REVIEW

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Claude Bernard's experimental method of head and hand

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Abstract

According to Claude Bernard, each of the sciences investigates different natural phenomena using experimental methods unique to that science, especially experimental medicine. However, Bernard also argued that these sciences share a "common" experimental method that depends on both the "head" and the "hand". What he accomplished with his common method is to combine both rationalism and empiricism—head and hand, respectively—to undergird the unity of the experimental sciences while maintaining their plurality. Bernard's experimental method as articulated in terms of the rational head and the empirical hand metaphor is relevant today to the unity of science vs. pluralism debate, as well as to the rationalism vs. empiricism debate and to the hypothesis-driven vs. data-driven science debate—each of which is explored in turn after briefly reconstructing Bernard's philosophy of experimental medicine. And his metaphor of head and hand provides a means for examining the natural and biomedical sciences as they evolve with regard to specialization.

Keywords: experimental medicine; empiricism; rationalism

Background

Claude Bernard's *Introduction à l'étude de la médecine expérimentale* (*Introduction*), originally published in 1865, certainly occupies a critical position in the development of experimental medicine and science [1-6]. In the introductory section, Bernard claims that "each kind of science presents different phenomena and complexities and difficulties of investigations peculiarly its own" [7]. Although the various experimental sciences investigate different phenomena using experimental methods unique to that science, according to Bernard, they do share a "common" experimental method.

> To be worthy of the name, an experimenter must be at once theorist and practitioner…We cannot separate these two things: head and hand. An able hand, without a head to direct it, is a blind tool; the head is powerless without its executive hand [7].

At one fell swoop, he combines both rationalism and empiricism, with the metaphor of head and hand, into a general or common experimental method to undergird the unity of the experimental sciences.

The question is whether Bernard's articulation of his experimental method in terms of the head and hand metaphor is relevant today not only for assisting contemporary philosophers of science and medicine to address the unity of science vs. pluralism debate [8, 9] but also the traditional debate over rationalism vs. empiricism [10, 11] and the contemporary debate over hypothesis-driven vs. data-driven science [12, 13]. The aim of this paper is to demonstrate "how the historical perspective [of Bernard and his head and hand metaphor] may aid and augment philosophical reflection," with respect to exploring and addressing these debates in the philosophy of science and medicine [14]. Bernard's relevance for contemporary issues in the biomedical sciences is illustrated, for example, with respect to the second biomedical revolution [15] and systems biology [16]. Moreover, Virtanen argues that Bernard's "teachings belong to the mainstream of modern philosophy of science, and furthermore, they continue to offer seminal suggestions for contemporary thought" [17]. For example, Bernard's experimental philosophy has been compared and even proposed as an antecedent to Popper's fallibilism [18, 19].

Bernard's philosophy of experimental medicine is reconstructed briefly in the following section and then utilized in a subsequent section to explore and analyze the unity of science vs. pluralism debate. In subsequent sections, Bernard's experimental method as articulated in terms of the head and hand metaphor is used to address the traditional debate between rationalists and empiricists, as well as the current debate between advocates of hypothesis-driven science and those of data-driven science. In the conclusion, Bernard's classic philosophical approach to the natural and biomedical sciences and their common experimental method is briefly discussed as providing a means to examine what these sciences share, especially in terms of his experimental method of the rational head and the empirical hand, as these sciences evolve particularly with respect to specialization.

Bernard's philosophy of experimental medicine

Bernard's *Introduction* is divided into three major parts. The first is concerned with experimental reasoning and covers the difference between observation and experiment, along with the role of an *a priori* idea and doubt in such reasoning. According to Bernard, an experiment involves altering the conditions under which an observation is made concerning a natural phenomenon while simple observation does not. Rather a simple observation is passive and descriptive while an experiment is active and explicative. He then details and summarizes the experimental method accordingly,

> (1) He [i.e., the "true scientist"] notes a fact; (2) *à propos* of this fact, an idea is born in his mind; (3) in the light of this idea, he reasons, devises an experiment, imagines and brings to pass its material conditions; (4) from this experiment, new phenomena result which must be observed, and so on and so forth [7].

Bernard's experimental method then is circular and iterative [15]. The method's first step is that the experimenter begins with an observable or a theoretical fact from which an idea or a hypothesis is formulated and articulated, which is next tested experimentally. The method concludes with newly observed phenomena, which the experimenter then uses to evaluate the hypothesis—to accept, reject, or modify it. And the whole process continues in an iterative manner, i.e., "so on and so forth," until scientific knowledge is founded "on deeper details." Throughout the chapter, Bernard wants to avoid over generalizations. And he warns against making only partial observations to support a favored hypothesis. Moreover, Bernard's experimental method involves experiments that do not simply test a hypothesis directly but at times reflect a series of experiments in which an independent variable is altered so as to compare or contrast it with a previous experiment within the series or even the same animal [20, 21]. As Bernard notes, such integrative or comparative experimentation is essential for examining complex phenomena like living organisms.

In the first part's second chapter, Bernard discusses the role of both *a priori* idea and doubt in his experimental method. An *a priori* idea is an "experimental idea…that presents itself in the form of an hypothesis the consequences of which must be submitted to the criterion of experiment, so that its value may be tested" [7]. Moreover, he claims that the end result of the experimental method is not absolute truth but rather a provisional truth upon which subsequent experimental activity continues to "retemper" scientific knowledge since what is only certain is what is known relative to the experimental method. And the means to this modest and humble stance is an open mind founded on "philosophical doubt," which is the "great experimental principle." Doubt, for Bernard, is neither Pyrrhonian nor radical skepticism in which knowledge is uncertain and truth unattainable; rather, it is a practical skepticism in which knowledge and truth are provisional and constantly under revision, representing current understanding. Bernard justifies his skeptical position with the claim that our observations, even experimental ones, are incomplete, "we are never sure of having seen everything" [7]. The question arises as to whether observations can ever be complete. Today, that question might be answerable through big-data science or the Fourth Industrial Revolution [22]. In Bernardian terms, big-data science might allow experimenters to determine the precise physico-chemical conditions for explicating the nature of organic life. What motivates Bernard's belief in experimental science, especially its verisimilitude, is the principle of determinism, which pertains to the necessary conditions or "immediate causes" of natural phenomena. For Bernard, this principle is what prompts the experimenter to investigate these phenomena and to question the theories explaining them.

In the *Introduction*'s remaining two parts, Bernard discusses experimentation as it pertains to living organisms. In the second part, Bernard uses the principle of determinism to defeat vitalism and to defend the commonality of the experimental method among the sciences. Vitalism was the notion that a vital force animates living organisms in terms of their "spontaneity" in contrast to a physico-chemical force for inanimate objects that lack such spontaneity [23]. Moreover, vitalists claimed that living organisms are independent of their external physico-chemical environment in contrast to inanimate objects. To counter this objection, Bernard argues that only warm-blooded animals are independent of the external environment; but the reason they are independent of that environment is that they are dependent on and are determined by an internal environment—his novel idea of the *milieu intérieur* [24, 25]. Bernard then insists that this milieu represents the physico-chemical environment of living organisms that the experimenter can investigate to identify their necessary conditions. Thus, he concludes that the science of animate bodies shares the same experimental method in attitude as does the science of inanimate bodies. "We must, therefore," to quote Bernard [7], "have recourse to analytic study of the successive phenomena of life, and must make use of the same experimental method which physicists and chemists employ in analyzing the phenomena of inorganic bodies."

Although experimenters in the sciences use a similar method, experimenters in the medical and physiological sciences, insists Bernard, must also include the organism's "harmonious whole" in which each of the living organism's parts contributes to its vitality. Analysis of the organism's parts through vivisection provides the information required to conduct a "physiological synthesis" to reconstruct the harmony among the parts and thereby to justify the analysis. As Bernard concludes, although medical and physiological scientists include the harmony of the whole, in terms of the investigated natural phenomena, still they conduct research

> through animal physico-chemistry, that is to say, through physics and chemistry worked out in the special field of life, where the necessary conditions of all phenomena of living organisms develop, create and support each other according to a definite idea and obedient to rigorous determinisms [7].

Thus, even though living organisms are incredibly complex, analysis of their inner physico-chemical environmental conditions is the means for understanding living phenomena and thereby intervening in them experimentally, especially for medicine with respect to developing rational and effective therapeutics.

In the third and final part of the *Introduction*, Bernard provides several examples from his own research to support his defense not only of the common experimental method among the sciences, but also of medicine's or physiology's unique situation for experimentally investigating living organisms and phenomena. As he notes in the part's first chapter, two starting points are available for conducting experiments: observational fact and hypothetical or theoretical fact. Bernard provides an example of the starting point consisting of an observational fact with a series of experiments in which he determined how the poison curare causes death. He began by injecting the poison subcutaneously in a frog. Upon examining changes in the physiological function of the frog's various organ systems, he discovered that the motor nerves to the muscles became dysfunctional. Bernard repeated this experiment several times on frogs to make sure of its reproducibility and facticity. Moreover, he tested curare on mammals and birds, to ensure the generalizability of the fact to other living organisms.

As Bernard notes, his experiments with curare conformed to his experimental method. He began with curare's observational facticity as a poison and then formulated the idea or hypothesis that curare must cause some physiological change in the organism, from which he conducted a series of experiments to determine what the change was. Based on his experiments and observations, he concluded that "*curare causes death by destroying all the motor nerves, without affecting the sensory nerves*" [7]. From this and other examples that Bernard presents in the chapter, he argued that the experimental method, as he has outlined it, is the means—and not "systematic or philosophic dissertations"—for erecting a sound edifice of scientific and medical knowledge.

In the next two chapters of the third part, Bernard discusses the role of experimental criticism in justifying scientific knowledge, especially in physiology and medicine. Experimental criticism is the cognitive faculty of casting "doubt on everything except the principle of scientific, rational determinism in the realm of facts" [7]. He goes on to identify three principles of determinism, which he claims are necessary guides for advancing science in terms of formulating theories that more accurately account for natural phenomena. The first principle pertains to contradictory facts in that experimental determinism avoids such facts. In other words, for Bernard, a positive experimental fact trumps a negative one. He gives the example of initially succeeding in eliciting diabetes in an animal model but then failing to repeat it. Rather than rejecting the experimental procedure, he proceeded to determine the precise experimental conditions required to elicit diabetes in the model. The next principle is that determinism "ejects causeless and irrational facts from science," since "a fact gains scientific value only through knowledge of its causation" [7]. To illustrate this principle, Bernard recounts an experiment in which ether was injected using a syringe into a fasting animal's intestine. What he subsequently observed was apparently fat within the lymphatics. However, further investigation revealed that the fat was oil dissolved from the syringe by the ether.

The final principle of determinism is that facts must be justified comparatively, by contrasting one experimental outcome to another as a type of "counterproof" or "counter experiment" [20, 21]. Bernard cautions the reader that an experimenter

> must not confuse a counter experiment or counterproof with what has been called comparative experiment…this is only a comparative observation resorted to, in complex circumstances, to simplify phenomena and to forearm oneself against unforeseen sources of error; counterproof, on the contrary, is a counter judgment dealing directly with the experimental conclusion and forming one of its necessary terms. Indeed, proof, in science, never establishes certainty without counterproof [7].

Bernard's worry was that "even when a fact seems logical, i.e., rational, we are never justified in omitting a counterproof or counter experiment, so that I consider this precept a kind of order which we must blindly follow even in cases which seem the clearest and most rational" [7]. Earlier Bernard encourages experimenters not to avoid counterproof since they "should always push their investigation to the point of counterproof; without that, their experimental reasoning would not be complete. Counterproof establishes the necessary determinism of phenomena; and thus alone can satisfy reason to which, as we have said, we must always bring back any true scientific criterion" [7].

For Bernard, as Raphael Scholl notes, counterproof was "the ideal core of a reasoning strategy" for investigating the "complexity of living organisms" [21]. The example he provides for this principle is the experiment in which he fed an animal a sugary "milk soup" and sacrificed it while it was ingesting the milk. He found sugar within the animal's suprahepatic vessel from which he concluded that the sugar within the vessel was from the soup. Bernard, however, performed a comparative experiment in which he feed meat to an animal fasting from sugar and upon inspection of the blood from its suprahepatic vessel he found sugar within it. As he concludes, the "comparative experiment led me to the discovery that sugar is constantly present in the blood of the suprahepatic veins, no matter what the animal's diet may be" [7]. Lastly, Bernard cautions experimenters to be vigilant about their use of scientific language so as not to deceive themselves about a fact: "we must be very careful never to abandon observation or put a word in place of a fact" [7].

In the last chapter of the *Introduction*'s final part, Bernard tackles the "philosophic obstacles" confronting experimental medicine, especially the obstacle of vague and meaningless terms and notions like vital force. He gives the example of when physicians, who are faced with a clinical conundrum, explain it by confessing, "This is life." "Life is nothing but a word," proclaims Bernard, "which means ignorance, and when we characterize a phenomenon as vital, it amounts to saying that we do not know its immediate cause or its conditions" [7]. For Bernard, experimental medicine must strive to determine the physico-chemical conditions for living phenomena, i.e., "to reduce vital properties to physico-chemical properties, and not physico-chemical properties to vital properties" [7]. Only through knowing these physico-chemical conditions and properties can the clinician intervene therapeutically to cure the patient and to understand the mechanism by which the therapy works. In other words, experimental medicine clarifies ambiguous terms and notions so that the physician does not act blindly or unintelligibly.

Another obstacle Bernard confronts is empiricism, which he believes is the gateway to experimental medicine but not its destination. For Bernard, experimental physicians

> do not believe that medicine as a science should stop at observation and empirical knowledge of phenomena or be satisfied with somewhat vague systems [rather]…With the help of experimentation, they must penetrate into the inmost phenomena of living machines and define their mechanism in its normal as well as its pathological state [7].

He goes on to give the example of treating fever with quinine. The empirical physician knows that the drug cures fever as an empirical fact without knowing what causes the disease, while the experimental physician strives to understand the fever's causative mechanism so as to understand how quinine cures the disease. In the end, for Bernard, "the true experimental method consists in a *logical* union of empiricism and experimentation" [7]. In other words, the true experimenter is not simply generating data as an empiricist but generating data in order to understand them as a rationalist. Reino Virtanen [17] calls Bernard's position "experimental rationalism." According to Virtanen, Bernard's position represented a middle position between rationalism and empiricism much like "Kant sought a middle ground between the rationalism of Liebniz and the empiricism of Hume" [17]. In other words, both the rational head and the empirical hand are required for conducting meaningful experiments.

Finally, Bernard discusses what he considers to be probably the two greatest obstacles to experimental medicine—medical doctrines and philosophical systems. As for medical doctrines, he asserts,

> experimental medicine, like all the experimental sciences, should not go beyond phenomena, it does not need to be tied to any system; it is neither vitalistic, nor animistic, nor organistic, nor solidistic, nor humoral; it is simply the science which tries to reach the immediate causes of vital phenomena in the healthy and in the morbid state [7].

For Bernard, experimental medicine must remain open to the deterministic conditions responsible for living phenomena. He also rejects philosophical systems, like Positivism, for the same reason that they close off the experimenter's open-mindedness. To quote Bernard, "We must therefore carefully avoid every species of system, because systems are not found in nature, but only in the mind of man. Positivism…has the fault of being a system" [7]. Interestingly, Bernard's position on Positivism has evoked controversy: on one side he is held responsible for its demise [19] and on the other he is considered one of the few French scientists remaining faithful to it [26-28].

Indeed, within the history and philosophy of medicine literature, there has been a rather lively discussion of the historical and philosophical context of Bernard's experimental method [20, 23, 27, 29-32]. Virtanen, who surveys the impact of several philosophers such as Descartes, Pascal, and Leibniz, on Bernard's experimental method, concludes that Bernard—through his erudition of the philosophical literature—developed "a philosophical frame of reference. This frame of reference was not too firmly put together, perhaps, and some of the pieces were lacking. But it is impossible to treat him as a pure experimentalist like Magendie, with only a casual interest in philosophy" [17]. And, for Bernard, the unknown in medical science can only be known through the experimental method, which is not reducible to or constrained by medical doctrines or philosophical systems. Indeed, he himself considers his treatise on experimental medicine not to be a set of "rules and precepts which experimenters should follow rigorously and absolutely" [7]. Rather, his intention for the treatise is to inspire physicians to embrace the experimental method, in terms of head and hand, to advance medicine on firm rational and empirical grounds. Lester King [33] best captures Bernard's concern over the proper relationship of the rational head and the empirical hand:

> If rationalism degenerated into unrestrained imagination, without the control of experience, it was bad. If experience rejected the critical exercise of reason, and the accumulated generalizations that theory had provided, it was bad. Each modality was subject to excess. For progress the excesses must be kept in check? But how?

For Bernard, the answer to King's question is the experimental method of head and hand and a proper balance or cooperation between them.

Unity of science vs. pluralism debate

The unity of science enjoys a historically deep tradition, with roots extending to the Presocratics [8]. It was of special interest to the Vienna Circle's logical positivists and empiricists [34]. For example, according to Rudolf Carnap, "all empirical statements can be expressed in a single language, all states of affairs are of one kind and are known by the same method" [35]. Besides Carnap, other logical positivists and empiricists, such as Ernest Nagel [36] and Carl Hempel [37], also developed strong positions on the unity of science based on (1) reductive ontological unity, i.e., higher scale entities and events can be reduced to lower scale entities and events, (2) theoretical unity, i.e., higher scale theories can be reduced to lower scale theories through bridge principles, and (3) eliminative semantic unity, i.e., higher scale terms and explanations can be reduced to lower scale terms and explanations. And Paul Oppenheim and Hilary Putnam [38] in their well-known essay, "The unity of science as a working hypothesis," postulated three overarching concepts to articulate a precise notion for the unity of science: (1) the unity of language in which terms of a special or secondary science are reduced to the terms of a fundamental or primary science; (2) the unity of laws in which laws of special sciences are reduced to those of a fundamental science; and (3) the unity of science itself in which the laws of the special sciences are not simply reduced to the laws of the fundamental science, but these laws are connected with one another to form a cohesive set of laws.

The unity of science came under criticism, especially by Jerry Fodor [39] and his working hypothesis of disunity. Fodor claimed that proponents of the unity of science rely on a strong or strict notion of reductionism and as a result they conflate the generality of physics with the science of physics as the epistemic and ontological foundation for the special sciences. Although Fodor's disunity of science was criticized [40], it became part of the intellectual landscape among contemporary philosophers of science in terms of a pluralistic (or perspectival) stance [41, 42]. This stance involves a distinction among the special sciences with respect to differences in terms of theories, laws, explanations, methodologies, and phenomena. And it assumes a strident anti-reductionism in the analysis of the special sciences and their practices. The result is that the special sciences yield a rather "dappled" view of the world in which the laws of these sciences are roughly cobbled together [43].

Bernard certainly would have appreciated and supported contemporary philosophers of science who advocate pluralism or the disunity of science among the special sciences. Indeed, as Paul Hirst notes, for Bernard "each science establishes the limits and forms of its own knowledge" [30]. According to Bernard's experimental reasoning, each mind or head of the experimental scientist is uniquely trained to address questions specific to that special science. Thus, a chemist thinks different thoughts about the inanimate bodies comprising chemistry than a biologist about animate bodies comprising biology. As Bernard reasoned,

> if vital phenomena differ from those of inorganic bodies in complexity and appearance, this difference obtains only by virtue of determined or determinable conditions proper to themselves. So if the sciences of life must differ from all others in explanation and in special laws, *they are not set apart by scientific method* [7].

For him then, although what distinguishes the special sciences are the explanations and laws proposed to account for the phenomena investigated by those sciences, these sciences do share a common experimental method of head and hand.

Consequently, for Bernard, the pluralistic stance he advocates must be situated within the basic experimental method of rational head and empirical hand that scientists across different scientific specialties share. "Methods of investigation and of scientific criticism," according to Bernard, "cannot vary from one science to another nor, for that matter, in different parts of the same science" [7]. Moreover, Bernard goes on to claim that empiricism is the first stage towards practicing a vibrant science that articulates hypotheses and theories and then tests them to explain natural phenomena. And he concludes that "empiricism is not the permanent state in any science," still it does not fully vanish from any science [7]. Finally, Bernard's unity of science as experimental method composed of head and hand can be combined with scientific pluralism. Even though each special science examines

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different phenomena often using different techniques still a common experimental reasoning unites them. In Bernardian terms, scientists may have different heads and hands; but they still have heads and hands, which has implications for the rationalism vs. empiricism debate.

Rationalism vs. empiricism debate

The debate between rationalism and empiricism is centuries, if not millennia, old [10, 11], especially within medicine [44-48]. John Warner [49] insists that much of the debate, especially in medicine, centers around the context in which rational and empirical are used. Thus, rational can refer to the reasonable or to the dogmatic, while empirical to unprejudiced observation or to mindless trial and error. During the nineteenth century, however, the debate crystallized into the "standard narrative" of "the rationalism of Descartes, Spinoza, and Leibniz" vs. "the empiricism of Locke, Berkeley, and Hume" [50]. As for rationalism, it was a popular topic within the medical literature of the nineteenth century [51-54]. Although clinicians provided different definitions for rationalism, these definitions did share a common theme: rationalism is the belief that reason—in contrast to the senses or experience—is the source of knowledge and the senses or experience simply play an ancillary role in knowing. Moreover, rationalists insist that innate knowledge and categories, like space, time, and causation, which are prior to experience, are responsible for knowing. Rationalism emphasizes reason and rational faculties as the source of knowing and understanding and provides the cognitive and epistemic resources and framework not simply for understanding sensory observations but also for identifying which sensory observations are important to understand in the first place.

On the other hand, empiricism is the belief that the source of knowledge—in contrast to reason—is experience, especially through the senses. Just as rationalism was a popular topic within the medical literature of the nineteenth century, so was empiricism, if not more so [53, 55-58]. A good example of empiricism within the French medical community is François Magendie, who employed Bernard as his assistant [1]. According to José Recio,

> Magendie's empiricism, an enemy of hypotheses and theories, opposed to reasoning becoming a part of observation, could be defined by a sentence which Magendie often repeated: "When I experiment, I have only my eyes and my ears, I have absolutely no brain" [19].

As Recio points out, the Magendie quote is taken from Bernard's writings. Although Magendie is often cast as a "strict empiricist" [59], he was not a "simple-minded empiricist" [4]. Indeed, in a lecture delivered before the Collège de France in 1834 Magendie [60] informed the audience that to formulate a "rational theory" for the pathology he witnessed during investigation of thoracic bruits he consciously avoided "blind empiricism." Moreover, as John Lesch points out concerning Bernard's empirical position, "By 1853 he [Bernard] was just beginning to move away from a naive empiricist posture and toward an appreciation of the role of ideas in research. In this way he was only retracing the steps already taken by Magendie more than ten years earlier" [4].

Empirical medicine, then, involves therapy based on experience without recourse to understanding the cause of the illness or how the therapy remedies the illness. For example, François Broussais complained against empiricism claiming it "pretends to find a remedy appropriate to the malady, without being at the trouble of explaining the malady, or how it is modified by the medicine" [61]. Empiricism, particularly in contrast to rationalism, emphasizes sensory observation and experience as the source of factual knowledge. Indeed, empiricism has little, if any, use for the rational faculties in terms of the source for knowing since knowledge is not possible unless first in the senses.

Besides this stringent form of empiricism, another form of empiricism called "rational empiricism" was prevalent in the nineteenth century medical literature [58, 62-64]. William Carpenter defined rational empiricism as "a mode of practice that may be regarded as best combining the advantages of scientific knowledge and of recorded experience" [65]. In other words, to make the best clinical decision, the physician as a rational empiricist depended on "both the intellect and the senses" [57]. And rational empiricism was considered a stop gap between unbridled empiricism and scientific medicine, during the late nineteenth and early twentieth centuries. For example, Sir Dyce Duckworth wrote,

> Rational empiricism, together with slowly progressive scientific medicine, are now being carried on by the best practitioners. In the immediate interests of the sick this must be so, and there can be no antagonism between them so long as the whole field of medicine is not covered by science [66].

However, scientific medicine was by mid-twentieth century to become the standard of the medical profession [67].

Bernard's notion of experimental method as articulated with the metaphor of head and hand has important implications for addressing the debate between rationalists and empiricists. Rationalism for Bernard is closely tied to "philosophic systems," which he cautions experimenters from embracing. As Bernard warns,

> When a man of science takes a philosophic system as his base in pursuing a scientific investigation, he goes astray in regions that are too far from reality, or else the system gives his mind a sort of false confidence and an inflexibility out of harmony with the freedom and suppleness that experimenters should always maintain in their researches [7].

Although Bernard does not explicitly define rationalism, still the rational is imperative for experimental medicine. For example, when discussing scientific reasoning, he insists that facts can only be incorporated into the scientific cannon when "their necessary conditions are defined in terms of rational determinism" [7]. And as Virtanen [17] points out, Bernard used Pascal's critique of "doctrinaire rationalism" to forge a rationalism in which he could incorporate reasoning appropriately into his experimental method. Bernard then proceeds to inform the reader that "philosophy, lacking the support or the counterpoise of science would rise out of sight and be lost in the clouds" [7]. In other words, philosophy as rationalism would posit conjectural or hypothetical entities unless tethered to science as empiricism. The epistemic fear for Bernard is that left to itself rationalism might conceive or postulate anything—a kind of ontological free-for-all. Observation or experience, then, should provide an empirical framework to constrain or prevent reason from positing artefact from speculative or unrestrained cognitive activity. In other words, reason needs to point to observations. Or, in Bernardian terms, "if we made an hypothesis which experiment could not verify, in that very act we should leave the experimental method to fall into the errors of the scholastics and makers of systems" [7].

Based on Bernard's head and hand metaphor with respect to the rationalist-empiricist debate, an empirically-directed rationalism is proposed in which observation or experience guides formulation and articulation of hypotheses and theories, which are then tested experimentally. If hypotheses and theories cannot be directed empirically, i.e., towards possible expected observations, then they are simply untrustworthy and so they are unreliable to yield sound scientific or medical knowledge. Besides empiricism directing rationalism, rationalism can guide empiricism. "Empiricism, which means experience at bottom (ἐμπ ε ι ρία, experience)," according to Bernard, "is only unconscious or non-rational experience, acquired by ever-day observations of facts, in which the experimental method itself originates…empiricism in its true sense is merely the first step in experimental medicine" [7]. For Bernard, "Empiricism may serve to accumulate facts, but it will never build science. The experimenter who does not know what he is looking for will not understand what he finds" [68]. Still science, especially experimental medicine, is at its roots empirical or experiential in nature. With this in mind, Bernard then claims that "science without guidance and high aspiration [from philosophy], would sail at random" [7]. In other words, science as only an empirical or technical hand would flounder in designing and conducting experiments and interpreting experimental results unless guided by the rational head of philosophy. The epistemic fear for Bernard is that empiricists might not know what observations are important or even how to interpret them meaningfully.

For Bernard, then, observations must be potentially reasonable or intelligible otherwise they run the risk of being meaningless. To make observations with no reasonable means for interpreting them is futile, simply because observations are not facts. A fact, according to Bernard Lonergan, "combines the concreteness of experience, the determinateness of accurate intelligence, and the absoluteness of rational judgment" [69]. In other words, a fact is the cognitive product of intelligibility when interpreting observations. If reasonable insights or inferences cannot be expected from analyzing the patterns found in observations and data, then what is the point of collecting them. "Men who gather observations," according to Bernard, "are useful only because their observations are afterward introduced into experimental reasoning; in other words, endless accumulation of observations leads nowhere" [7]. Based on his position, a rationally-directed empiricism is proposed in which reason provides a rational framework to guide the collection of observations and data, which can be generated experimentally, and to interpret them meaningfully.

In sum, for Bernard, both rationalism and empiricism are required for the successful practice of experimental medicine; and to a large extent they complement or supplement one another in that the rational head and empirical hand must cooperate with one another. They simply cannot function independently of one another but rather they must work together in a harmonizing fashion. The proposed complementarity model for addressing the debate over rationalism and empiricism, consists of a cyclical relationship between empirically-directed rationalism and rationally-directed empiricism. On the one hand, beginning with empirically-directed rationalism, observation or experience constrains or guides rational inferring or conjecturing since reason should point to an observation. And, in turn, rational inferring or conjecturing, with respect to rationally-directed empiricism, can subsequently shape or conduct the collection and analysis of observations. On the other hand, beginning with rationally-directed empiricism, rational inferring or conjecturing constrains or guides observation and experience. And, in turn, observation and experience, with respect to empirically-directed rationalism, can then shape further rational inferring or conjecturing. Thus, in this cyclical process, reason and experience complement one another as they progress iteratively towards a more accurate and practical understanding and knowledge of phenomena. Otherwise, as Bernard warned early in the *Introduction*, without the head the hand is "a blind tool" while the head without a hand is "powerless" [7].

Hypothesis-driven vs data-driven science debate

Bernard's combination of rationalism and empiricism, as articulated in terms of empirically-directed rationalism and rationally-directed empiricism, is relevant to the contemporary debate over hypothesis-driven and data-driven science. Unfortunately, there is not a consensus definition for hypothesis-driven science within the scientific literature because of the considerable variation in defining the notion of hypothesis among the various scientific specialties [70]. Although there is no consensus definition, hypothesis-driven science can be defined operationally as a linear process in which an experimenter formulates a hypothesis or question based on an observation or theory and then proceeds to test the hypothesis experimentally [71, 72]. Data-driven science, also known as data-intensive or data-discovery science, has also eluded a consensus definition within the literature because of its cross-disciplinarity among the sciences [73-75]. However, a rather useful working definition is "a set of fundamental principles that support and guide the principled extraction of information and knowledge from data" [76]. Data-mining algorithms, along with pattern-analytic and causal-analytic algorithms, are probably the most fundamental principles of data-driven science [77-80].

Traditional hypothesis-driven science is often contrasted with data-driven science and the latter is thought to be the successor to the former [12, 13]. Indeed, advocates of data-driven science champion it as the future for scientific practice and knowledge. Their reason is because of the complexity associated with many natural phenomena. In other words, hypothesis-driven science is limited in terms of formulating theories that can provide comprehensive or complete accounts or explanations for these phenomena. Unfortunately, as the history of science testifies, few, if any, scientific theories have stood the test of time simply because anomalies eventually emerge that the theory cannot explain, which leads to its replacement by a theory that can explain the anomalies [81]. Consequently, science's historical landscape is littered with abandoned theories of little or no use to anyone except historians, and possibly philosophers, of science [82].

On the other hand, data-driven science, as its proponents insist, is not subject to this epistemic limitation [22, 83]. Rather, through use of computational algorithms to analyze big data obtained from (almost exhaustively) quantifying natural phenomena, accounts of these phenomena are possible without resorting to theories and may also give rise to novel theories that better account for natural phenomena than theories derived from hypothesis-driven science. However, advocates of hypothesis-driven science counter that data-driven science is incapable of providing meaningful interpretation of its big data without an explanatory theoretical framework, which only hypothesis-driven science can provide [84]. But zealots of data-driven science reject this criticism. For example, Chris Anderson [85] claims that big data-driven science signals the end of theories simply because data can "speak" for themselves, while critics like Fulvio Mazzocchi [86] protest Anderson's sensationalist claim.

As for the previous two debates, Bernard's experimental philosophy in terms of the head and hand metaphor has important implications for the debate between hypothesis-driven and data-driven science. To that end, empirically-directed rationalism is combined with hypothesis-driven science to yield an empirically-directed hypothesis-driven science. In Bernardian terms, the empirical hand is directing or empowering the rational head. Specifically, empirically-directed rationalism provides an empirical framework to guide hypothesis-driven science in terms of hypothesis and theory formation and thereby facilitates hypothesis-driven science's experimental investigation of natural phenomena. And as Bernard acknowledged, experimental "habit may give a kind of empirical knowledge of things sufficient to guide practitioners, even though they cannot always precisely account for it at first" [7]. For example, he reports experiments conducted on rabbits in which he severed the sympathetic nerves thereby expecting theoretically the animal's body temperature to drop. However, he found just the opposite. Bernard then informs the reader, "I at once abandoned theories and hypothesis, to observe and study the fact itself, so as to define the experimental conditions as precisely as possible" [7]. And he concluded that these experiments opened new avenues for investigating and understanding thermo-regulatory nerves. In other words, his experimental habit provided a framework that enabled him to formulate hypotheses that advanced theoretical understanding of the physiological regulation of body temperature.

In turn, rationally-directed empiricism is combined with data-driven science to yield a rationally-directed data-driven science. In Bernardian terms, the rational head is directing or enabling the empirical hand. Specifically, rationally-directed empiricism can guide data-driven science by providing the necessary cognitive or rational framework for collecting and then interpreting data and observations. For example, Bernard's experimentation with curare illustrates this type of science. "In cases where we make an experiment in which both preconceived idea and reasoning seem completely lacking," as Bernard confesses, "we yet necessarily reason by syllogism without knowing it" [7]. And he goes on to outline his reasoning in the curare experiments. To quote Bernard:

In the case of curare, I instinctively reasoned in the following way: no phenomenon is without a cause, and consequently no poisoning without a physiological lesion peculiar or proper to the poison used; now, thought I, curare must cause death by an activity special to itself and by acting on certain definite organic parts. So by poisoning an animal with curare and by examining the properties of its various tissues immediately after death, I can perhaps find and study the lesions peculiar to it [7].

And he concludes, "In every enterprise, in fact, the mind [head] is always reasoning, and, even when we seem to act [hand] without a motive, an instructive logic still *directs* the mind" [7]. Moreover, rationally-directed data-driven science can also assist in devising novel means for generating not simply more data but the type of data that required for making or leading to unpredicted or unexpected discoveries.

Importantly, then, rather than contrasting empirically-directed hypothesis-driven science with rationally-directed data-driven science in binary oppositional terms, a complementary approach for integrating them into scientific practice is proposed. And the complementary relationship between them is not simply cyclical but also iterative in that both hypotheses and data reinforce and supplement one another as science progresses to a more accurate and practical understanding and explanation of natural phenomena [87]. Consequently, both the rationalism of empirically-directed hypothesis-driven science and the empiricism of rationally-directed data-drive science are two sides of the same epistemic coin.

In terms of the proposed complementarity model, empirically-directed hypothesis-driven science provides an empirical framework to guide the formulation of hypotheses so that those hypotheses can point to the observations and data needed to accept or reject the hypotheses. In turn, rationally-directed data-driven science provides a rational framework not only to guide the generation of these observations and data but also to interpret them intelligibly. Furthermore, rationally-directed data-driven science can also involve the design of investigative and experimental methods, which are exploratory rather than justificatory [88, 89] and can lead to novel and unpredictable discoveries through discovery science [90, 91]. In contemporary biology, for instance, omics experiments with microRNAs, metagenomics, proteomics, and metabolomics can be implemented as exploratory opportunities, rather than opportunities to generate data to test a hypothesis [92-94]. But still these omics experiments must be guided rationally and not simply be involved in generating an unintelligible data deluge.

Additionally, empirically-directed rationalism has a unique relationship to traditional hypothesis-driven science and provides a foundation for it in two ways. First, for hypothesis-driven science, scientists generally begin with a corpus of scientific facts about a natural phenomenon under investigation, as illustrated by Bernard's first step in his experimental method. This corpus can be used to formulate an idea or a hypothesis and then utilized to design investigative experiments to generate and collect observations and data, which in turn are interpreted as facts that are used to accept or reject the hypothesis. In a traditional sense, then, empirically-directed rationalism enables hypothesis-driven science to formulate a hypothesis, which can predict an observation so that the hypothesis is either verified or falsified in a strong epistemic sense.

Second, in a less traditional sense, although the corpus of scientific facts can be used to suggest hypotheses, these hypotheses need not be tested through an empirically-directed process; rather, they may provide an opportunity to investigate natural phenomena in terms of exploratory hypotheses, which consists of empirically motivated inferences and conjectures that outstrip more conservative generation of hypothesis in terms of traditional hypothesis-driven science. Empirically-directed rationalism endows, then, hypothesis-driven science with the capacity to formulate a hypothesis that simply points to or is able to point to an observation, so that the hypothesis is not tested as being either verified or falsified in a strong epistemic sense but rather in a weak sense in which the hypothesis can be utilized to strategize how best to design an experiment that points to an observation that might lead to a novel or unpredictable discovery. Bernard's work on the thermo-regulatory nerves in rabbits is an excellent example of how a preliminary expectation in change of body temperature by severing the nerves was not a test of a specific hypothesis but rather the nerve-severing experiments led Bernard to formulate hypotheses that drove his investigation of the biological phenomenon.

In sum, rather than contrasting hypothesis-driven science with data-driven science the two sciences can cooperate in a complementary fashion to investigate and explain natural phenomena. To that end, empirically-directed hypothesis-driven science offers an empirical framework for proposing hypotheses that are not only tested in a strong epistemic sense but also in a weak epistemic sense in that hypotheses can be proposed to explore natural phenomena, as long as the hypotheses are directed empirically. In turn, rationally-directed data-driven science provides a rational framework for constructing experiments and for interpreting the data. However, experiments can also be constructed to explore natural phenomena, as long as the experimental data are directed rationally. In Bernardian terms, the head and hand must cooperate and complement one another in conducting experimental science.

Conclusion

Although Bernard supported a pluralistic stance towards the experimental sciences, he considered the experimental method as a common means to unify them. In other words, an experimenter regardless of the science is an embodied agent, i.e., with the rational head and the empirical hand. However, he did acknowledge the initial importance of empiricism in scientific investigations. According to Bernard, "before foreseeing facts according to the laws which govern them, we must first observe them empirically or by chance; just as before experimenting along the lines of a scientific theory, we must first experiment empirically, in order to see" [7]. Consequently, the head cannot understand facts without first seeing or even presaging them empirically or experimentally. Likewise, the hand cannot conduct an experiment unless guided by hypothesis or rational or theoretical framework. Moreover, the unity of science was part of the very *terra firma* of science itself. "The different kinds of human knowledge," insisted Bernard, "are so entangled and so interdependent in their evolution, that we cannot possibly believe that any individual influence can advance them unless the elements of progress are present in the scientific soil itself" [7].

For Bernard the experimental method is constantly evolving, especially in terms of its reasoning and technology, which would eventually lead to scientific and medical specializations [95-98]. "The human mind," as Bernard addresses it, "has at different periods of its evolution passed successively through *feeling*, *reason* and *experiment*" [7]. Feeling brought about theology, then reason scholasticism, and finally experiment truth. And the truth derived from such experimentation was to cut nature more finely in terms of its joints thereby resulting in specialization, especially in medicine. As Fiorenzo Conti remarks, Bernard's "experimental work contributed to the development of various medical branches (anaesthesia, surgery, pharmacology, internal medicine, toxicology and neurology)" [15].

Besides the evolution of experimental reasoning, Bernard believed that the evolution of experimental technology is also critical for advancing science. "I am convinced that, in experimental sciences that are evolving, and especially in those as complex as biology," noted Bernard, "discovery of a new tool for observation or experiment is much more useful than any number of systematic or philosophic dissertations" [7]. Consequently, it is the evolution of reasoning as head and of technology as hand that allows for specialization in the natural sciences, as well as in medicine as an experimental enterprise. In sum, Bernard's contribution to experimental medicine would eventually result in the rise of biomedical specializations.

Finally, Bernard's trope of head and hand is an apt metaphor for exploring experimental medicine, especially in terms of its mapping onto the traditional debate over rationalism and empiricism and its significance for advancing the contemporary debate over the hypothesis-driven vs. data-driven science. For example, Bernard's warning to avoid vague and meaningless terms, such as vital force, for interpreting experimental results has importance consequences for empirically-directed rationalism/hypothesis-driven science in that hypotheses need to point to observations that can be evaluated in physico-chemical terms and conditions. Moreover, his denouncement of medical doctrines and philosophical systems for overstepping the phenomenon provides a solid foundation for empirically-directed rationalism/hypothesis-driven science. In other words, such doctrines and systems must not blind an experimenter's open-mindedness. Another important example is Bernard's distinction between the activity of experimentation and the passivity of observation, which is important for grounding a rationally-directed empiricism/data-driven science. In other words, experimentation often requires more than simply manipulating a biological phenomenon but rather requires considerable critical reasoning for both designing and conducting experiments and then analyzing their results. Moreover, the three principles of determinism are critical for rationally-directed empiricism/data-driven science in the sense that these principles are essential for guiding empirical investigation in terms of avoiding either contrary or causeless experimental results.

In conclusion, Bernard's experimental method as articulated in terms of the head and hand metaphor is relevant not only to the current debates over the unity of science vs. pluralism and hypothesis-driven vs. data-driven science but also to the traditional debate between rationalism and empiricism. Specifically, for the unity of science vs. pluralism debate Bernard's notion of a common experimental method unifies the experimental sciences but his emphasis on unique experimental approaches based on the specific science supports the plurality of the special sciences. As for the traditional debate between rationalism and empiricism, Bernard's head and hand metaphor is instrumental in proposing an empirically-directed rationalism and a rationally-directed empiricism. These latter two notions are important in formulating the proposed complementarity model between hypothesis-driven and data-driven science. That model consists of an empirically-directed hypothesis-driven science and a rationally-directed data-driven science in which both sciences complement and reinforce one another as scientists investigate particularly complex natural phenomena. Overall, Bernard's experimental method aids and promotes philosophical reflection on both traditional and contemporary issues in the philosophy of science and medicine.

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