Progress in Neurobiology 78 (2006) 322–326

progress in Neurobiology

www.elsevier.com/locate/pneurobio

Reflections on the interaction of the mind and brain

Benjamin Libet *

Center for Neuroscience, University of California at Davis, Davis, CA 95616, USA

Abstract

Problems associated with the topic of the mind–brain interaction are reviewed and analyzed. If there is an interaction, then the ‘‘mind’’ and ‘‘brain’’ are independent variables; the mind represents subjective experience and is therefore a non-physical phenomenon. This fact led to the need for a field theory, termed here the ‘‘cerebral mental field’’ (CMF). By definition, the CMF is a system property produced by the appropriate activities of billions of neurons. An experimental test of this theory is possible and a test design is presented. The most direct experimental evidence has been obtained by use of intracranial stimulating and recording electrodes. Important information has also been developed, however, with extracranial imaging techniques. These can be very fast (in ms), but the cerebral neuronal events that produce changes in physiological properties require a time delay for their processing. A number of surprising time factors affecting the appearance of a subjective somatosensory experience are described, and their wider implications are discussed. Among these is a delay (up to 0.5 s) in the generation of a sensory awareness. Thus, unconscious cerebral processes precede a subjective sensory experience. If this can be generalized to all kinds of subjective experiences, it would mean that all mental events begin unconsciously and not just those that never become conscious. In spite of the delay for a sensory experience, subjectively there appears to be no delay. Evidence was developed to demonstrate that this phenomenon depends on an antedating of the delayed experience. There is a subjective referral backward in time to coincide with the time of the primary cortical response to the earliest arriving sensory signal. The subjective referral in time is analogous to the well-known subjective referral in space. In conclusion, features of the CMF can be correlated with brain events, even though the CMF is non-physical, by study of subjective reports from the human subject.

Keywords: J.C. Eccles; Mind–brain problem; Conscious field; Subjective experience; Referred sensations; Non-physical mental

Contents

1. Introduction

The generally held assumption that mind and brain can interact indicates from the outset that two different phenomenological entities exist. Conscious mind can only be regarded as a subjective experience, which is accessible only to the individual who has it. Thus, it can only be studied by reports given by the subject her/himself. It cannot be observed or studied by an external observer with any type of physical device. In this sense, subjective experience (the conscious mind) appears to be a non-physical phenomenon. Indeed, it was recognized as far back as Gottfried Leibniz (1646–1716) that if one could look into the brain and observe all its nerve cell

Abbreviations: CMF, cerebral mental field; DCR, direct cortical response

* Tel.: +1 530 750 5046; fax: +1 530 757 8827.

0301-0082/$ – see front matter
doi:10.1016/j.pneurobio.2006.02.003

activities, one would not see anything to indicate the existence of a conscious mind. In contrast, Pierre-Simone Marquis de Laplace (1749–1827) believed that if the nature of the molecules and structures in any system were known, one could describe and predict all of its behaviors (Laplace, 1914). Laplace was thus the ultimate materialist! Even if one believes Laplace's views, they could never be tested, of course, because impossibly large numbers of elements are involved. It is also necessary to accommodate the unpredictable effects of random events (chaos theory) and the uncertainty principle of Werner Heisenberg (1901–1976). Similar untestabilities apply to any materialist theory of mind.

How do the materialist's molecules and structures give rise to subjective experience? Simply stating that some (unknown) configuration of neuronal activities equals consciousness (subjective experience) avoids or begs the problem.

2. Contributions of John Eccles to the problem of mind–brain interactions

At this point it is relevant to consider the contributions of Sir John Carew Eccles (1903–1997) to the problem of mind–brain interactions. "Jack" (to his colleagues) was a remarkable contributor even to a field far removed from his superb experimental discoveries on the mechanisms of synaptic transmission and functional controls within the central nervous system (see the reports of Brownstone, 2006; Burke, 2006; Willis, 2006; Hultborn, 2006; Wolpaw and Carp, 2006; Andersen, 2006; Ito, 2006; Wiesendanger, 2006). This was the field of the mind, including consciousness, the self, and how the brain might perform these functions.

Eccles' interest in these mental functions was evidently fostered by his association with his mentor, Sir Charles Sherrington (1857–1952) at the University of Oxford. Early in his career (1925–1937), Eccles spent some years with Sherrington as an undergraduate, pre- and post-doctoral researcher, and faculty member (see Stuart and Pierce, 2006). Sherrington had a keen interest in how a human mind could be generated by the brain, a topic he discussed and analyzed in his book, "Man on his Nature" (Sherrington, 1940). In that book he stated (p. 413) "That our being should consist of *two* fundamental elements offers, I suppose, no greater inherent improbability than that it should rest on one only." By two elements, Sherrington presumably meant the "mental" versus the "physical" (neuronal) process. This view appealed to Eccles' predisposition to this question. Sherrington evidently implored Eccles not to give up his interest in and pursuit of views of the mind and brain. Accordingly, even for his first book on experimental neuroscience, Eccles chose the title, "The Neurophysiological Basis of Mind—The Principles of Neurobiology" (Eccles, 1953). Very little direct discussion of mind appears in that book, however!

Eccles did much to foster interest in the mind-body problem, but his contribution was mostly at the philosophical level. His positions are clearly described in the 1997 book by Karl Popper (1902–1994) and Eccles, "The Self and its Brain" (Popper and Eccles, 1977). Note the unique relationship in this title, "self" as owner of "brain!" The physicist, Henry Margenau, provided a view of the mind as a field that could interact with the brain even with no energy expenditure (Margenau, 1984). This supported Eccles' bias on the nature of mind–brain interaction (for his change of heart, see p. 145 in Eccles, 1994).

It is especially noteworthy that Eccles' models of mind–brain interaction were presented without any experimental evidence or experimental designs for testing. That was due at least partly to the untestability of the models. Curiously, an absence of experimental testability did not bother Eccles. When asked if his view that a field of "psychons" (his units of mental function; see Wiesendanger, 2006) could mediate unity of subjective experience (Eccles, 1990) was untestable, Eccles replied that he knew of no way to test that hypothesis (personal communication). But he argued that the hypothesis had explanatory power, and, as such, he believed it had some usefulness and even validity.

In an interesting work with the physicist, Friedrich Beck, Eccles proposed that his hypothesis is a scientifically valid solution of voluntary action (Beck and Eccles, 1992; see also their 1998 and 2003 articles). Variations in the probability of release of synaptic transmitter, produced by intention to act, could determine whether an act occurs. But this ingenious model is not testable with respect to the action of intention in this system.

In summary, the role of Eccles in problems of mind and brain was as a stimulus to work in this field but not as a producer of scientifically valid solutions to the problem (see also Bennett and Hacker, 2002; Wiesendanger, 2006). Nonetheless, Eccles was curiously satisfied with his ingenious but untestable models as solutions.

3. The cerebral mental field (CMF)

Hiroomi Umezawa and his followers proposed a mental field model, which they termed a "quantum field theory." It was claimed by the authors that this theory is distinguishable from "quantum mechanics" (Umezawa, 1993). Their model is mostly mathematical, however, and it is not clear how it can be tested. In the interpretation of quantum theory by Nils Bohr (1885–1962), mind and matter are two aspects of one undivided process. David Böhm (1917–1992) adopted this idea (see Böhm and Factor, 1985). But this does not solve the problem of how the neuronal activity aspect can also be directly related to the subjective, non-physical aspect of mind. If subjective experience is a non-physical phenomenon, what is it?

It should be added that subjective experience also involves an integrative property. That is, although billions of individual nerve cell actions give rise to conscious awareness, the actual experience is a unified one. For example, if you look at any object in your external visual field, it appears as a smoothly organized structure, even though we know that several separate areas in the cerebral visual system are contributing colors, spatial configurations, motion, and meaning (interpretation) to it. This has been termed the "binding" phenomenon. There have been attempts to account for this by certain neuronal functions. For example, Wolf Singer and colleagues claim to have found a synchronization of rhythmic electrical potentials between areas of the brain that might be involved in binding (Gray and Singer, 1989). But even if this is a valid neuronal correlate of binding, one still has to explain how it gives rise to the non-physical integrated subjective experience.

In summary, how can one account for and study an integrative but non-physical phenomenon that is the conscious mind? For this, one is virtually forced to adopt a field approach. The field would not be a ''mysterious ghost'' independent of the brain (viz. Ryle, 1949). Rather, it would be a system property of the neuronal activity elements that give rise to it. It is well known that systems can have properties not predictable on the basis of the elements that produce the system. For example, the properties of benzene are not directly predictable from the six carbon and six hydrogen atoms that constitute the C-6 benzene structure. Or, as pointed out by Roger Sperry (1913–1994), the properties of a wheel are not evident in the spokes and makeup of the rim when not arranged into a wheel structure (Sperry, 1980; Doty, 1998).

Eccles realized that some sort of field would have to be postulated to account for the integrative aspects of the mind. For the elements in the brain that give rise to the field, Eccles (1994) postulated the existence of organized bundles of neurons that he called ''psychons'' (see Wiesendanger, 2006). Each psychon could represent a mental event or process. Eccles, in collaboration with Beck, proposed that synaptic probability for release of its neural transmitter is affected by random quantum inputs (Beck and Eccles, 1992, 1998, 2003). Such inputs could not be detected by any physical measurement and could thus be a mental action that is not externally apparent. A field of appropriate psychons, acting together, would produce an integrated mental experience. Eccles admitted that such a process was not testable (personal communication). But, in accordance with Popper's dictum (Popper, 1992), a non-testable proposal cannot have scientific validity. If a proposal cannot be contradicted, one can say anything without being shown wrong. On these grounds, Eccles type of theory simply cannot be accepted as scientific.

In contrast, the CMF theory proposed by me (Libet, 1994) is potentially testable. I described a design for conducting such tests. The procedures for this are potentially practicable. The proposed experimental test is simple in principle but difficult to carry out. A small slab of sensory cortex (subserving any modality) is neuronally isolated but kept viable by making all the cortical cuts subpially. This allows the blood vessels in the pia to project into the isolated slab and provide blood flow from the arterial branches that dip vertically into the cortex. The prediction is that electrical stimulation of the sensory slab will produce a subjective response reportable by the subject. That is, activity in the isolated slab can contribute by producing its own portion of the CMF.

The CMF is not a Cartesian dualistic phenomenon; it is not separable from the brain. Rather, it is proposed to be a localizable system property produced by appropriate neuronal activities, and it cannot exist without them. Again, it is not a ''ghost'' in the machine. But, as a system produced by billions of nerve cell actions, it can have properties not directly predictable from these neuronal activities. It is a non-physical phenomenon, like the subjective experience that it represents. The process by which the CMF arises from its contributing elements is not describable. It must simply be regarded as a new fundamental ''given'' phenomenon in nature, which is different from other fundamental ''givens,'' like gravity or electromagnetism.

3.1. Delay of awareness

One strange feature of the CMF is the experimentally demonstrated one that awareness of a sensory event does not appear until up to 0.5 s after the initial response of the sensory cortex to the arrival of the fastest projection to the cerebral cortex (Libet et al., 1991). This is true for near-threshold sensory stimuli; stronger stimuli require less time for awareness. But, in spite of the actual delay, the individual perceives the normal sensory stimulus without any appreciable delay beyond that for conduction time of the sensory projection from periphery to sensory cortex (Libet et al., 1979). A further experiment showed that up to 0.5 s of neural activity had to occur for the actual awareness to appear (Libet et al., 1979). Somehow, the subjective time of the actually delayed awareness appears without delay. It is as if this delayed awareness is subjectively referred backwards in time to the time of the primary evoked response of the sensory cortex. When there is no primary evoked potential, there is no backward referral. Note also that weak stimuli appear after a delay when the primary projection pathway is interrupted by a stroke (Libet et al., 1979).

The process by which ''backward referral in time'' is achieved is not known (Libet, 2004). ''Referral in space'' is a well-known phenomenon, however. The responses of the primary visual cortex show a configuration that is different from the subjectively perceived image. Additionally, the cortical representations of color, motion, and meaning are integrated in the subjective image. This requires substantial subjective referral to produce the perceived image. One might say that subjective referrals in space and in time ''correct'' the distortions of both the visual image and somatosensory event that are imposed on the neural representations of the events.

Since the referrals are all subjective they are presumably functions of the CMF. In a broader sense, all of the neuronal activities that lead to a conscious awareness, as in thinking thoughts, may also be referrals into the CMF.

3.2. Unconscious mental functions versus conscious ones

Mental awareness can be delayed by up to ~0.5 s. Therefore, processes that are unconscious, that is without awareness, must precede it. If one extrapolates this situation for all mental events (admittedly without direct evidence), then all mental events are initiated and developed *unconsciously.* Indeed, most mental events are probably *completely* unconscious (see Velmans, 1991). The chief difference between conscious and unconscious events could be the duration of the processes giving rise to them. If the duration is too brief, the event remains unconscious; it only reaches the awareness level if the duration is sufficiently long. Such a distinction based on duration of processes has been termed the ''time-on'' theory (Libet et al., 1991; Libet, 2004). Direct evidence for this theory is reported there.

3.3. Neuronal processes responsible for the ''time-on'' duration

There are at least two different views about ''time-on'' duration. (1) Excitatory levels build up with repetition of neuronal discharge, until a critical number or kind of neurons discharge. (2) Alternatively, repetitive events are all similar, and awareness appears simply after a suitable duration of such similar events; that is, duration per se is the responsible variable. Pockett (2004) and Pollen (2004) promulgate the first alternative whereas I maintain that the second alternative is the more likely one (Libet, 2006). The following evidence favors the second alternative.

When electrical stimuli are applied to the cerebral cortex, a typical response, the direct cortical response (DCR), appears at the electrode site and travels to surrounding areas of cortex. DCRs were discovered in the mid-1900s and were believed to be dendritic in origin. Sydney Ochs and his colleagues developed convincing evidence that pyramidal cells at the stimulus site fire impulses to adjacent areas by way of subcortical projections (Ochs and Clark, 1968). This indicated that repetitive DCRs would all be neuronally similar events. DCRs responding to a repetitive train of stimuli to the human cortex and lasting 0.5 s are all virtually identical in amplitude and form (Libet, 1973). This finding is not suggestive of the first alternative (excitatory buildup), but it is certainly consistent with the second one.

Another experimental observation appears to contradict the ''excitatory buildup'' alternative. When a stimulus to the sensory cortex is allowed to continue beyond the required 0.5 s for up to 5.0 s, the near-threshold sensation that appears after the 0.5 s portion of the stimulus continues to be felt during the remaining stimulus period up to its 5.0 s limit. But the subjective intensity of the sensation remains at the near-threshold level; it does not get stronger! If sensory awareness appears at 0.5 s due to an excitatory buildup, then that sensation should become increasingly stronger during the remaining portion of the 5.0 s train, but it does not (Libet, 2006). Note that the sensation is a weak, near-threshold one, so a postulated further excitatory buildup should continue, predicting an increasingly stronger sensation. This simply does not occur!

Most of the discussion thus far about ''time-on'' duration has been based on intracranial studies on conscious human subjects. It is therefore understandable why few such studies have been undertaken. Such work requires an interested experimental neurosurgeon like Bertram Feinstein (1914–1978), proper facilities associated with the neurosurgical operating and adjacent hospital spaces, and human subjects willing to cooperate during the neurosurgical procedure or afterwards when electrodes are implanted in functionally relevant structures as part of the post-operative therapy. In Feinstein and Libet's experience at the Mt. Zion Hospital Neurological Institute-San Francisco in 1957–1978, most of the potential subjects were keenly interested in contributing to the research program. More recently, Kimford Meador and his colleagues have carried out similar studies at the Medical College of Georgia. In general, their studies have confirmed the findings of Libet et al. (1979) on the issues concerning the minimum delay for awareness (see, e.g., Meador et al., 2000).

4. Extracranial studies

In recent decades, brain imaging studies, including PET scans and MRI, have been numerous and significant. They can provide information on changes in blood flow in localized areas of the brain, as well as activity-dependent changes in specific metabolites. David Ingvar and his colleagues initiated direct study of blood flow patterns (for review, see Ingvar, 1999). In their initial experiments, changes in local blood flow were observed not only during voluntary acts but also when the subject *imagined* voluntary action (fictive movement).

Observations of changes in physiological processes like blood flow can be made very quickly (1.0 ms or less) when using imaging techniques. PET or MRI process the neuronal changes responsible for the actual changes at a far slower rate, however. Accordingly, the metabolites that produce the observed changes appear well after any discharge by the relevant nerve cells or even activity in their dendrites. Therefore, imaging techniques are limited in their ability to describe the timing of the neuronal actions, but they do indicate that a significant change has occurred. For example, a recent study by Frith and colleagues (de Fockert et al., 2004) demonstrated that conscious subjective events occur in subjects whose primary visual areas of cortex are not functional.

5. Concluding thoughts

The nature of the interaction between mind and brain is clearly difficult to understand, since it involves the production of non-physical subjective experiences by appropriate neuronal activities. If an experimental test of the CMF was to be carried out, like that described above, it might confirm or contradict the kind of alternatives possible for a mind–brain interaction. The eminent neuroscientist, Robert W. Doty, has remarked to me that he does not believe that a CMF test will produce a positive response. But if it does indeed deliver a positive confirmation, this will create a Galilean type of revolution in neuroscience, and science in general!

Acknowledgements

For our experimental intracranial studies, I am indebted to the cooperative patients who underwent therapeutic neurosurgery and to my colleagues, Bertram Feinstein, W. Watson Alberts, Elwood (Bob) Wright Jr., and Curtis Gleason. I would also like to express my gratitude for the possibility to work with Eccles on cellular issues in Canberra, Australia (1956–1957) and his sustained interest in and support of my subsequent studies on the human brain. Re the latter, many leading neuroscientists initially

thought I was wasting my time! When Eccles heard that I had new experimental evidence on brain processes in consciousness, he promptly invited me to participate in a ''Study Week'' at the Vatican, chaired by Eccles in 1964 (see Eccles, 1966). The meeting included such luminaries as Lord Edgar Adrian (1899–1977), Ragnar Granit (1900–1991), Herbert Jasper (1906–1999), Roger Sperry, and many others. It was held in the 15th century house of Pius IV with its particularly charming and stylish architecture. Granit stated there that my discovery of a delay for a conscious experience was probably very significant. Eccles also invited me to another Vatican meeting in 1988. My supporters also included Anders Lundberg, whom I met in Canberra in 1956 and with whom I have remained close friends thereafter. I also received supportive interest from Per Andersen, Richard Schmitt, and Henry Morgenau. My dear friend, Ruth Strauss and her late husband, George, were keenly interested from the start. My wife, Fay, our children (Julian, Moreen, Ralph, and Gayla, and grandson Victor) were also in this ever-supportive group.

References

Andersen, P., 2006. Inhibitory circuits in the thalamus and hippocampus—An appraisal after 40 years. Prog. Neurobiol. 78, 264–271.

Beck, F., Eccles, J.C., 1992. Quantum aspects of brain activity and the role of consciousness. Proc. Natl. Acad. Sci. U.S.A. 89, 11357–11361.

Beck, F., Eccles, J.C. (deceased), 1998. Quantum processes in the brain: a scientific basis of consciousness. Ninchi Kagaku (Cognitive Studies). Bull. Japanese Cogn. Sci. Soc. 5, 95–109 (in English).

Beck, F., Eccles, J.C. (deceased), 2003. Quantum processes in the brain: a scientific basis of, consciousness. In: Osaka, N. (Ed.), Neural Basis of Consciousness. John Benjamins Publishing Company, Philadelphia, pp. 141–165. (Note: This article is a modest expansion of Beck and Eccles, 1998 as written by F. Beck several years after Eccles' demise).

Bennett, M.R., Hacker, P.M., 2002. The motor system in neuroscience: a history and analysis of conceptual developments. Prog. Neurobiol. 67, 1–52.

Böhm, D., Factor, D. (Eds.), 1985. Unfolding Meaning: A Weekend of Dialogue with David Böhm. Routledge, London, p. 177.

Brownstone, R.M., 2006. Beginning at the end: Repetitive firing properties in the final common pathway. Prog. Neurobiol. 78, 156–172.

Burke, R.E., 2006. John Eccles' pioneering role in understanding central synaptic transmission. Prog. Neurobiol. 78, 173–188.

de Fockert, J., Rees, G., Frith, C., Lavie, N., 2004. Neural correlates of attentional capture in visual search. J. Cogn. Neurosci. 5, 751–759.

Doty, R.W., 1998. Five mysteries of the mind, and their consequences. Neuropsychologia 36, 1069–1076.

Eccles, J.C., 1953. The Neurophysiological Basis of Mind—The Principles of Neurophysiology. Clarendon, Oxford, UK, p. 314.

Eccles, J.C. (Ed.), 1966. Brain and Conscious Experience. Springer–Verlag, New York, p. 591.

Eccles, J.C., 1990. A unitary hypothesis of mind–brain interaction in cerebral cortex. Proc. R. Soc., London B 240, 433–451.

Eccles, J.C., 1994. How the Self Controls its Brain. Springer–Verlag, Berlin, p. 197.

Gray, C.M., Singer, W., 1989. Stimulus-specific neuronal oscillations in orientation columns of cat visual cortex. Proc. Natl. Acad. Sci. U.S.A. 86, 1698–1702.

Hultborn, H., 2006. Spinal reflexes; mechanisms and concepts: From Eccles to Lundberg and beyond. Prog. Neurobiol. 78, 215–232.

Ingvar, D.H., 1999. On volition: a neuro-physiologically oriented essay. In: Libet, B., Freeman, A., Sutherland, K. (Eds.), The Volitional Brain: Towards a Neuroscience of Free Will. Imprint Academic, Thorverton, UK, pp. 1–10.

Ito, M., 2006. Cerebellar circuitry as a neuronal machine. Prog. Neurobiol. 78, 272–303.

Laplace, P.S., 1914. A Philosophical Essay on Probabilities. Truscott, F.W., Emory, F.I. (Translaters). Dover, New York (1951).

Libet, B., 1973. Electrical stimulation of cortex in human subjects and conscious sensory aspects. In: Iggo, A. (Ed.), Handbook of Sensory Physiology. Springer–Verlag, Berlin, pp. 743–790.

Libet, B., 1994. A testable field theory of mind–brain interaction. J. Consci. Stud. 1, 119–126.

Libet, B., 2004. Mind Time. The Temporal Factor in Consciousness. Harvard University Press, Cambridge, MA, p. 248.

Libet, B., in press. The timing of brain events. Conscious. Cogn.

Libet, B., Wright Jr., E.W., Feinstein, B., Pearl, D.K., 1979. Subjective referral of the timing for a conscious sensory experience: a functional role for the somatosensory specific projection system in man. Brain 102, 193–224.

Libet, B., Pearl, D.K., Morledge, D.E., Gleason, C.A., Hosobuchi, Y., Barbaro, N.M., 1991. Control of the transition from sensory detection to sensory awareness in man by the duration of a thalamic stimulus: the cerebral ''time-on'' factor. Brain 114, 1731–1757.

Margenau, H., 1984. The Miracle of Existence. Oxbow, Woodbridge, CT, 143 pp.

Meador, K., Ray, P.G., Ray, L.J., Loring, D.W., 2000. Train duration effects on perception: sensory deficit, neglect, and cerebrallateralization. J. Clin. Neurophysiol. 17, 406–413.

Ochs, S., Clark, F.J., 1968. Tetrodotoxin analysis of direct cortical responses. Electroencephalogr. Clin. Neurophysiol. 24, 101–107.

Pockett, S., 2004. Hypnosis and the death of ''subjective backward referral''. Conscious. Cogn. 13, 621–625.

Pollen, D., 2004. Brain stimulation and conscious experience. Conscious. Cogn. 13, 626–645.

Popper, K.R., 1992. In Search of a Better World: Lectures and Essays from Thirty Years. Routledge, London, p. 245.

Popper, K.R., Eccles, J.C., 1977. The Self and Its Brain. Springer–Verlag, Berlin, p. 597.

Ryle, G., 1949. The Concept of Mind. Hutchinson, London, p. 344.

Sherrington, C.S., 1940. Man on His Nature. Cambridge University Press, Cambridge, UK, p. 413.

Sperry, R.W., 1980. Mind–brain interaction: mentalism, yes; dualism, no. Neuroscience 5, 195–206.

Stuart, D.G., Pierce, P.A., 2006. The academic lineage of Sir John Carew Eccles (1903–1997). Prog. Neurobiol. 78, 136–155.

Umezawa, H., 1993. Advanced Field Theory: Micro, Macro, and Thermal Physics. American Institute of Physics, New York, p. 238.

Velmans, M., 1991. Is human information processing conscious? Behav. Brain Sci. 14, 651–669.

Wiesendanger, M., 2006. Eccles' perspective of the forebrain, its role in skilled movement, and the mind-brain problem. Prog. Neurobiol. 78, 304–321.

Willis, W.D., 2006. John Eccles' studies of spinal cord presynaptic inhibition. Prog. Neurobiol. 78, 189–214.

Wolpaw, J.R., Carp, J.S., 2006. Plasticity from muscle to brain. Prog. Neurobiol. 78, 233–263.