motion, the decomposition of the act of work into its smallest measurable units.

CARE AND FEEDING OF THE HUMAN MOTOR

Studies of the basic principles of muscle physiology underscored the critical role of diet and nutrition in creating labor power. As André Liesse put it: "Human labor, considered from a physiological point of view, could be evaluated in terms of calories and kilogrammeters."[40] But which diet was appropriate for the optimal performance of the worker? Some German physiologists asked whether "our worker with his poor diet of potatoes can satisfy all his needs," pointing to chronic lack of protein in the national diet. "The iron of the steam engine is also used up over time [and] protein-rich nutrition gives the worker well-formed, powerful muscles."[41] The diet of the working man became a *cause célèbre* of physiologists whose search for the proper combination of nutritional elements was frequently linked to the first comparative nutritional studies of workers of different cities or nations. Von Voit, Rubner, and others found that fats and meats were necessary for reproducing the body's albumin supply, while starches and sugars were necessary for regulating and properly utilizing protein. How much of the required starch might be derived from different foodstuffs remained unresolved.

One common argument, for example, was that the English workers' diet of meat and wheat-flour bread could account for their superior productivity, whereas the German workers' diet of potatoes constituted an economic disadvantage. This controversy culminated in the famous "Brot versus Kartoffel" debate in the 1870s and 1880s, when von Voit calculated that the worker should consume roughly 70 percent of his carbohydrate diet in bread and the remaining 30 percent in "the form of potatoes and vegetables."[42]

The diet of the French worker caused concern among physiologists who tried to ascertain whether different kinds of work and different individuals demonstrated different metabolic rates. As early as 1858, Hirn questioned whether "the caloric sum, which, for example, produces chemical reactions in our bodies, is not different when we are at rest, and when we work, when we raise a weight, when we meet resistance." He also correlated the "age, sex, and temperament" (for example, "nervous and bilious, lymphatic, strong and robust") with three measurements: (1) calometric; (2) the oxygen inhaled and expelled; and (3) a dyanometric calculation of the work produced "when the individual functions as a motor."[43] In the 1860s, Jules-Auguste Béclard performed simple experiments on human subjects to measure the amount of heat produced in the body before, during, and immediately after physical work to determine the quantitative relationship between each of these phases of work.[44] Richet and Hirn attempted to ascertain whether "the machine is subject to the universal law of thermodyamic equivalence, that is, if it consumes heat in order to furnish positive work, or whether it also accumulates heat during rest or 'negative work.' "[45] The distinguished physician and political figure, Paul Bert, devoted a two-volume work entitled *La Machine humaine* (1867–68) to a study of the diet of English prisoners.[46]

By the 1890s ambitious experiments were frequently undertaken to provide data on the comparative caloric requirements of different social groups. Armand Gautier, a professor of physiology at the University of Paris and, in 1870, director of the first laboratory of chemical biology established in France, attempted to construct a profile of different social groups and different nationalities, according to their food consumption and chemical wastes, an ingenious effort at physiology "from below."[47] Gautier asked how could "the needs and losses of the energy of the man whose organs function normally" be measured, and how do they "vary according to this same activity?"[48] For Gautier, the laws of physiology ordained that in a healthy organism the alimentary needs of a normal adult man will "always be proportional to the expenditure of energy of which he is the center; and such is the principle of a new method which in its turn will give us the measure of those needs." Gautier believed his calculations were vastly superior to those using general statistics on the food consumption of large human communities or to those relying on the observation of individual cases.[49] In short, the dietary requirements of different groups could be scientifically forecasted by the comparative analysis of their excretory products.

Employing a *respiratory calorimeter,* similar to the one used by Rubner and further developed by the American physiologist W. O. Atwater, Gautier measured an experimental human subject who "eats, works and sleeps in the chamber for several days." The device established the quantities of heat lost, work accomplished, oxygen absorbed, and water, carbonic acid and excretory matter lost" in precise figures.[50] Gautier employed two broad groupings, work and rest, subsequently combining his own studies with those already accomplished by other physiologists to produce a comparative picture (table 5.1) of the daily consumption of nutrients by different social groups and different types of workers.

On the basis of these calculations, Gautier believed he could find the minimum number of calories necessary to power a worker or soldier at different tasks. Gautier distinguished between the nutritional requirements of work performance and the caloric requirements of a body concerned only with maintaining heat and other normal functions. As a result, physiologists could distinguish quantitatively between "useful work," or economic work "appreciable in terms of its results," and the total energy required by the body under any circumstances.[51] For a worker at rest 2604 calories in 24 hours might suffice, whereas a worker at hard work requires 3556 calories, "an increase destined to furnish the supplement of energy necessary for the labor of a worker without excess."[52] For fatiguing work, an average of 3800 calories was required, but for "exceptionally severe work" 5000 utilizable calories might be required."[53] Other physiologists had found that in extremely demanding work, for example, among the Russian woodcutters of Astrakhan, the miners of Tomsk, or German brickmakers, more than 5000 calories daily was hardly extraordinary.[54] These figures calculated the relative nutritional values required for each task, for a given number of hours of work, and for a precise number of days and months.

TABLE 5.1

Daily Dietary Consumption According to Social Groups (in grams)

	Protein (Gr.)	Fats (Gr.)	Carbohydrates (Gr.)	Source
Alimentation at rest				
French bourgeois with moderate exercise	120	70	330	Gautier
Average Paris population	115	48	333	Gautier
English bourgeois with moderate exercise	92	72	352	Forster
German worker	137	72	352	Voit/Pettenkofer
Swedish soldier (peacetime)	130	40	530	Almen
Prisoners	87	22	305	Schüster
Silesian peasant	80	16	552	Meiner
Average	108	49	403	
Alimentation during work				
French worker (much work)	190	90	600	Gautier
English blacksmith (fatiguing work)	176	71	666	Playfair
Swedish worker	146	44	504	Hildesheim
French soldier (wartime)	192	40	651	Gautier
Swedish soldier (during a campaign)	146	59	557	Almen
Bavarian soldier	118	56	500	Voit
German soldier	130	40	550	Moleshcott
Average	150	60	563	

Source: André Liesse, *Le Travail: Aux point de vue scientifique, industriel, et social* (Paris: Guillaumin, 1899), p. 23.

Gautier emphasized that observing the worker in the working milieu rather than in the laboratory might yield more useful information about nutritional requirements. The actual workday demanded different calculations to determine the ratio between the food, the energy required, and the amount of work. To calculate the ratio of "utilizable amount of labor" to the actual work expended, Gautier studied the wine and spirit workers of Midi, in the South of France. Their primary task was to raise the level of the water or wine in large vats by means of a pump over the course of nine or ten hours. By breaking the work down to its component parts, Gautier estimated that the total work expended by a "good worker" laboring "to the borders of fatigue," was about 250,700 kilogrammeters and that studies of other laborers and mountain climbers also showed that "a good workman furnishes in a day of eight to ten hours from 260,000 to 280,000 kilogrammeters" of work.[55] This measure necessarily includes the energy expended in all the body's functions and does not, of course, entirely translate into *utilizable* work.

To his surprise, Gautier discovered that an actual work situation hardly measured up to his expected calculations. In fact, caloric consumption and work performance were more elastic than he had anticipated. In the case of the wine workers, the principle of entropy, or loss of energy, could be reaily demonstrated. Gautier calculated that only 25 to 65 percent was translated into useful work. Their total work expenditure usually required a considerable amount of "additional daily foods" (an average of 1779 calories over and above the daily amount required without work). He also calculated that although the additional calories should theoretically be sufficient for any work that might be required, in fact, less than a third of this potential energy was converted into "real and tangible work." He could only explain this discrepancy by hypothesizing that the "total energy dispensed by the human being during work" diminishes over time.[56] In other words, fatigue accounted for the extraordinary inefficiency of output that Gautier confronted in the Midi wine workers.

Gautier's simple caloric measurements could not adequately explain the complex physiology of energy production, nor could they account for the "loss" of caloric energy in the actual work. In contrast to the more optimistic Chauveau, Gautier suspected that "the human machine, from a muscular point of view, was capable of a rather weak efficiency when compared with the maintenance necessary."[57]

Gautier ultimately concluded that the wine workers were not economizing their energy output to full advantage. The "loss" of energy in transforming caloric intake to work performance could also be explained by the lack of economy of force exercised by the worker, by the differential course of fatigue, and by the inefficient use of time and motion during work. Gautier had clearly reached the point where the search for the laws of muscular thermodynamics became a science of fatigue. The principle of energy conservation had become a *fait social,* an empirical reality that could be precisely measured and quantified in terms of specific work performance. By the turn of the century, energy conservation became the fundamental fact not only of nature but of society as well.

THE LAWS OF FATIGUE: ANGELO MOSSO AND THE INVENTION OF THE ERGOGRAPH

The physiology of the muscles, of nutrition, and the empirical observations of Gautier—all led to the same conclusion: fatigue was the chief source of the body's resistance to work and lack of efficiency. Fatigue was identified as the natural barrier to the efficient use of the human motor. Before 1870 there were hardly any studies of fatigue, by 1890 the floodgates released an outpouring of literature on all aspects of fatigue. Already in 1867, Marey identified the central role of fatigue in his law of human effort: "A muscle is subordinate to two influences, one is reparative: nutrition; the other is exhausting: its motor function. The body's capacity to produce motion varies according to the one or the other influence affecting it."[58] Fatigue represented the corporal analogue of the second law of thermodynamics, diminishing the intensity of the energy converted in the working body, tending toward decline and eventually, inertia. A dynamic force, autonomous of the will, fatigue was subject only to the physiological laws of function. The science of fatigue could determine "the best conditions for production and indicate which person is most suited for the work accomplished, which tool is most appropriate for which organism, or which task; it makes possible a rational selection of persons for the diverse professions in conformity with their well-being and happiness. Each superfluous fatigue can be eliminated." The science of fatigue was "a *hygiene of efficiency.*"[59]

In the early 1870s, Hugo Kronecker, a German physiologist who had once worked with Marey in Paris, made tracings of the contractions of frogs' muscles over a period of time. Kronecker observed that in a fatigued muscle, the intensity of the contractions diminished with *regularity* until the organism was incapable of working.[60] He concluded that fatigue had its own dynamic laws—as heat is converted into work—revealing an economy of decline that was irreversible.

The author of the classical text of the new science of fatigue was Angelo Mosso of Turin, an Italian physiologist and educational reformer. His *La Fatica* (1891) instantly became a minor sensation, the result of a decade of laboratory investigation and a synthesis of German physiology and French technique. Mosso had studied with Jacob Moleschott and Carl Ludwig in the early 1870s, and in 1873 worked closely with Kronecker whom, he later noted, "first fired me with the desire of applying myself to the study of fatigue." He also absorbed the practical experimentalism of Marey (a debt he always acknowledged) with whom he had worked briefly in Paris in 1874. Combining a profound admiration for German physiology with a solid grasp of the inscription techniques pioneered by Ludwig, Helmholtz, and Marey, Mosso placed the study of fatigue within the canon of mechanical materialism.

Mosso considered the law of energy conservation to be "the greatest discovery of the last century." Its irrefutable principles were "the thread of *Ariadne* which guides us in our search of the unknown; by their means the most secret region of science becomes illuminated by a ray of light."[61] In 1884 Mosso invented the first efficient and accurate measure of fatigue, the *ergograph* (register of work). With this device he constructed "an instrument which would measure exactly the mechanical work of the muscles of man and the changes which, as the effect of fatigue, may be produced during the work of the muscles themselves." His ergograph consisted of two parts. First, Mosso built a supporting platform and metal glove that fixed the hand and forearm in such a way that the index and ring fingers could not be moved, while permitting the middle finger to remain free. Attached to the unhindered finger was a string and a weight that then set in motion a registering apparatus.[62] By raising the weight, the forearm muscles were isolated and quickly fatigued, establishing a tracing of their diminishing intensity.

With the aid of the ergograph Mosso produced hundreds of graphic representations of fatigue, or "fatigue curves," which plotted the rate of fatigue in different individuals and with different weights. Mosso's first studies, conducted on his own laboratory assistants, contrasted sharply with the uniform results of Kronecker's research in the muscles of frogs. Mosso's tracings showed remarkable variety on the "fatigue curves" of different subjects, including those of relatively equal strength, age, sex, or occupation. While some individuals maintained muscle contractions of relatively equal height and intensity, dropping off markedly once fatigue set in, others demonstrated a more gradual decline of muscle force under exactly the same conditions. These early studies seemed to indicate that "the way of living, the night's rest, the emotions, mental fatigue, exert an obvious influence upon the curve of fatigue."

But fatigue exhibited unpredictable and frequently perplexing behaviors. For example, the feeling of physical tiredness was often totally unrelated to the actual onset and course of fatigue. Fatigue also differed from individual to individual, displaying an astonishing variety of patterns. Muscle fatigue and brain, or mental, fatigue were sometimes mutually constitutive, but just as often they were mutually exclusive: "There are some people, robust so far as the development and energy of their muscles are concerned who are incapable of any intellectual work."[63] Mosso recounted his witnessing of physically fit soldiers being forced to take written examinations to prove they were literate: "I have often seen great strong men perspire until drops of sweat fell upon the paper. At Lecco I saw one faint during the examination, then, feeling better, demanded another trial; but on the threshold . . . he turned pale and fell into a fresh faint."[64]

These apparent differences only strengthened Mosso's unshakeable determination to demonstrate that fatigue's dynamic laws remained constant. His great purpose was to eliminate all subjective aspects from the study of fatigue, to find its discrete and therefore unchanging laws of motion. To resolve these quandaries, Mosso subjected all types of fatigue to intense observation and quantification. Paradoxically, the result of these studies, he argued, was to show that the "intimate and most characteristic feature of our individuality—the manner in which we fatigue" was also subordinate to the laws of nature. "If, every day at the same hours we were to make a series of contractions with the same weight, and in the same rhythm, we obtain tracings which all had the same outline, and thus we should convince ourselves of the constancy of individual fatigue."[65]

Experimenting on his assistants with electrodes attached to the arms, Mosso compared the involuntary spasms of their muscles produced by mild shocks to voluntary movements with strikingly similar results. His conclusion was that each person fatigues differently, but that each individual's fatigue curve displays the same regularity, and the same pattern, regardless of the causes of fatigue, and independent of the kind of work performed. Even intellectual fatigue, Mosso asserted, displayed the same regularities as physical fatigue. Those who fatigue gradually in physical labor, fatigue gradually in mental work; those who fatigue rapidly in mental work, fall prey to its effects more quickly in physical labor. Ergographic tracings during arduous intellectual exertion showed that mental fatigue visibly diminished the efficacy of muscular contraction.[66]

Moreover, Mosso contended that fatigue was a poison. In a famous experiment he injected the blood of a fatigued dog into the body of a rested one to show how the toxins immediately produced the characteristics of fatigue. Immediately after receiving the fateful injection of tired blood, the rested dog became exhausted. With this experiment Mosso claimed two decisive discoveries: First, that fatigue was an objective phenemenon with laws directly analogous to the laws of energy. Second, fatigue demonstrated a consistent "diminution of muscular force," which could be graphically represented and measured.[67] Mosso's "law of exhaustion" holds that the course of fatigue is always constant and independent of the work done. Fatigue obeys its own dictates—a fatigued body refuses to work until sufficient rest and nutrition replenishes its supply of energy. Mosso thus posited his *primary law of fatigue and of sensation*—namely, "that intensity is not at all proportional to the intensity of the external cause which produces them." Simply stated, the exhaustion of our bodies does not increase in a direct ratio to the work we do. Fatigue often begins to show its effects before the *potential* for work has ended. In this sense fatigue exhibits a protective dimension. It "saves us from the injury which lesser sensibility would involve from the organism."[68]

Mosso's breakthrough resonated far beyond his Turin laboratory. He believed that if fatigue could be carefully observed and studied under controlled conditions, then "the conservation of the internal energy of the muscles" could be enhanced.[69] The discovery of the laws of fatigue would lead directly, he hoped, to its more efficient control, if not to its ultimate conquest. The science of fatigue thus went beyond "muscular thermodynamics" to the direct investigation of the sources of resistance to work. The psychologist, mathematician, and aesthetic theorist Charles Henry called the 1894 French translation of Mosso's work "a new chapter in animal mechanics." The discovery of the "curves of exhaustion of different animated motors" permitted the calculation of fatigue in various activities: the movements of the body in the march, on the track, and so forth.[70] Marey's method of graphically representing motion—the decomposition of motion into micrological units over time—was applied, not to the body as a whole, nor even to the limbs and muscles, but to the phenomenon of fatigue. Henry's prescient remarks foretold how laboratory research in the "excellence of the animal motor," and the discovery of its law of motion, would soon be applied to actual situations.

THE SCIENCE OF ERGOGRAPHY

Within a year of the publication of Mosso's work in French, Fremont's sensational photographs of the forgers appeared in *Le Monde Moderne*. By 1900 laboratories devoted to the experimental science of the "human motor" were established in almost all continental countries. Ergographic fatigue studies were taken of "the maximum utility of work under a variety of conditions." Mosso's Turin laboratory produced extensive research on the conditions governing the optimum of work intervals necessary for reducing physical and mental fatigue.[71] His original ergograph was improved and extended to ever-more complex forms of work, while overcoming the "artificial limits created by the fixation of the digits" by measuring the upper arms, legs, and torso.[72] Some of Mosso's students compared involuntary and voluntary muscle fatigue; some plotted the effect of fatigue on the neuromuscular system; others charted the relationship between fatigue curves and different types of intellectual work.[73]

Marey and Mosso's pioneering work soon spawned a second generation of field and laboratory researches, first in France and Belgium, and later in Germany. In Belgium, the philanthropist and social philosopher Ernest Solvay established an institute of energetic physiology bearing his name, Laboratoire d'Énergétique Solvay, which after 1902 was renamed the Institut de Physiologie de Bruxelles and was directed by the capable Polish-born and Paris-trained physiologist, Josefa Ioteyko.[74] Solvay was motivated by his conviction that "all the factors which directly or indirectly intervene in the organic phenomena relevant to the human being living in society have a physio-energetic value capable of determination by means of the same unit"—a belief that became a search to improve "social efficiency."[75]

In addition to the physiological institute, Solvay founded several other institutes, including an institute of sociology to realize his plan for developing a science of "physio- and psycho-sociological energetics." The physiological institute attempted to derive precise mathematical correlations of age, sex, and occupation with energy consumption; to compare the rates of plant and animal growth; and above all, to provide a mathematical basis for subsequent research in fatigue.[76] Solvay also combined physiology with the psychological studies of intelligence and mental fatigue pioneered by Alfred Binet, the French psychologist (and inventor of the intelligence test), to create a new social science based on translating the laws of energy conservation to social forces. Charles Henry's "measurement of intellectual and energetic nature according to the laws of statistical probability" in 1906 was a first effort to calculate social phenomena mathematically in accordance with energetics.[77]

After 1900 the journals of the German, French, and Belgian scientific academies overflowed with literature on every aspect of fatigue. Physiologists turned "their attention to analyzing fatigue, the manner in which it affects the output of nervous and muscular energy, the functions of circulation and respiration, and the production of organic poisons, or auto-intoxication."[78] Ergonomic studies investigated the influence of weight, rhythm, heat, cold, anemia, blood chemistry, and other factors on the fatigued body. Fatigue experts—for example, Ioteyko and Henry in Belgium, Jules Amar and Armand Imbert in France, Kronecker in Germany, and Mosso in Italy—engaged in the search for physiological laws of the body's economy and for ways of reducing the effects of fatigue. By defining the normal limits of this fatigue, they hoped, "over-exertion may be avoided with certainty."[79] Fatigue became the most important "criteria of expenditure of energy."[80]

By the first decade of the century, Ioteyko's innumerable studies of fatigue, combined with those of Mosso, Kronecker, Henry, Binet, Fernand Lagrange, and others, produced what might be called an "objective phenomenology" of fatigue and its representations. In 1904 Ioteyko provided the new science of fatigue with its first official name, *ergographie,* or "ergography" after Mosso's instrument. Ioteyko defined fatigue as "the diminution of effort as a function of time." In the same year she announced that "we have all of the elements necessary for the establishment of a mathematical law of effort and of fatigue," which she attempted to express mathematically in a series of papers devoted to the "fatigue quotient."[81]

According to Ioteyko, Mosso's great achievement was to plot the course of fatigue independent of the tiredness experienced. However, when Ioteyko tested her students at the University of Brussels and at the Solvay Institute between 1899 and 1900, she discovered that fatigue was not constant but highly idiosyncratic.[82] Despite individual differences in "fatigability," Ioteyko found that each fatigue curve revealed a distinct, though paradoxical pattern: muscles that were accustomed to work fatigued most rapidly at first but their capacity to work was rapidly restored as work continued. From this fact she concluded that "fatigued muscles worked more economically" and that "training" augments efficiency at the moment of fatigue, constituting "a self-regulating mechanism of fatigue."[83]

The notion that fatigue was largely self-regulating and demonstrated an economy of efficiency—not unlike the law of the least effort—also led to investigations of the varying *forms* of fatigue arising from different tasks or activities. If Mosso "was content with tracing individual fatigue characteristics," subsequent researchers found that the curves of one person did change markedly under altered conditions of work. For example, Ioteyko observed that fatigue was cumulative, "though not directly in proportion to the work done." An increased amount of work could be compensated for by slower pace or a proportional amount of rest so that "the accumulation of fatigue varied with the intervals of rest between the curves."[84] Fatigue thus demonstrated its own dynamic laws of motion, representing a local, self-regulating and economic character that could be traced ergographically. Above all, the laws of fatigue were distinct from the subjective feelings that accompanied different kinds of work, as "the sentiment of fatigue" was distinguished from its objective course, often lagging behind it.[85] Fatigue accumulated at a rate initially imperceptible to the individual, since the tiredness becomes conscious only at a later stage: "This central and conscious mechanism, intervenes late, appearing only when the peripheral mechanism is not sufficiently attended to. [Thus the feeling of fatigue] is an expression of a particular state of the muscles becoming conscious at a particular moment."[86]

The chemical basis of fatigue remained particularly perplexing. Was fatigue the result of chemical changes and the product of the nervous system, or were chemical changes in the muscles produced by fatigue? The problem had vexed Mosso, who expressed his belief in the former. Also puzzling was the physiochemical explanation for the tenacity of fatigue. Once the muscle became tired, only rest permitted it to recover its capacity. Chauveau believed that this phenomenon was a function of lessened muscular elasticity, whereas Zaccaria Treves (a student of Mosso) attributed these apparently intractable effects to an impairment of the spinal cord. Ioteyko, on the other hand, pointed to the weakened power in the synapses of the nerves.[87] By 1900 most researchers had concluded that the nervous system provoked the debilitating chemical reactions as fatigue intensified. But they also found that fatigue did not originate "centrally" in the nervous system nor in the chemistry of the blood, but "peripherally" in the muscles directly undergoing fatigue. In short, the course of fatigue might be modified if the conditions of fatigue could be altered.[88] Fatigue, noted the French hygienist Jules Amar, was "fundamentally an *intoxication;* if the brain and the muscles function in a disorderly fashion as a result of excessive effort or too great a rate of exertion, the blood is no longer able to cope with its task of purification. The waste products of this intense cellular activity accumulate; the blood loaded with toxic produces fatigue in any animal into whose veins it is injected."[89] The intoxication of fatigue could be eliminated only through the prophylactic of reduced work.

The early laboratory studies of fatigue were limited to tracings of specific, isolated muscles subjected to artificially induced stress. The impact of fatigue on the working body as a whole and the effects of different kinds of mechanical work under real conditions were still inaccessible to the fatigue curves. In 1903 a Parisian doctor, A.-M. Bloch, undertook the first general survey *(Enquête)* of fatigue. He asked workers in various strenuous occupations two questions: "When you work a lot, where do you feel fatigue; does the fatigue always occur in the same place?" At first the answers appeared paradoxical: The baker kneading dough all night complained of leg pains; the forger did not, as one might expect, complain of fatigue in his arms or shoulders, but instead, of difficulties in his back or kidneys; and the shoemaker, bending over his last, complained of abdomen pains. Bloch concluded that there was a rational explanation for these phenomena. Those groups of muscles "immobilized" by contractions were subject to extreme fatigue, while those that remained more active were spared "even in excessive work." Bloch immediately recognized the practical implications for education or military training: "One must exercise the auxiliary muscle groups . . . as often as possible."[90]

Fatigue could now be classified according to its "degree of intensity," its "pathological effect," or "conditions of origin." The intensity of fatigue ranged widely from the minutely observable "diminution of effort" perceptible only in the ergographic fatigue curves; to the "sentiment of fatigue"; to exhaustion; to the "fièvre du surmenage," which incapacitates the exhausted body; finally to "auto-intoxication," or death by excess fatigue toxins—as in the example of the famous Athenian (or contemporary) marathon runner who crosses the finish line and expires.[91]

Each degree of fatigue corresponded to a specific set of physiological and mental symptoms. Philippe Tissié noted the following distinctions: "lassitude," or weariness, which disappears after rest; "l'épuisement," or enervation, which decreases the capacity for recuperation and provokes symptoms such as rapid heartbeat or arterial tension; "le surmenage," or exhaustion, which impairs the appetite, suppresses sleep, causes hypertension; and finally, "le forcage," or extreme exhaustion, which constitutes "a serious illness" resulting in pathological psychic reactions, such as the "dissociation of the self."[92] Fernand Lagrange, a French physician and expert on clinical aspects of fatigue, claimed to have discovered an entirely new fatigue, "l'essouflément," or "breathlessness," which he described as "a malaise produced by the body as a result of a violent exercise or intense muscular effort," such as a last-minute dash for a train. According to Lagrange, fatigue was aggravated by "an excess of speed, an excess of intensity and excess of time."[93] Even dietary excess could produce fatigue, as "an excess of alimentary excitation fatigues the nerves of the digestive system."[94] Different types of fatigue were also classified according to their origins. "Active fatigue" was an effect of the muscles and of voluntary behavior, while "passive fatigue" resulted from modern stresses—for example, the effect of "railroad travel," of modern forms of communication. Finally there were sedentary, or "intellectual fatigue," "emotional fatigue," and the fatigue from extreme physical pain *(fatigue dolorifique).*[95]

For the majority of these European researchers, it was axiomatic that the experience of fatigue was intimately connected to the demands of industrial society. Fatigue was a pathology of productive, routinized labor, of the intensified pace of life in the modern factory, and in society. Yet, Ioteyko proposed that the sensation of fatigue also be considered "a defense which protects us against the dangers of a work pursued to the extreme."[96] Biologically, fatigue "could be considered to be a generalized defense of the organism against excitations which are too intense or too prolonged." In this case, fatigue is an "immediate defense" like the "peripheral paralysis" of the overtired muscle. "The entire mechanism of fatigue is founded on the protection of the nervous centres from noxious excitations." Finally, fatigue is also a "consecutive defense" that prepares and accustoms the body to increased work and "renders the organism resistant to fatigue." She called this a "prophylactic fatigue, kinétophylactique, or esthophylactique, which safeguards movement" from overwork. Included in her definition of fatigue as protection is also *ennui,* "the sentiment with which we defend against monotonous work."[97]

Clearly, for Ioteyko fatigue had a normative dimension, which, like pain, protects us against the sufferings inflicted by work and by society. Fatigue thus revealed two faces of modernity. On the one side it was a defense, marking the limits of the body's ability to convert energy into work, a limit beyond which the human motor could not function. On the other, fatigue was the body's method of economizing its energy, acting as a regulator of the body's expenditure of energy. In order that science have a true knowledge of fatigue and its costs to modernity, it must determine, Ioteyko claimed, the individual constitution, the conditions of work, and the most economic way of accomplishing it. Not only useless or wasteful fatigue had to be eliminated, but the productive side of fatigue, the individual's fatigue quotient, also had to be directly acknowledged in the modern workplace. "It is not impossible," she believed, "within the impassable limits of the law of the conservation of energy, to communicate an activity to the human motor which will favor the liberation of one form of energy rather than another."[98] This knowledge of fatigue could also serve the interests of productivity, by regulating the expenditure of energy of the human motor, ensure its most economical working, and "guide the animal machine to adapt to the best conditions for work."[99]

A FATIGUE VACCINE?

The search for the laws of fatigue were accompanied by an equally intense search to discover its chemical properties. If the ergonomic approach might result in the optimal deployment of the body's energy economy, the chemical approach promised an even greater panacea: the discovery of a vaccine against fatigue. In 1904 a German physiologist at the University of Erlangen, Wilhelm Weichardt, called attention to his remarkable experiments with the blood chemistry of fatigued rats. By subjecting the rodents to strenuous physical exercise, he produced the symptoms of pathological fatigue—lowering of the body temperature and shortness of breath. By accelerating this excessive exercise, he artificially induced in the rats a kind of "narcosis," during which breathing gradually slowed to "a complete standstill."[100] However, when he permitted the rats a brief respite from this tortuous labor, they restored themselves "remarkably quickly." Weichardt could not resist the analogy to a brief thundershower, in which fatigue approached "like a dark cloud which quickly approaches, sinking ever more closely to the ground like a dead-tired mass." Weichardt's experiments showed that "in this pure, uncomplicated fatigue, substances grow in living organisms" and that if the fatigue does not cease, these substances rapidly accumulate, causing "stupor" and then death.[101]

Weichardt believed that the chief cause of death by exhaustion was the gradual "strangulation" of the animal's life-giving properties by a specific fatigue toxin. The increasing spasms evinced in fatigued muscles, as demonstrated by Marey and Mosso, and by Claude Bernard's investigations of the structure of fatigued muscles, further indicated to Weichardt that "the fatigue of the most different organs could be traced back largely to the accumulation of deleteriously acting metabolic products," which causes exhaustion if not counteracted by oxygen. Fatigue, in short, does not simply produce exhaustion but "exhaustion causes fatigue to an equal degree."[102]

Weichardt contended that these "poisonous" fatigue substances that quickly exhausted the body were the key to conquering fatigue. He acknowledged that other fatigue experts, like Ioteyko, were extremely skeptical of discovering the chemical basis of the fatigue toxins.[103] However, he noted that developments in both immunology and blood-serum analysis had made possible a breakthrough, not only in analyzing the fatigue toxins, but in producing a chemical antidote. As Mosso had already shown, a dog injected with the blood of an exhausted dog becomes tired. Conversely, the production of antitoxin capable of resisting fatigue might be equally successful in reversing its effects. Weichardt concentrated his efforts on producing *in vitro* a fatigue substance "independent of the body of the animal"—in other words, a fatigue vaccine.

Weichardt was unflagging in his efforts to eliminate fatigue by first distilling its pure chemical essence and, then, by creating an immunizing substance. Not completely heartless, he occasionally regretted his ruthlessness in pursuing the fatigue toxins in his experimental rodents. It was "personally uncomfortable for me to conduct these studies," he wrote, "especially since the animal must not be given the slightest opportunity to recuperate," lest the fatigue toxins be sullied. But it was the only way. He named the fatigue toxins that he produced (from albumin) in his chemical laboratory "kenotoxins." When injected with this material, the experimental rats displayed extreme fatigue but as Weichardt predicted, soon developed an "active kenotoxin immunity" and resistance to fatigue.[104] He then experimentally produced a similar chemical that might be resistant to fatigue—an immunizing substance he called "antikenotoxin." Antikenotoxin was then injected into the bloodstream of the rodents, suppressing the fatigue toxins and allowing them to outperform their fatigued compatriots. Weichardt was euphoric: the possibilities for human use were legion.

Weichardt's moment arrived when he prepared to inject human subjects with his new substance. In 1903 he tested his antikenotoxin on several groups, employing both the ergograph and the Griesbach *aesthesiometer,* a more sophisticated device that measured fatigue on the surface of the skin. He also used a new method that Weichardt devised for his own purposes. It consisted of a 2.5 kilogram dumbbell that the subject held horizontally and moved from the front to the side with outstretched arms to the accompaniment of a metronome. The subject also lifted his right and, then, left foot to knee-level. This simple exercise became "gradually more difficult, and suddenly the arms sank as a consequence of the most extreme fatigue."[105] The number of seconds that elapsed before this inevitable outcome was a more reliable indicator of the onset of fatigue than the ergograph, which tested only the forearm muscles. Even small amounts of antikenotoxin subcutaneously injected in the subjects resulted in an increased capacity for the exercise. Exhaustion occurred significantly later than in those subjects who received a placebo.[106]

On 30 June 1909, armed with sprayers containing amounts of 1 percent antikenotoxin solution, Weichardt and an assistant appeared in a Berlin secondary school, where they sprayed a classroom with the chemical. The unsuspecting students were told that the sprayers contained materials to improve air quality. The room was sprayed in the morning; in the afternoon a series of mathematical exercises were provided to test fatigue by the Kraepelin error method (see chapter 6). The result was extraordinary. Although the students had already completed five hours of instruction, they performed their prescribed calculations with "considerable improvement." The speed of calculation increased by 50 percent; the number of errors were reduced; and some students, usually tired and sleepy afterwards, were now fresher than in the morning.[107]

German scientists immediately began experimenting with the vaccine by converting it to a gas and filling laboratories and classrooms with it. The enthusiasm that accompanied the discovery of the fatigue vaccine did not fully abate until 1914, when several influential physiologists concluded that Weichardt's claims had been exaggerated. First, the substance only partially combatted fatigue but in no way eliminated it, since it did not affect the "negative side" of fatigue—the exhaustion of the body's own materials in the effort.[108] Second, other researchers demonstrated that kenotoxin was not produced, as Weichardt believed, by fatigued muscles alone, but was frequently present in equal measure in relaxed muscles.[109] Finally, on the eve of the Great War, the heightened interest of German and Austrian military physicians in the benefits of a fatigue vaccine delivered a fatal blow to Weichardt's hopes to deliver mankind from fatigue. Experiments conducted by the Austro-Hungarian army concluded that the performance of those men injected or sprayed with the antikenotoxin did not much differ from those who received an ineffectual chemical.[110]

On this front, the battle against fatigue proved chimerical. But exposing the vaccine's illusory powers led to a more important discovery. In contrast to the antikenotoxin subjects, a control group injected with concentrated caffeine exhibited marked spurts in energy and productivity. This further intensified the search for other "nerve whips," or stimulants, which, like tea, coffee, or cocaine seemed to erase the signs of fatigue. In the long run, however, these too were inefficient, since they only either masked the real symptoms of fatigue until complete physical exhaustion set in, or were absorbed by the muscle toxins until they required ever-more dangerous amounts to provide more work.[111] With the failure of Weichardt's vaccine, it became evident that the battle against fatigue would not be won in the laboratory and that the war would have to be waged on other fronts.