Protophenomena and their Physical Correlates

Bruce J. MacLennan, Ph.D.

Department of Electrical Engineering and Computer Science

University of Tennessee

Knoxville, TN 37996

Possible Referees/Reviewers:

Prof. David Chalmers, Philosophy Program, Research School of Social Sciences, The Australian National University, chalmers@anu.edu.au

Prof. Norman D. Cook, Informatics Faculty, Kansai University, cook@res.kutc.kansai-u.ac.jp

Karl Pribram, MD, PhD, Distinguished Research Professor of Psychology and Cognitive Neuroscience, Psychology Department, Georgetown University, pribramk@georgetown.edu

Prof. Galen Strawson, Department of Philosophy, The University of Reading, g.strawson@reading.ac.uk

David Skrbina, PhD, Department of Literature, Philosophy, and the Arts, Univ. of Michigan, Dearborn, skrbina@umd.umich.edu

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Abstract

Philosophers distinguish several senses of "consciousness," but the most problematic is *phenomenal consciousness*, which refers to one's subjective awareness of the external world and of one's own mental state, to the experience of being *someone*. Understanding how phenomenal consciousness is related to physical processes has been dubbed by David Chalmers the *Hard Problem* of consciousness, because it addresses, without evasion, the relation of mind and matter. This paper presents a method that addresses the Hard Problem in terms of *protophenomena*, elementary units of embodied subjectivity, and permits the formulation of detailed, experimentally verifiable hypotheses about protophenomena and their physical correlates. Moreover, these techniques reveal theoretical preconditions for phenomenal consciousness in non-biological systems, such as robots, and allow formulation of empirically verifiable hypotheses relating to non-biological consciousness.

Key words: Hard Problem, neurophenomenology, phenomenal consciousness, protophenomena, qualia, robot consciousness, zombie problem

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1. THE HARD PROBLEM

Philosophers distinguish *functional consciousness*, which refers to the cognitive and behavioral functions of consciousness in an organism, from *phenomenal consciousness*, which refers to the subjective experience of awareness (e.g., Block, 1995). Functional consciousness presents many challenging scientific problems, including the integration of multimodal sensory information, memory, emotion, motivation, planning, and action in order to promote the survival of the organism and its species, and how these functions are implemented in a nervous system. Although these problems are challenging, they present no fundamental epistemological problem, because they can addressed by the usual methods of empirical science. Unfortunately, these methods are unsuitable for addressing the principal question of phenomenal consciousness, which David Chalmers (1995, 1996) has called the *Hard Problem*: the relation of subjective experience to physical processes in the nervous system (see also Strawson, 1994, 2006; MacLennan, 1995, 1996a). The problem is that current physical theory says nothing about subjective experience, and so there seems to be no inconsistency in the possibility of these neurological processes taking place exactly as they do, but without accompanying subjective experience — the so-called "zombie problem" (Campbell, 1970; Kirk, 1974; Kripke, 1980). Closely related is the problem of robot consciousness, which is a good test case for any proposed theory of consciousness. Could a robot be conscious, and if so, under what conditions?

Because of a fundamental difference in kind between the shared experience of third-person observation, on which most science is based, and the private experience of first-person awareness, it is an epistemological error to attempt a reduction of first-person phenomena to third-person phenomena (Strawson, 1994, 2006; Chalmers, 1996, Pt. 2; MacLennan, 1995, 1996a). Therefore a different empirical approach is required to solve the Hard Problem.

2. PROTOPHENOMENAL ANALYSIS

Protophenomenal analysis is based on the observation that the conscious state has parts that stand in relation to each other (including relations in time). Therefore, although a reduction of phenomenal consciousness to physical processes is impossible, it is possible to reduce conscious phenomena to simpler conscious phenomena. As a simple example, visual experience, which is extended in perceptual space, can be divided into elementary patches of brightness, color, texture, and so forth (although even vision is more complicated than this example suggests; e.g., Pribram, 2004, p. 10; MacLennan, 2003, 2010). In many cases these simpler phenomena can be correlated with activity in specific brain regions. Therefore, phenomenal consciousness can be investigated through *neurophenomenological reduction*, that is, parallel reductions in the realms of subjective experience and neurobiology. Obviously the latter depends on neuroscientific investigation, but the former requires skill in *experimental phenomenology* (Ihde, 1986; McCall, 1983), which elucidates the structure of conscious experience by means of careful and publicly validated internal observation and experiment. The parallel reductive processes inform each other, suggesting hypotheses and experiments on each side.

Reduction must stop somewhere, and on the neurological side one usually stops at the single neuron as the unit of neural activity. (The unit of analysis in not uncontested, since various researchers have defended both larger units, such as the microcolumn, and smaller units, such as the dendritic spine.) Likewise, while it is conceivable that the conscious state is a continuum, and infinitely divisible, a good working hypothesis is that there are smallest units of subjectivity, which have been called *protophenomena* (Chalmers, 1996, pp. 126–7, 298–9; Cook, 2000, 2002a, 2002b, chs. 6–7, 2008; MacLennan, 1996a; cf. *proto-qualia* in Llinas, 1988; *phenomenisca* in MacLennan, 1995). William

James referred to them as "aboriginal atoms of consciousness" and "mental atoms" (1890/1955, vol. I, ch. 6, p. 149). Since, apparently, one's conscious state is correlated with the activity of masses of neurons, to a first approximation a protophenomenon can be understood as the contribution to the conscious state made by a single neuron. For example, neurons in primary sensory cortices have receptive fields, which are simple ranges of stimuli to which they respond (e.g., an oriented edge at a particular location in the visual field), and the corresponding protophenomenon would be something like the visual experience of that edge.

These simple visual examples are easy to understand, but apt to mislead, suggesting that protophenomena are "raw sense data" (such as a localized "red-here-now"). Therefore, we need to emphasize that protophenomena are taken to be the elements of the entire conscious state, including perceptions and their interpretations, but also recalled memories, discursive thoughts, imagination, intuitions, intentions, emotions, moods, motor actions, and so on — all that constitutes conscious mental life.

Phenomenology studies the structure of *phenomena*, which in this context are things that appear (Greek, *phainetai*) in conscious experience. Protophenomena are the elementary constituents of phenomena, but we might not be conscious of them in isolation, for they are very small. For example, if we suppose that there is one protophenomenon for each neuron, there may be 30 to 100 billion protophenomena in the conscious state. It sounds paradoxical to say that we might not be conscious of the elementary constituents of the conscious state, but the claim can be understood by analogy, for protophenomena are analogous, in the subjective realm, to the individually imperceivable atoms of which macroscopic physical objects are made. Solid, visible objects are made from atoms, but in isolation atoms are neither visible nor solid, though visibility and solidity are consequences of their properties and relations when combined in large numbers. So also conscious phenomena are a consequence of the coherent activity of vast numbers of individual protophenomena ("atoms of consciousness"), whose individual contributions are generally below our level of awareness. (To put it more operationally, the addition or deletion of a protophenomenon to a phenomenon is no more likely to affect one's behavior than is the addition or deletion of an atom to a macroscopic object.)

The atomic analogy is also helpful in understanding protophenomenal interdependencies, for macroscopic objects owe their existence and properties to interatomic and intermolecular forces that bind the individual atoms into coherently behaving wholes. So also there are dependencies among protophenomena that parallel, in phenomenal space, the connections among neurons in physical space. As a neuron's activity is a function of its own past activity and of the activity of the neurons from which it gets its input, so the intensity of a protophenomenon in the conscious state is a function of the protophenomena on which it depends and its own past intensity. (MacLennan, 1996b, presents a first approximation to a mathematical description of protophenomenal interdependence.)

Since there does not seem to be any essential difference between the neurons in different sensory cortices, indeed throughout cerebral cortex, it is likely that sensory qualities are a consequence of the interconnections among neurons rather than of properties inherent to the neurons. Protophenomenal analysis thus implies a *structural theory of qualia*; that is, the qualitative characters of protophenomena are not inherent but arise by virtue of their interconnections. This is supported by a variety of observations, including the well-known phenomenon of referred pain, in which neurons in sensory cortex reassign themselves from an amputated limb to other parts of the body (e.g., Karl, Birbaumer, Lutzenberger, Cohen & Flor, 2001), and recent experiments by Sur (2004) demonstrating that neurons in auditory cortex could be "rewired" to support visual phenomena. Thus the protophenomenal quality of a neuron is not inherent to the neuron, but depends on the neuron's interconnections with other neurons, and likewise on the dependence of the corresponding protophenomenon on the protophenomena corresponding to these other neurons.

A related issue is the fact that much of what our brains do is unconscious, and so protophenomenal analysis must account for the fact that some neurophysiological processes have associated conscious phenomena, but others do not. Possible solutions are presented elsewhere (MacLennan 1996a, 2008).

The importance of protophenomena for the Hard Problem is that they correspond to small-scale neurophysiological processes, which we call the *correlative activity* of the protophenomena, which take place at certain *activity sites* in the brain. These processes have not been identified definitively, but there are several likely candidates, including the binding of neurotransmitters to their receptors, somatic membrane potential, and the opening of ion channels when a nerve impulse is generated. Their identity is an empirical matter, but experimental evidence is currently lacking.

Therefore, the possibility of robot consciousness depends on what sort of physical processes have accompanying protophenomena, and in particular on whether protophenomena accompany nonbiological (or even non-neural) processes. Hence, identifying what physical processes support protophenomena is fundamental to determining whether robots could have phenomenal consciousness (MacLennan, 2009).

3. PHYSICAL SUBSTRATES FOR PHENOMENAL CONSCIOUSNESS

The simplest hypothesis is that the intensity of a protophenomenon in consciousness is correlated to some activity in a corresponding neuron, for example, its impulse rate. But if we try to be more precise, we see that there many physical processes that could be the correlative activity. A few of the possibilities are the impulse rate at the axon hillock, the ion flux across the somatic membrane, and the somatic membrane potential. However, some neuroscientists have argued that conscious experience is more likely associated with graded electrical fields and currents in the dendritic tree, rather than in the all-or-nothing firing of action potentials (Pribram, 1971, pp. 104–5, 1991, pp. 7–8, 2004). This suggests that the relevant physical processes might be neurotransmitter flux across the synapse, binding of neurotransmitter molecules to receptors, or the membrane potential of a dendritic spine. We do not yet have the required experimental evidence, but identifying the correlative activities will be relevant to whether physical processes in a robot might have protophenomena.

Seeing the variety of possible correlative activities in a neuron raises the question of why some physical processes should have protophenomena but not others. Norman D. Cook has suggested one answer, arguing that a protophenomenon corresponds to the opening of a nerve cell to its intercellular environment when the impulse is generated (Cook, 2000, 2002a, 2002b, chs. 6–7, 2008). He explains that

> the momentary opening of the cell membrane at the time of the action potential is the single-cell protophenomenon ... underlying "subjectivity" – literally, the opening up of the cell to the surrounding biochemical solution and a brief, controlled breakdown of the barrier between cellular "self" and the external world (Cook, 2002a).

This opening of a cell to its environment increases the correlation between its internal and external states, increasing the mutual information between the interior and the exterior and decreasing the entropy of the entire system. This is a fundamental information process, an elementary act of proto-cognition, and so it is an attractive as the possible physical correlates of protophenomena.

Addressing the question of what sorts of physical processes support consciousness, Chalmers (1996, ch. 8) suggested that any *physical information space* has associated protophenomena, which would permit non-biological consciousness, but his idea is based on a vague notion of "differences that make a difference." The central issue is that information, in a cognitive sense, depends on distinctions that have a function or purpose, or that are relevant. In a biological sense, relevance can be grounded, ultimately, in the survival of the individual or its group, that is, in inclusive fitness (Burghardt, 1970). In our experiments demonstrating the evolution of communication in a population of machines, we have shown how this idea can be transferred to nonbiological nonequilibrium systems (MacLennan, 1992, 2006; MacLennan & Burghardt, 1993). Information is relevant to the persistence of the population in its nonequilibrium state, to its "survival."

Hence our approach to the Hard Problem combines Cook's and Chalmers' insights with thermodynamics, since living things must act to maintain internal organization, to keep their entropy low. From the pioneering work of Schrödinger (*What is Life?*, 1945/1967) to recent work by Eric Schneider (2005), it is apparent that living systems maintain themselves in a far-from-equilibrium state by using free energy and matter to create and sustain internal order, that is, to decrease internal entropy. Furthermore, even the simplest life forms use information, which is mathematically equivalent to negative entropy, to improve their ability to survive. When a cell senses its environment, it decreases the independence of the internal and external states, thus decreasing entropy (increasing information). Although information theory has a problematic relation to thermodynamics through the shared concept of entropy, it nevertheless provides a basis for addressing the issue of relevance in information. Thus entropy, with ties to organization and survival on one side and to information and intelligence on the other, is fundamental to understanding "differences that make a difference," and to explicating the physical information spaces that correspond to protophenomena.

Therefore we have been developing an empirically verifiable theory of phenomenal consciousness that relates the intensities of protophenomena and their mutual interdependence to the fundamental thermodynamics of order and information. Such a theory will provide a basis for determining the possibility or actuality of phenomenal consciousness in robots and in the non-human universe at large. There are several significant research questions: Can Chalmers' notions of physical information spaces and “differences that make a difference” be explained in terms of the thermodynamics of order and information? What does this theory suggest are the most plausible physical activity sites associated with protophenomena? Which psychophysical experiments could discriminate among hypotheses concerning the physical processes that could be the correlative activity of protophenomena?

4. THEORETICAL INVESTIGATIONS

In the remainder of the paper, we will present our ongoing investigations of protophenomena. A principal task is to consolidate the preceding hypotheses into a theory integrating protophenomenal analysis, information theory, and thermodynamics in order to account for phenomenal consciousness and its physical correlates. The approach is primarily theoretical and uses entropy as the principal organizing concept. We are developing the theory mathematically and in a sufficiently general way so that we can understand its applicability to non-biological self-sustaining non-equilibrium systems (i.e., artificial life forms). The goal is a sufficiently precise theory of phenomenal consciousness (both biological and non-) to permit experimental investigation. Eventually the theory will have to be validated in the context of human phenomenal consciousness (which is a given), and the physical processes associated with protophenomena and their relationships need to be identified more precisely.

More specifically, the mathematical analysis is grounded in thermodynamics, information theory, cellular biochemistry, and neuroscience. We are formalizing the idea that information processes in neurons serve functions that can be explained in terms of thermodynamics (in particular the Maximum Entropy Production Principle). To the extent that this analysis is independent of the specifics of neural cell biology, it will suggest (but not establish) physical preconditions for non-biological phenomenal consciousness.

Therefore, we are analyzing the information processing of a single neuron in these terms. Aside from the obvious connection between the brain and consciousness, the neuron is the primary agent making "decisions that make a difference." Our current focus is the pyramidal cell, but we do not expect the results to depend on the cell type. The challenge is that a neuron does not survive as an individual, independent organism, so the connection to thermodynamics is very indirect (via the survival of the organism and, more accurately, the survival of its species).

This analysis can be carried to a deeper level, focusing on those processes that mediate the connection of a cell (and in particular a neuron) to its environment: receptor binding and gated ion channels. In addition to their role in opening the cell to its environment and increasing the mutual information between "self" and "other," these receptors and channels can be considered elementary decision-making units, which contribute to the function of the neuron.

We can focus deeper yet, on the allosteric proteins that constitute these receptors and gates, and that implement the information processing networks within the cell (Bray, 1995). The binding of regulator molecules to an allosteric protein changes its function in the cell, which is a very direct embodiment of decisions that make a difference, and so it approaches the hypothesized fundamental requirements for an activity site and brings the information-theoretical and thermodynamical notions of entropy nearly to identity.

Finally, we must close the loop between these very low level physical information processes and the entropy-decreasing self-organization of entire organisms, and indeed of species and ecosystems. The goal is an overarching framework for a theory of physical activity sites and their corresponding protophenomena.

5. EMPIRICAL INVESTIGATIONS

Another objective of our research is to define experimental protocols to identify physical correlates of protophenomena, which will be based on existing neuroscience research and adapted to artificial systems. Eventual conduct of these experiments would serve to confirm or disconfirm the possibility of phenomenal consciousness in robots and other physical systems.

The first task is to identify, from among the various potential activity sites, those that are most plausible on the basis of the theoretical analysis.

The second task is to outline one or more experimental protocols capable of confirming or refuting hypotheses that particular physical processes are the correlative activity of protophenomena. The basic idea can be explained easily, but the actual experiments could be formidable. The approach depends on identifying at least one activity site whose protophenomenon is salient and relatively isolable in consciousness so that a human subject can report the experiences resulting from physical interventions in its neural locus. The complications are the "smallness" (in experiential terms) of individual protophenomena and their typically dense interdependence with other protophenomena, which corresponds to the dense interconnectivity of most neurons. Roughly speaking, the goal is to identify one or more neurons whose individual activity can be determined reliably through conscious experience. Therefore, we are surveying the neuropsychological literature to identify promising protophenomena with known neural loci.

Within a protophenomenon's neural locus there are several candidates for correlative activity (e.g., neurotransmitter flux across the synapse, neurotransmitter receptor activity, dendritic spine potential, somatic potential, ion flux at the axon hillock). For each possible activity site the hypothesis to be tested is that a certain kind of correlative physical activity is necessary and sufficient for the corresponding protophenomenon's presence in the conscious state. Its sufficiency is established by creating the physical activity artificially in the absence of the normal stimulus and with more proximal connections suppressed, and showing that this intensifies the protophenomenon. Necessity is established by replacing the activity site by another physical system that is functionally equivalent but makes use of different physical processes. Persistence in consciousness would show that the natural process is not necessary, and would demonstrate at least one artificial process sufficient to maintain the protophenomenon's presence. Conversely, its absence from consciousness would tend to disconfirm these conclusions, suggesting that the correlative activity depends on the natural process. By systematically investigating each possible correlative activity in this way, we can determine what sort of neural process corresponds to protophenomenal intensity and — more importantly for robot consciousness — we may discover other physical processes that have associated protophenomena. If none of the individual possibilities show clear evidence of being activity sites, then it might be necessary to investigate combinations of two or more possibilities by similar methods. It is also likely that conscious *state*, *content*, and *process* (Pribram, 2004) have different kinds of correlative activity, would be another topic for investigation.

Obviously, experimental interventions of this sort present enormous practical challenges, and ethical ones as well. Nevertheless, by defining them clearly we plan to demonstrate that hypotheses about protophenomena have empirical content, and are thus scientific, even if the experiments cannot be conducted at this time.

Therefore we are reviewing current and proposed experimental techniques in neuropsychology to determine which experiments may be feasible now or in the near future. For example, Losonczy, Makara, and Magee (2008) have developed techniques for delivering individual neurotransmitter molecules to individual dendritic spines with a spatial resolution of 1 micron and a time resolution of 1 millisecond. Although these procedures were not applied in vivo, their work shows that the sorts of experiments we have in mind are not impossible. The recently developed *optogenetics* technique uses light-sensitive proteins to control channels and enzymes with neuron-level millisecond-precision in intact animals (Zemelman, Lee, Ng & Miesenböck, 2002; Zhang, Wang, Brauner, et al., 2007). More precise control can be achieved by *two-photon glutamate uncaging*, which the molecule to be activated can be controlled by the coincidence of two lights (Pettit, Wang, Gee & Augustine 1997).

By means such as these we may develop a series of "crucial experiments" to determine the nature of activity sites in humans and to identify preconditions for artificial activity sites (if any). These experiments would constitute an agenda for solving the Hard Problem scientifically and applying it to artificial phenomenal consciousness.

6. REFERENCES

Block, N. (1995). On a confusion about a function of consciousness. *Behavioral and Brain Sciences*, 18, 265–66.

Bray, D. (1995). Protein molecules as computational elements in living cells. *Nature*, 376, 307–12.

Burghardt, G. M. (1970). Defining ‘communication’. In: Johnston, J. W., Jr., Moulton, D. G., Turk, A. (Eds.), *Communication by Chemical Signals,* Appleton-Century-Crofts, New York, pp. 5–18.

Campbell, K. K. (1970). *Body and mind*. Doubleday, New York.

Chalmers, D. J. (1995). Facing up to the problem of consciousness. *Journal of Consciousness Studies*, 2, 200–219.

Chalmers, D. J. (1996). *The conscious mind*. Oxford University Press, New York.

Chalmers, D. J. (2002). Consciousness and its place in nature. In: Chalmers, D. J. (Ed.), *Philosophy of Mind: Classical and Contemporary Readings*, Oxford, Oxford.

Cook, N. D. (2000). On defining awareness and consciousness: The importance of the neuronal membrane. In: *Proceeding of the Tokyo-99 Conference on Consciousness*, World Scientific, Singapore.

Cook, N. D. (2002a). Bihemispheric language: How the two hemispheres collaborate in the processing of language. In: Crow, T. (Ed.), *The Speciation of Modern Homo Sapiens*, Proceedings of the British Academy, London.

Cook, N. D. (2002b). *Tone of voice and mind: The connections between intonation, emotion, cognition and consciousness.* John Benjamins, Amsterdam.

Cook, N. D. (2008). The neuron-level phenomena underlying cognition and consciousness: Synaptic activity and the action potential. *Neuroscience*, 153(3), 556–70.

Freeman, A. (Ed.) (2006). *Consciousness and its place in nature: Does physicalism entail panpsychism?* Imprint Academic, Charlottesville, VA. Revision of *Journal of Consciousness Studies*, 13 (2006), nos. 10–11.

Ihde, D. (1986). *Experimental phenomenology: An introduction.* State University of New York Press, Albany.

James, W. (1890/1955). *The Principles of Psychology*, Authorized Ed. Dover edition of Henry Holt edition, New York.

Karl, A., Birbaumer, N., Lutzenberger, W., Cohen, L.G., Flor, H. (2001). Reorganization of motor and somatosensory cortex in upper extremity amputees with phantom limb pain. *The Journal of Neuroscience*, 21, 3609–18.

Kirk, R. (1974). Zombies versus materialists. *Aristotelian Society*, 48 (suppl.), 135–52.

Kripke, S. A. (1980). *Naming and necessity*. Harvard University Press, Cambridge, MA.

Llinas, R. R. (1988). The intrinsic electrophysiological properties of mammalian neurons. *Science*, 242, 1654–64.

Losonczy, A., Makara, J. K., Magee, J. C. (2008). Compartmentalized dendritic plasticity and input feature storage in neurons. *Nature*, 452, 436–40.

MacLennan, B. J. (1992) Synthetic ethology: An approach to the study of communication. In: Langton, C. G., Taylor, C. Farmer, J. D., Rasmussen, S. (Eds.), *Artificial Life II. The Second Workshop on the Synthesis and Simulation of Living Systems,* MIT Press, Redwood City, pp. 631–658.

MacLennan, B. J. (1995). The investigation of consciousness through phenomenology and neuroscience. In King, J., Pribram, K. H. (Eds.), *Scale in conscious experience: Is the brain too important to be left to specialists to study?* Lawrence Erlbaum, Hillsdale, NJ, pp. 25–43.

MacLennan, B. J. (1996a). The elements of consciousness and their neurodynamical correlates. *Journal of Consciousness Studies*, 3 (5/6), 409−24. Reprinted in: Shear, J. (Ed.), *Explaining consciousness: The hard problem*. MIT, Cambridge, MA, 1997, pp. 249–66.

MacLennan, B. J. (1996b). *Protophenomena and their neurodynamical correlates* (Technical Report UT-CS-96-331). Knoxville, TN: University of Tennessee, Knoxville, Department of Computer Science. Available at <web.eecs.utk.edu/~mclennan>.

MacLennan, B. J. (1999a). Neurophenomenological constraints and pushing back the subjectivity barrier. *Behavioral and Brain Sciences*, 22, 961–63.

MacLennan, B. J. (1999b) *The protophenomenal structure of consciousness with especial application to the experience of color: Extended version* (Technical Report UT-CS-99-418). Knoxville, TN: University of Tennessee, Knoxville, Department of Computer Science. Available at <web.eecs.utk.edu/~mclennan>.

MacLennan, B. J. (2003). Color as a material, not an optical, property. *Behavioral and Brain Sciences*, 26, 37–8.

MacLennan, B. J. (2006) Making meaning in computers: Synthetic ethology revisited. In: Loula, A., Gudwin, R., Queiroz, J. (Eds.), *Artificial Cognition Systems*, IGI Global, Hershey, ch. 9 (pp. 252–83).

MacLennan, B. J. (2008). Consciousness: Natural and artificial. *Synthesis Philosophica*, 22(2), 401–33.

MacLennan, B. J. (2009). Robots react but can they feel? A protophenomenological analysis. In:

Vallverdú, J., Casacuberta, D. (Eds.), *Handbook of Research on Synthetic Emotions and Sociable Robotics: New Applications in Affective Computing and Artificial Intelligence*, IGI Global, Hershey, NJ, pp. 133–53.

MacLennan, B. J. (2010). Protophenomena: The elements of consciousness and their relation to the brain. In: Batthyány, A. Elitzur, A., Constant, D. (Eds.), *Irreducibly Conscious: Selected Papers on Consciousness*, Universitätsverlag Winter, Heidelberg & New York, pp. 189–214.

MacLennan, B. J., Burghardt, G. M. (1993). Synthetic ethology and the evolution of cooperative communication. *Adaptive Behavior*, 2, 161–188.

McCall, R. J. (1983). *Phenomenological psychology: An introduction. With a glossary of some key Heideggerian terms.* University of Wisconsin Press, Madison.

Pettit, D. L., Wang, S. S., Gee, K. R., & Augustine, G. J. (1997). "Chemical two-photon uncaging: a novel approach to mapping glutamate receptors." *Neuron*, 19(3), 465–71.

Pribram, K. H. (1971). *Languages of the brain: Experimental paradoxes and principles in neuropsychology*. Prentice-Hall, Englewood Cliffs.

Pribram, K. H. (1991). *Brain and perception. Holonomy and structure in figural processing*. Lawrence Erlbaum, Hillsdale.

Pribram, K. H. (2004). Consciousness reassessed. *Mind and Matter*, 2(1), 7–35.

Schneider, E. D. (2005). *Into the cool: Energy flow, thermodynamics, and life*. University of Chicago Pr., Chicago.

Schrödinger, E. (1967). *What is life? The physical aspect of the living cell & mind and matter*. Cambridge: Cambridge University Pr.

Strawson, G. (1994). *Mental reality*. MIT Pr., Cambridge.

Strawson, G. (2006). Realistic monism. In Freeman (2006), pp. 3–31.

Sur, M. (2004). Rewiring cortex: Cross-modal plasticity and its implications for cortical development and function. In: Calvert, G. A., Spence, C., Stein, B. E (Eds.), *Handbook of multisensory processing*, MIT Press, Cambridge, MA, pp. 681–94.

Zemelman, B. V., Lee, G. A., Ng, M., Miesenböck, G. (2002). “Selective photostimulation of genetically chARGed neurons.” *Neuron*, 33(1): 15–22. doi:10.1016/S0896-6273(01)00574-8.

Zhang, F., Wang, L. P., Brauner, M., et al. (2007). “Multimodal fast optical interrogation of neural circuitry.” *Nature*, 446 (7136): 633–9. doi:10.1038/nature05744.