

Neurosurgery and consciousness: historical sketch and future possibilities

Historical vignette

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Neurosurgery has played an important role in the development of neuroscience and the science of consciousness. In this paper, the authors reflect on some of the historical contributions of neurosurgeons to the science of consciousness and discuss the ways in which clinical neurosurgery can contribute to the science of consciousness in the 21st century. An approach to the “hard problem” is proposed based on the principles of psychophysics, and the opportunities offered by intracranial recording and stimulation in patients capable of reporting changes in subjective experience are discussed. Such an approach will allow the systematic study and description of the bridging relationships between neurobiology and conscious experience.

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*Conscious subjective experience is what is most important
and meaningful to us as human beings.*

BENJAMIN LIBET⁴⁹

The ancient civilizations of Egypt and Greece debated the location of the soul, a vital life force that permeated the body and defined an individual human being.⁷³ As scientific knowledge evolved, so have the questions, from the location of the soul to the pursuit of the location of specific psychological functions in the 19th and 20th centuries, and thence today to the relationship between consciousness and functional networks of the brain. A renewed transdisciplinary science of consciousness has emerged in the last two decades, and developing a naturalistic account of consciousness is now recognized as one of the major scientific challenges of the 21st century.^{4,75,76} In 2001, Francis Crick delivered a lecture titled “Consciousness and Neurosurgery” to the Congress of Neurological Surgeons in the US, and his call for neurosurgeons to actively engage with consciousness research received a warm response.¹⁹ However, in many countries

a large clinical workload combined with rationing in academic medicine poses challenges for neurosurgeons wishing to participate in such transdisciplinary research. In the United Kingdom, two neurosurgical units have recently contributed to consciousness-related research.^{57,70} This dearth of activity is unfortunate, as clinical reports have historically played a vital role in informing and constraining theories of consciousness.

The philosopher John Searle has stated, “Consciousness refers to those states of sentience or awareness that typically begin when we wake from a dreamless sleep and continue through the day until we fall asleep again, die, go into a coma or otherwise become ‘unconscious.’”⁷⁵ Most mental functions take place unconsciously, whereas others are accompanied by conscious experience.⁸⁴ The philosopher David Chalmers distinguished between the “easy” and “hard” problems of consciousness. The easy problems are about defining the neural counterparts of mental functions without necessarily accounting for the corresponding experiences: for example, defining the neural substrates of visual processing. In contrast, hard problem is about the relationship between conscious experience and the brain. The hard problem is both a philosophical and an empirical problem. The philosophical part involves how to concep-

Abbreviations used in this paper: ILN = thalamic intralaminar nuclei; NCC = neural correlate of consciousness.

tualize the relationships between qualitative consciousness and quantitative brain states. The empirical part consists of specifying those relationships. Although the hard problem is widely acknowledged to be the key to unlocking the many specific questions about consciousness (such as the function of consciousness), it has been recognized that most contemporary approaches to consciousness research do not address this central issue.¹⁶

In this paper, we reflect on some of the historical contributions of neurosurgeons to the science of consciousness and discuss the ways in which clinical neurosurgery can contribute to the science of consciousness today. We propose an approach to the hard problem based on the principles of psychophysics and discuss the opportunities offered by intracranial recording and stimulation in patients capable of reporting changes in subjective experience. Such an approach will allow the systematic study and description of the bridging relationships between neurobiology and conscious experience.

Historical Sketch

Many neurosurgeons have contributed to our knowledge of conscious states by reporting conditions in which parts of the brain are damaged, removed, or stimulated (Table 1). Walter Dandy and Sir Geoffrey Jefferson noted that extensive resections of the cerebral hemispheres—with preserved consciousness afterward—demonstrate that neither hemisphere alone is necessary for consciousness, and that subcortical structures must play a crucial role. Dandy's last publication, "The location of the conscious center in the brain; the corpus striatum,"²⁰ was an analysis of 10 cases resulting in postoperative coma, through which he sought to identify the seat of consciousness. He ascribed the seat of consciousness to the head of the caudate and lentiform nucleus, due to their proximity to the line of operative resection and necrosis noted at autopsy. Dandy stated, "Moreover, the part of the brain that is injured and is responsible for this change [loss of consciousness] must be in the immediate environs of the line of resection of the frontal lobe or lobes. There is only one part of the brain that could meet this condition i.e. the corpus striatum."²⁰

Jefferson reported the impairment of consciousness

in patients with posterior fossa lesions and basal injuries of the brain, and suggested that the brainstem plays an essential role in consciousness, complementing emerging animal studies on the role of the brainstem reticular formation in arousal mechanisms.¹ Jefferson stated, "But cortical lesions pure and simple do not seem to produce it [impaired consciousness] nor do massive excisions of the cerebral lobes, as I can well testify...Yet a small central and basal injury certainly does so."⁴⁰ He advocated the classification of head injuries according to the level of stupor rather than by skull fracture,⁴¹ and proposed definitions of impaired states of consciousness. He suggested the term "parasomnia" to represent a state in which there is no response to stimuli, verbal or mechanical, except those of a reflex nature.⁴⁰ The terminology of impaired states of consciousness was later refined,⁶⁶ and the need for a clinical tool to assess such states consistently led to the development of the Glasgow Coma Scale.⁸¹ Jefferson wrote extensively on the nature of the mind.^{38,39,43,44,74} He was influenced by Sir Charles Scott Sherrington (1857–1952), his father's friend, from whom he sought advice on correlations between their work.⁷⁴ Jefferson wrote of the mind-body relationship:⁴⁴

It has required the two centuries after 1740 to formulate the nervous impulse from the mediaeval concept of the animal spirits. And except that we admit now that we have no reason to believe that mental activities are carried out by processes very different from the impulses in the peripheral nerves and spinal cord, we still do not know how they produce the aggregate of mental processes that we call mind. That was Sherrington's conclusion.

Wilder Penfield was Sherrington's student as a Rhodes scholar from Princeton and again following his internship at the Brigham Hospital.²⁷ Sherrington's experiments on mammalian physiology and his pioneering concept of integration in the nervous system, with its highest expression in the human mind, heavily influenced Penfield's future career.^{27,59,77} In his book *The Mystery of the Mind: A Critical Study of Consciousness and the Human Brain*, Penfield states:⁵⁹

My professional career was shaped, I suppose, in the neurophysiological laboratory of Professor Sherrington at Oxford. Eventually it was continued in the wards and operating rooms of the Montreal Neurological Institute. Other preoccupations

TABLE 1: Contributions of neurosurgeons to consciousness research

Neurosurgeon	Clinical Observation	Contribution to Consciousness Research
Walter Dandy (1886–1946)	postop coma, ²⁰ hemispherectomy ²¹	noted that cerebral hemisphere is not necessary for consciousness, highlighted importance of subcortical structures
Sir Geoffrey Jefferson (1886–1961)	impaired consciousness in posterior fossa lesions & head injuries, cortical resection ^{40,42}	discussed the brainstem's role in consciousness, contributed to clinical management of impaired states of consciousness
Wilder Penfield (1891–1976)	cortical stimulation ^{61,64,86}	established role of cerebral cortex & cortical-subcortical interaction in consciousness, demonstrated dissociation btwn experience of volition & somatosensory function
Bertram Feinstein (1914–1978)	cortical & subcortical stimulation & recording ⁴⁹	studied spatiotemporal relationships btwn neurophysiology & conscious experience, established foundation of contemporary neuroscientific studies on nature of free will
Joseph Bogen (1926–2005)	hemispherotomy & subsequent neuropsychological testing ^{14,34,79}	facilitated development of cognitive neuroscience & the relationships btwn cognitive functions & consciousness

were many and varied, but beneath them all was the sense of wonder and a profound curiosity about the mind. My planned objective, as I turned from studying the animal brain to that of man, was to come to understand the mechanisms of the human brain and to discover whether, and perhaps how, these mechanisms account for what the mind does.

Penfield demonstrated that auditory, somatosensory, and visual experiences, emotions, vivid recollections of (unverified) memories, movements, and vocalizations could be evoked by stimulation of the cerebral cortex during awake surgery for epilepsy.^{61,64,86} Movements and sensations (and reactions to them) were experienced as involuntary,⁸⁶ demonstrating the distinction between the experience of volition and the neural processes that mediate somatosensory functions. He noted that severing transcortical association fibers does not have a major impact on cortical functions and consciousness,^{65,86} and concluded that the interaction between the cerebral cortex, subcortical structures, and brainstem is essential for consciousness. He proposed the centrencephalic integrating system as the core structure mediating such an interaction, comprising the intralaminar systems of the thalamus, the reticular formation of the brainstem, and the nonspecific projection systems with connections to both hemispheres;^{58,62} he states,⁵⁸

Consciousness exists only in association with the passage of electrical potentials through ever-changing circuits of the brain-stem and cortex. One cannot say that consciousness is here, or there. But certainly, without centrencephalic integration it is non-existent. Thanks to this central organizing activity, the cortex is active in ever-changing functional patterns. Who is to say, at any moment, that brain-stem potentials are more important in a given mental process than those moving through the cortex? Who is to say the reverse?"

Penfield adopted a form of dualism on the brain-consciousness relationship, but struggled with the traditional question of how the two separate elements are connected. In 1975 (first edition), Penfield stated,⁵⁹

For my own part, after years of striving to explain the mind on the basis of brain-action alone, I have come to the conclusion that it is simpler (and far easier to be logical) if one adopts the hypothesis that our being does consist of two fundamental elements. If that is true, it could still be true that energy required comes to the mind during waking hours through the highest brain mechanism.

Bertram Feinstein contributed to early work on electrical stimulation and thermal ablation of the basal ganglia for movement disorders,^{2,3,29,30,35,46} but his perhaps lesser known contribution, one of immense importance to neuroscience, was his collaboration with the neuroscientist Benjamin Libet (1916–2007) on a series of experiments on the relationship between the brain and conscious experience.⁴⁹ In a study involving 92 patients undergoing stereotactic surgery for dyskinesias, Feinstein and Libet⁵⁰ demonstrated a 500-millisecond time delay from direct stimulation of the somatosensory cortex to the arrival of the sensation in conscious awareness. In subsequent work, Libet asked whether conscious intentions can actually influence neurobiology; as he states,⁴⁸ "Appropriate nerve cell activities can certainly influence the content, or even the existence, of subjective experiences. Is the reverse true? That is, can our conscious intentions really influence or direct the nerve cell activities in the perfor-

mance of a freely voluntary act?" This was addressed when Libet and coworkers used electroencephalography and electromyography in conjunction with an electronic clock face paradigm (Wundt clock) to demonstrate that cerebral events (readiness potentials) encoding motor commands for voluntary actions are initiated before the conscious intention to act is perceived (and therefore unconsciously).⁵¹ This classic work has been replicated^{132,37,78} and continues to influence contemporary debates on human motor control and volition.³⁶ Libet recalls in his autobiography that not many neurosurgeons at the time were willing to use clinical opportunities for research,⁴⁷ but his example clearly demonstrates the fruits of such collaboration.

In 1955, Joseph Bogen met neurobiologist Roger Sperry, who at the time was researching split-brain cats.¹⁰ Against the background of an evolving trend in epilepsy surgery toward functional hemispherotomies,²⁸ Bogen presented to Sperry an essay titled "A Rationale for Splitting the Human Brain."^{10,11} Subsequently in 1962, Bogen, in collaboration with Philip J Vogel, performed a complete callosotomy and anterior commissurotomy on patient WJ.¹⁴ The postoperative neuropsychological tests performed by Sperry and Michael Gazzaniga heralded the era of split-brain research,^{34,79} a paradigm that was key to the development of cognitive neuroscience and that of conscious states. As Sperry stated,⁸⁰

Careful testing of the independent function of each hemisphere separately suggests that the unified world of inner experience is also divided into two separate right and left systems, each hemisphere apparently conscious within itself but unaware of the perceptual, learning and related memory experiences of its partner within the same cranium.

The key question for consciousness raised by these studies is whether the unity of personal consciousness is also split, leaving two new centers of consciousness (one in each hemisphere) where once there was one. If consciousness is constituted within cortical regions alone (or the interaction among cortical regions), then this would follow. However, if subcortical structures and their interaction with various cortical regions are constitutive (rather than enabling) of conscious experience, then the contents of the patient's experience may switch between right and left hemispheres rather than (arguably the normal case of) drawing on both hemispheres at once.^{6,54}

Bogen^{9,12,13} observed the development of modern consciousness studies from its germination in the 1950s to its height in the decade of the brain and was in a unique position to formulate a theory of consciousness based on neurosurgical perspectives. He considered the thalamic intralaminar nuclei (ILN) to be the seat of arousal (state of consciousness) because bilateral lesions of the ILN were associated with loss of consciousness. Bogen stated,¹² "Falsification of this proposal is straightforward: find someone with essentially complete, bilateral destruction of ILN whom we would consider conscious." He was also mindful to include nonhuman species in a theory of consciousness and took note of the awareness of phylogenetically ancient homeostatic functions such as nausea, thirst, and respiration, which are often overlooked in recent discussions on consciousness.^{12,13} Bogen de-

scribed himself as a mentalistic physicalist. He believed that consciousness derives exclusively from the brain, but remained agnostic on the existence of nonmaterial influences, which he considered unfalsifiable.¹⁰

Future Possibilities

How can the physical activities of nerve cells in the brain give rise to the nonphysical phenomena of conscious subjective experiences, which include sensory awareness of the external world, thoughts, feelings of beauty, inspiration, spirituality, soulfulness and so on? How can the gap between the “physical” (the brain) and the “mental” (our conscious, subjective experiences) be bridged?

BENJAMIN LIBET⁴⁸

A Neuroscientific Philosophy of Mind

Human beings experience a large variety of conscious content, including simple sensations (such as thirst, nausea, and pain), perceptual experiences (such as visual, auditory, tactile, and taste sensations), thought, volition, and self-consciousness. These experiences can be objectively described and communicated and thus studied scientifically. They also have a structure and as such can be described in informational terms. This corresponds to the functionalist program in the philosophy of mind or the cognitive program within psychology. There is, however, another aspect of consciousness that philosophers have dubbed “qualia” (plural), the raw feels that differentiate one conscious sensation from another. For example, the quale (singular) of redness is that quality of experience that makes an experience of redness just that and not the experience of greenness, the musical note B-sharp, or the smell of a rose. These raw feels are accessible only to the unique individual experiencing them. While I can tell you that I see a red car and this can convey a great deal of information about the content of my experience, it cannot convey the raw feel (quale) of the redness. It is perfectly conceivable that the quale I experience when I describe something as red is the same quale that you experience when you describe something as green, and vice versa, but neither of us would detect any discrepancy in our descriptions of what we see. Two qualia in each of our respective experiences (at least in the same modality) could be swapped while leaving the structure (the informational content) the same. There is, therefore, an irreducible subjective element to consciousness. The hard problem of consciousness, which logically surfaces prior to questions about the functions of consciousness, involves how a physical system in this universe (such as the brain) can harbor a world of inner subjective experiences.

One influential approach to the hard problem posits that consciousness is a fundamental, nonreducible aspect of nature that arises from the brain. The philosopher David Chalmers articulates this position as follows:¹⁶

Given that reductive explanation [of consciousness] fails, non-reductive explanation is the natural choice. Although a remarkable number of phenomena have turned out to be explicable wholly in terms of entities simpler than themselves, this is not universal. In physics, it occasionally happens that an entity has to be taken as fundamental. Fundamental entities are not explained in terms of anything simpler. Instead, one takes them

as basic and gives a theory of how they relate to everything else in the world.

The empirical part of such an approach for consciousness would involve establishing systematic relationships between neurophysiology and conscious experience. This is a form of dualism that does not undermine neuroscience (or scientific explanation), and is an approach respected by many scientists and philosophers^{12,16,49,59,75,76,79,85} as one that allows an empirical science of consciousness to proceed.

How Can Contemporary Neurosurgical Practice Contribute to Consciousness Research?

A solution to the hard problem of consciousness must ultimately bridge the domain of phenomenology of experience and neurobiology. Future progress in this field for neurosurgeons will depend on the development of new methods to characterize brain function and their application to the established paradigms of lesion studies, neuropsychological testing, and brain stimulation and recording to answer specific questions about the nature of consciousness.⁷¹ For example, the study of residual cognitive function using functional MRI and electrophysiology in states of globally impaired consciousness has emerged as an important paradigm for the study of consciousness (see the work of Steven Laureys and colleagues at <http://www.coma.ulg.ac.be/index.html>). Such contexts highlight the distinction between the “background” state of arousal mediated by subcortical structures, and the specific “contents” of consciousness mediated by the cerebral cortex. This, in turn, may parallel the apparent introspective distinction between the state of being aware (that which is common to all specific conscious experiences) and the informative “objects” of awareness, those composite structures that transiently populate each conscious moment. The key question is whether the role of subcortical structures is constitutive as suggested by the earlier findings of Penfield and Jasper,⁶³ or merely enabling. As Crick and Koch¹⁸ framed this question, is the role of such structures a characteristic part of consciousness, or is it analogous to the electricity supply to a television set? While an equivalent of the human thalamocortical system is readily identified in other mammals, evidence of additional subcortical structures playing a constitutive role in consciousness would widely extend the range of animal species to be considered as potential bearers of consciousness.^{15,55}

Intracranial recording and stimulation are performed for a variety of clinical indications^{5,8,23,25,83} and have a number of distinct advantages in characterizing brain function relevant to consciousness. These are the finer spatiotemporal resolutions (as compared to modalities such as scalp electroencephalography, functional MRI, and PET), the ability to define the firing patterns of neurons, the capability of modifying stimulation parameters, and, when performed in awake individuals, the ability to obtain subjective reports, which allows systematic relationships to be established between neural activity and conscious experience. Intracranial studies are prevalent in many areas of neuroscience,^{17,26} but only a few have focused on the relationship between neurophysiology and conscious experience (Table 2).^{23,31,32,45}

TABLE 2: Intracranial studies relevant to consciousness research

Type of Intracranial Study	Example
recordings obtained by electrodes in fixed positions (single neuron firings, event-related potentials, & local field potentials) can be correlated w/ specific changes in conscious experience	Kreiman & coworkers ⁴⁵ showed that a consciously perceived visual percept activates specific neurons in medial temporal lobe (for example, a neuron fires in response to seeing the face of former president Clinton); some of these neurons did not fire if conscious percept was suppressed in a flash suppression paradigm during which retinal input was unchanged; they concluded that activity of stimuli-specific neurons in medial temporal lobe correlates directly w/ the subjective experience of vision
the study of changes in conscious experience induced by brain stimulation	extensive series were reported by Penfield ⁶⁵ & Libet ⁴⁹ & their coworkers; more recently, Fried & coworkers ³² found that stimulating parts of medial frontal lobe results in an “urge” to move part of limb or feeling it had actually moved; higher stimulation intensities resulted in actual movement; Desmurget & coworkers ²³ reported similar results following stimulation of posterior parietal cortex, in which higher stimulation intensities led to a belief that movement had occurred rather than actual movement; these findings indicate a wide neuronal network involved in generation of voluntary action
study of timing of specific conscious experiences in relation to underlying neural event	Fried & coworkers ³² demonstrated that activity of individual neurons in medial frontal lobe changed significantly before conscious intention to act was experienced, in agreement w/ earlier reports; ^{37,51,78} findings highlight relationships btwn motor circuits & experience of volition; earlier observations that surgical disconnection of supplementary motor area from precentral gyrus does not impair voluntary action highlights role of cortical-subcortical interactions in voluntary action ⁶⁵

These studies provide snapshots of the spatiotemporal relationships between neural activity and conscious experience. The key question is what sort of neural activity is sufficient to constitute a neural correlate of consciousness? Here, the necessary and sufficient structures for consciousness must be distinguished. To establish that neural event A is a necessary condition for conscious event B, it must be shown that conscious event B ceases whenever neural event A ceases, and that whenever conscious event B occurs, neural event A always occurs. Certain brain regions found to be necessary for specific aspects of consciousness have been referred to as the corresponding “consciousness center,”^{13,20,67} but this is a potentially misleading conclusion unless it can also be demonstrated that some aspect of the neural activity occurring there is also sufficient for such experiences. For example, the finding that bilateral lesions of the ILN cause loss of consciousness indicates that this part of the brain is necessary for consciousness, but it does not indicate what other structures also need to be functioning. To establish that a neural event A is sufficient for a conscious event B, it must be shown that when neural event A occurs, conscious event B also occurs. Brain stimulation will elicit the sufficient neural structures for a specific conscious experience and, in conjunction with neural recording and self-reports of experience, provide a unique means to study this relationship. It is becoming increasingly apparent that a sufficient condition for any given conscious experience must be articulated in terms of functional networks (in the context of overall brain function) in addition to discrete anatomical localities. The multimodal methods that enable such networks to be defined are only now emerging.^{22,52,68}

Neurosurgery and Inner Psychophysics

The search for the neural correlates of consciousness (NCC) advocated by Francis Crick and Christof Koch two decades ago has fostered rapid progress in conscious-

ness research.^{18,53,69,82} However, the NCC project has not, nor was it designed to, provide new insights on the hard problem of consciousness.¹⁸ The aim of the NCC project is:⁸²

...to examine how brain activity changes when a specific content of consciousness changes – for example, a visual stimulus becomes visible or invisible – while everything else, including the overall level of consciousness as well as the sensory input, remains as constant as possible...The goal is to follow the footprints of consciousness in the brain by ultimately identifying the neural correlates of consciousness (NCC) – the minimum neuronal mechanisms that are jointly sufficient for any one specific conscious percept.

The experimental paradigms commonly used include perceptual alterations in phenomena such as binocular rivalry, change blindness, or bistable figures. As such, the NCC approach yields information on the neuronal processes related to specific conscious percepts but sets to one side issues related to the qualitative component (the hard problem) of consciousness. In our view, progress on the hard problem requires a renewed experimental focus on mapping the forms of relationship between carefully chosen physiological parameters of neural systems (Searle’s “meat in the head”) and the basic sensations (“raw feels”), which comprise experience rather than the representational objects of perceptual experience that are the staple of NCC-inspired research. The outline of this approach has emerged out of existing collaborations between consciousness researchers and neurosurgical teams, that is, the synthesis of basic conceptual and experimental paradigms pioneered by psychophysics in the 19th century with direct stimulation of the brain in awake subjects capable of reporting changes in their ongoing experience.

Psychophysics represents the earliest scientific paradigm for the study of the relationship between physical and mental events. Pioneered by Ernst Weber (1795–1878) and Gustav Fechner (1801–1887), the aim was to empirically derive mathematical functions by systemati-

cally mapping variations in physical attributes of stimuli (the independent variable) to variations in the reported sensations they would elicit (the dependent variable); that is, psychophysics sought to identify “bridge laws” between the domains of physics and conscious sensation. The careful methods developed in psychophysics were subsequently applied to many areas of experimental psychology and formed the historical foundation for that discipline.²⁴ Alas, psychophysics appears to have disappeared from the radar of contemporary consciousness research. Even that otherwise encyclopedic reference resource for consciousness researchers, *The Oxford Companion to Consciousness*, fails to contain an entry on psychophysics.⁷ When Penfield and coworkers systematically applied early electrical stimulation techniques to specific regions and systematically mapped patients’ reported experiences, they were applying, in the most basic form, a psychophysics methodology. The independent variable was the presence or absence of electrical stimulation at a particular location on the cerebral cortex, and the bridging laws related that physical change with changes in conscious experience. In fact, such a development had been anticipated by Fechner, who predicted the development of an “inner psychophysics” describing bridging laws between brain physiology and conscious experience (Faw W: Modern consciousness science as Fechner’s inner psychophysics. Poster presented at 11th annual meeting of the Association for the Scientific Study of Consciousness, Las Vegas, Nevada, 2007). Fechner understood “inner psychophysics” to be the logical extension of the “outer psychophysics” he had pioneered. When Libet and Feinstein later systematically mapped the relationship between the duration of electrical brain stimulation and the occurrence of conscious sensations, they were implementing Fechner’s “inner psychophysics” approach. In doing so, they discovered a fundamental psychophysical relationship of immense importance to subsequent theories of consciousness: a duration threshold of approximately 500 milliseconds was required for electrical stimulation of the sensory cortex to be translated into conscious experience.⁵⁰

Libet’s observation of a psychophysical limit for duration of stimulation to reach consciousness provides a natural bridge to connect two contemporary but seemingly unconnected theories, one a purely cognitive theory of conscious representations and the other a neuroimaging driven theory of functional organization within the CNS. The Higher-Order Thought theory of David Rosenthal⁷² holds that for a (in this case neural) representation to be conscious it must itself be the object of representation at a higher-order level of the same cognitive system. Rosenthal’s theory is based entirely within the framework of cognitive psychology and as such makes no reference to a neural mechanism of implementation. Karl Friston’s predictive coding theory³³ postulates the interplay of feed-forward and feedback connections between multiple layers of a hierarchically layered neural system as the basic functional unit of the nervous system, a functional unit that can be reiterated by evolution to form either a parallel series or an extended hierarchy of recursive loops to meet ever more complex processing and self-regulatory demands. Combining these approaches,

Libet’s time threshold can be accounted for by the time required for information to feed forward from lower-order neural representations to a higher-order processing layer, which generates representations of predicted outputs from this lower-order processing and feeds back modulating input to this lower level, to minimize the discrepancy between the actual outputs of the lower-order process and the predictions of the higher-order monitoring system. The point here is not whether Libet (or either of these theories) is correct (see the journal *Consciousness and Cognition*, volume 11, issue 2 [2002] for critiques of Libet’s work) but that basic psychophysical observations can uncover hidden relationships between seemingly disparate bodies of theory. Such encounters between theory and observation have been the hallmarks of progress in the history of science.

We propose that establishing basic psychophysical relationships (bridging laws) between quantitative changes in parameters of neural states and qualitative changes in reported conscious sensations is a vital step for the development of consciousness research. To date, the collaboration between Libet and Feinstein represents both the simplest and the most sophisticated attempt to systematically apply the methodological framework of Fechner’s “inner psychophysics” to the hard problem of the brain-consciousness relationship. By themselves, the bridge laws established by an explicit inner psychophysics program do not amount to a solution of the hard problem. However, if such a solution is to be had, it must necessarily explain the set of empirical bridging laws that may be stated as mathematical functions between parameters of neural activity and the qualities of conscious experience. An important component of success in this approach must be the careful choice of the parameters of brain stimulation that are selected for systematic experimental variation. The simple variation of the intensity and duration of stimulation used in earlier studies should be augmented with systematic modulation of oscillatory dynamics including frequency, amplitude, and phase (timing relationships).⁵⁶ The spatial and temporal dynamics of oscillatory inputs to neural systems require systematic mapping to conscious experience in the next phases of the “inner psychophysics” research program. Although such work appears to have ceased with the end of the seminal collaboration between Libet and Feinstein, it is a project that can be renewed if appropriate alliances can once again be forged between skilled neurosurgeons and equally skilled consciousness researchers. It is from the specification of empirical constraints on the relationships between neural systems and qualia that we expect real progress on the hard problem to emerge. If surgeons and researchers will take up this challenge together, neurosurgery will likely be at the center of the next major developments in the science of consciousness.

Conclusions

Rapid progress has been made in the two decades since the scientific project of identifying the neural correlates of consciousness was outlined.¹⁸ It is perhaps naïve to believe that progress toward a solution to the hard (mind-body) problem will be made with similar speed. Neurosurgeons have played an important role in some of the major advances in neuroscience, many of them initi-

ated by their curiosity about the human mind. In 1963, Penfield wrote on the future of neurosurgery in an essay titled "Neurosurgery—Yesterday, Today, Tomorrow".⁶⁰

Tomorrow? What of tomorrow? I believe that a new day will dawn tomorrow and that in its light will be found an understanding of the nervous system. Mental as well as physical activity will then be recognized as a function of the brain, and neurosurgery and psychiatry will gradually lose the separate authority conferred upon them by ignorance until there remains only neurology. Neurology will then stand forth as a single discipline to which internist, psychologist, surgeon, chemist and physiologist will contribute.

Almost half a century later, we clearly have further to go. The continued input of neurosurgeons will be crucial to future progress in the neurosciences and to the hard problem of consciousness in particular. As clinicians we are continually busy with our daily routines; the key, however, remains not hesitating to pause to acknowledge the human mind and pursue its study when the opportunity allows.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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