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Carmela Morabito

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Dexterity and Degeneracy, for a “Neural Phenomenology”

Carmela Morabito

Nowadays the parallels between cognitive sciences and phenomenology are widely recognized. In this paper an attempt is made to look at them from a historic-epistemological perspective, focusing on the concept of ‘open architecture’ developed in the 40’s by the Soviet neuropsychologist Nikolaj Bernstein to explain the richness of intelligent behaviour in the light of the morphological and physiological details of the brain. Bernstein’s concept of “dexterity” will be analysed in relation to what Gerald Edelman calls the “degeneracy” of the nervous system, to emphasise the crucial role of “dynamical constraints” in the environment, in the human body with his sensory-motor capacities, and in the brain. These two concepts refer to the “openness” of our mental and behavioural processes, whose plasticity is one of the conditions of possibility (à la Kant) of many species-specific traits of human powerful adaptability to the environment.

Phenomenology and Cognitive Neurosciences

«Among the fundamental properties of conscious experience are the following two: first, consciousness is highly integrated or unified—every conscious state constitutes a unified whole that cannot effectively be subdivided into independent components—and second, at the same time, it is highly differentiated or informative—there is an enormous number of different conscious states, each of which can lead to different behavioural consequences. The distributed neural processes underlying conscious experience also share these properties: they are highly integrated and, at the same

time, highly differentiated. We believe that this convergence between neurobiology and phenomenology is not a mere coincidence»¹.

The biggest challenge to contemporary cognitive neurosciences is explaining the cerebral mechanisms of consciousness, its emergence as a product of specific neural processes and interactions between brain, body and environment.

The aim is to understand how the general properties of consciousness emerge from the properties of brain as a complex system, a system whose functions constitutively need the interaction between the organism and its environment (also in a social and cultural sense).

Consciousness is a peculiar cerebral process with two main properties: it is extremely unitary (integrated) and complex (differentiated) at the same time. The states of consciousness cannot be divided in single parts and are extraordinarily variable.

The neural mechanisms of integration and differentiation are worth analysing.

Which are the correlations between subjective experience and the brain, in its “open” architecture and functioning?

In the second half of 20th century, cognitive psychology models underestimated the experiential dimension of consciousness. Assuming a theoretical frame clearly related to William James’ grounding of consciousness in the whole brain, contemporary neurosciences look instead for the neural basis of consciousness: not in single neurons or in single cerebral areas, but in complex systemic processes. Conscious experience is not the function of a single area of the brain, since it is associated with many activity pattern changes occurring simultaneously in many regions of the brain.

The neural processes at the basis of conscious experience share its main characteristics: unity, coherence, *privateness* and variability, the latter being essential to control the brain capacity of coping with innumerable and unpredictable situations.

Studying the structure and dynamic functioning of the brain in diseases confirms the enormous variability and individuality of each single brain at all the levels in which it is organised, from biochemistry to morphology. Clinical data give an indisputable evidence of the organism’s

1 G.M. EDELMAN, G. TONONI, *A Universe of Consciousness. How Matter Becomes Imagination*, p. 11

struggle to overcome pathogenic factors. Neuropsychology has shown in how many different ways an organism can rapidly “re-integrate” himself after a lesion (e.g. in anosognosia or hemi-inattention) within an always changing network that is never interrupted. Dynamic integration allows the brain to “fill the gap” by surrogating—more or less—any impaired function.

At this point, two basic questions can be put forward: how can the brain maintain its unity and coherence despite being so deeply characterized by multiplicity and variability at the same time? How can intelligent behaviour vary continuously even when the organism’s goals remain the same?

An answer can be put forward starting from individual experience, from the analysis of behaviour.

Bernstein:

Dexterity, Movement, Mind

It is exactly in the study of the connection between behaviour (even pathologic or dysfunctional) and brain functioning that Nikolai Alexandrovic Bernstein (1896-1966) finds the way to “enter” the mind-body system in its dynamic and adaptive dimensions.

Bernstein aimed at understanding how the brain controls movement: in athletes, in labour movements (he founded and directed the Biomechanic Laboratory in the Central Institute of Labour in Moscow), and in the veterans wounded during the war—people suffering from different motor pathologies and dealing with their motor deficits in different ways. He devoted all his research activity to this topic, from the 40’s to 1966, when he died.

«A rare case of a scientist who practically devoted his whole life to one problem: the physiological mechanisms of human movements and motor actions»: with these words Lurija refers to Bernstein’s studies on movement on a strictly physiological ground, without acknowledging the neuropsychological dimension of his studies on movement and brain and their relevance for a neurologically plausible model of the mind. But he studied movement to understand the brain, and the brain to understand the mind. In this connection lie the deeply heuristic value of his interdisciplinary approach and the relevance of his thought for cognitive neurosciences at large.

Bernstein studied the origins and mechanisms of voluntary movement, the nature of movement coordination, motor skills and exercise, grounding his analysis in the concept of dexterity².

The organism is constantly engaged in coping with an always changing environment; even the body and his motor capacities are always subtly changing. Assuming that to act dexterously is to adapt flexibly to many novel circumstances, dexterity is a special level of neuropsychological functioning: it is a process aimed at solving motor problems, not at producing particular patterns of movement, hence its psychological relevance. In that process, three elements are of fundamental importance: behaviour, mind and nervous system.

- «Dexterity is the ability to find a motor solution for any external situation, that is, to adequately solve any emerging motor problem
- correctly (i.e., adequately and accurately)
 - quickly (with respect to both decision making and achieving a correct result)
 - rationally (i.e., expediently and economically), and
 - resourcefully (i.e., quick-wittedly and initiatively)»³.

With these words Bernstein summarizes his detailed analysis of dexterity and its main features. It is a psychophysical capacity, or rather an ability defining the relationship between the nervous system and skills. It refers to the quickness, agility, flexibility and skilfulness of the human body. It is exercisable and builds «a bridge to the area of genuine intellect»⁴, because it consists in finding a motor solution for any situation and in any condition; it therefore solves the problem correctly—that is, adequately and accurately, quickly and successfully.

With a very interesting terminological choice, Bernstein refers to the basic feature of dexterity with the term “extravertedness” just to posit the relation to the external world as the psychophysiological core of this concept: dexterity always refers to the environment and it always has an element of extemporaneousness. «Demand for dexterity is not in the

2 N. BERNSTEIN, «On Dexterity and Its Development», transl. by M. L. Latash, in: M. L. LATASH, M. T. TURVEY (dir.), *Dexterity and Its Development* Lawrence Erlbaum Associates, Publisher, Mahwah, New Jersey, 1996. [1946-1947, originally published in Russia only in 1991].

3 N. BERNSTEIN *On Dexterity and Its Development*, p. 228.

4 N. BERNSTEIN, *op. cit.*, p. 19.

movements themselves, but in the surrounding conditions. [...] It is not in the motor act itself but is revealed by its interaction with the changing external conditions»⁵.

Here lies the experiential dimension of the link between mind, body and behaviour: development leads to an increase in the requirements for an ability to adjust quickly to new, changing environments; to solve unexpected, nonstandard motor tasks; to successfully overcome unforeseen circumstances.

Dexterity, Movement, Nervous System

Considering the variability of behaviour and the many different ways the organism can adaptively answer to unforeseen requests from the environment (always restructuring his adaptive strategies on the basis of his experience and expectations), Bernstein emphasizes the existence of multiple choices in the brain to create new possible associative connections between external needs, the endogenous chemical activity and the organism's goal-directed actions.

Plasticity, adaptability and flexibility are the main characteristics of the brain, underlying the capacity of complex organisms to adapt themselves to the most diverse environmental situations. With *On Dexterity* Bernstein challenged—in the 40's—the very foundations of traditional psychological and neuroscientific theories of behaviour with an ecological action-based theory of development. Dexterity is not a property of body movements as such, but a property of movement in situations. One cannot move dexterously; one can only solve a motor problem dexterously. According to Bernstein, if a real behavioural science has to be independent from the notion of reflex and from Behaviourism, it has to be based on embodied-action, thus reasserting the primacy of actions. This primacy imposes a radical shift in skill acquisition theories and—more in general—in physiology⁶. With these

5 N. BERNSTEIN, *op. cit.*, p. 208-210.

6 «Movements are the means by which the organism does not simply passively interact with the environment, but actively *acts upon it* in whatever way is necessary. ... The remarkable structurality and completeness of a motor act makes it impossible to treat it as an arbitrary collection of successive reflex elements ... [We need] to find a bridge between the *physiology of reactions*, with which psychophysicists have been exclusively concerned for some

assumptions, Bernstein goes beyond the limits of traditional physiology based on the reflex theory (either in its Pavlovian or Behavioural versions): the organism is a self-regulating system that reaches its goals on the basis of its genetic code, its sensory-motor capacities, and its environmental constraints. In so doing he produces a great qualitative change from within the materialistic and dialectic conception of the organism-environment relationship⁷.

Bernstein's approach is a necessary shift from movement to action, from the body—with its many degrees of freedom—to effective behaviour and to mind: «it is the brain or the muscle the ruling Czar, when you jump, walk, or run?»⁸.

Functional actions are primary and the control of movements and postures is secondary. Movements are not the building blocks of actions. In fact the control of movements is one of the results of the development of actions.

Bernstein summarized his theory of motor learning with the phrase “Repetition without Repetition” (a whole new way of thinking about behaviour): absolute repetition of a movement pattern is not possible

time, and the *physiology of activity*» in N. BERNSTEIN, *The Coordination and Regulation of Movements*, p. 144-147. Moving from the study of motor coordination Bernstein delineates a new conceptual frame: Physiology of Activity (not of simple reactions to stimuli), and in so doing he allows for a real consilience between neurophysiology, psychology and cybernetics, merging and synthesizing clinical and experimental data. To understand action, physiology and psychology, biomechanics and the Information Theory need to be integrated. Had Bernstein's *Dexterity* been published just when it was written, between 1946 and 1949, it would have offered a powerful theoretical support to Gibson's emerging ecological analysis.

7 Leontjev clearly states that «in the theory of Marxism the teaching about human activity, about its development and its forms, has decisively important significance for psychology. As is known, Marx begins his remarkable *Theses on Feuerbach* with the indication of the “chief defect of all hitherto existing materialism”. He believes that reality was taken by Feuerbach only in the form of an object, in the form of contemplation, and not as a human activity, not subjectively. [...] Marx had in mind the fact that cognition was considered then only as the result of the effect of objects on the recognizing subject, on his sense organs, and not as a product of the development of his activity in an objective world» in A. LEONTJEV, *Activity, Consciousness, Personality*, p. 39.

8 N. BERNSTEIN, *On dexterity and its development*, p. 255.

because of the inherent variability and complexity of the environment. According to the principles of self-organizing dynamics, Repetition without Repetition will tend to lead to the production of stable, smooth, and efficient solutions to motor problems.

This variability is not “noise” for the nervous system, but a fundamental environmental fact that exerts a selective pressure on the evolution of the nervous system.

This concept of motor learning brings to a new definition—an ecological one—of what is learned and of motor skill: what is learned when a skill is acquired is typically the process of solving a specific motor problem, not the abstract movements that might accompany the mature adult’s solution. There is a:

«functional non-univocality between impulses and effects: Changes in muscle tension bring about a movement and the movement affects the condition of the muscles by shortening or stretching them causing further changes in their tension. [...] Consequently, this form of interaction does not presuppose a one-to-one correspondence between force and movement, that is...one and the same sequence of changes in forces may produce different movements on successive repetitions»⁹.

The nervous system is not mechanical (as an input-output mechanism, indeed a merely reactive system); on the contrary it is an active self-organizing, dynamic, system in which alterations in the activities of a single part may cause radical reorganizations of the whole¹⁰.

Motor dexterity is very closely related to the functioning of the brain cortex. These brain areas are the youngest in the history of brain development, and they are, so to say, soaked with the ability to absorb one’s individual life experience. «Switchability and plasticity were born together with the brain cortex»¹¹.

Bernstein’s ideas of the relationship between structure and function in the brain offer a great contribution to what is called today “integrative neuroscience”: specific brain areas (Brodmann areas) are considered

9 N. BERNSTEIN, *The coordination and regulation of movement*, p. 62.

10 «Movements are not to be seen as chains of details, rather as structured broken down into details; they are structural wholes, characterised at the same time by a high degree of differentiation of the elements and by differences in the relations among the parts» N. BERNSTEIN, *op. cit.*, p. 78.

11 N. BERNSTEIN, *On dexterity and its development*, p. 222.

as possible locations of functional operators participating in logical operations performed by certain neural networks. One and the same operator can participate in various external brain functions, which are based on certain combinations of many operators.

«It would be very hard now to dispute the fact that the increase in the morphological, localizational differentiation of the brain substrate is a very strong factor favouring the development of non-local wave processes both inside and on the surface of the brain»¹².

Studying motor coordination, Bernstein defines the “true categories” (1935) for the organization of movement and of the brain itself in relation to mind.

«Biological activity implies the cognition of the surrounding world through action and the regulation of action within it. This leads to *knowledge through action and revision through practice* which is the cornerstone of the entire dialectical-materialistic theory of knowledge»¹³.

Edelman: a Neurobiological Theory of Mind

In the selectionistic theory of the brain (“Neural Darwinism”) formulated by Gerald M. Edelman (1929-2014)—that may be defined as “paradigmatic” of contemporary cognitive neurosciences—redundancy, complexity, plasticity, individual and historical dimension play an essential role in understanding the brain in its development and stochastic and epigenetic functioning. Each brain is necessarily unique since it is continuously modified by what one perceives and by the way one moves in the environment, i.e. by experience.

Different structures may have the same function or lead to the same result. This is what Edelman calls the *Degeneracy* of the nervous system: in the brain, extraordinary complex and degenerate neural pathways embody the epigenetic processes through which a great variability in anatomical structures and in neuronal connectivity is produced all along each individual’s life.

12 N. BERNSTEIN, *op. cit.*, p. 274.

13 N. BERNSTEIN, *The coordination and regulation of movement*, p. 119-120.

Each brain is unique. Adopting a selectionistic theory of the brain it is possible to correlate neural mechanisms and the phenomenological properties of consciousness, since the key properties of conscious experience emerge from the brain as a complex system whose rich functioning actually requires variability: «We emphatically do not identify consciousness in its full range as arising solely in the brain, since we believe that higher brain functions require interactions both with the world and with other persons»¹⁴.

Underlying consciousness there are neural processes that are at once highly integrated and continuously changing, thus highly differentiated¹⁵. Consciousness emerges from this peculiar cerebral organization, at the same time deeply integrated and differentiated, “sculpted” by individual experience and culture; «the brain is not organized like a computer, its functioning rests instead on such properties as variability, differential amplification, degeneracy and value»¹⁶.

«As intricate as the microstructure of neuronal connections may be, this intricacy is magnified by the number of different interactions, in space and time, that can affect synaptic transmission. The brain contains a variety of chemicals called neurotransmitters and neuromodulators that bind to a variety of receptors and act on various biochemical pathways. The chemical identity of these neurotransmitters and of their receptors, the statistic of their release, and the time and place of electrical and biochemical interactions all govern the thresholds of response of neurons in an extraordinarily intricate and variable manner. Furthermore, as a result of the release of the neurotransmitters, electrical signalling not only takes place, but leads to changes in the biochemistry and even in gene expression of the target neurons. This molecular intricacy and the resulting dynamics superimpose several more layers of variability on that of the neuroanatomical picture, contributing to what may be called the historical uniqueness of each brain»¹⁷.

14 G.M. EDELMAN, G. TONONI, *A universe of consciousness*, p. XII.

15 Already in the late 19th century, Sherrington's neurophysiological work suggested that integration keeps place with differentiation; the same dialectic between integration and differentiation is emphasized by Lashley in the 20's.

16 G.M. EDELMAN, G. TONONI, *op. cit.*, p. 93.

17 G.M. EDELMAN, G. TONONI, *op. cit.*, p. 41-42.

The key-concept to understand brain functioning is indeed “Degeneracy”¹⁸: it is a prominent characteristic of biological complexity and of evolution itself, being both a prerequisite for, and an inevitable outcome of, natural selection¹⁹.

It is the ability of structurally different elements of a system to perform the same function or the same output; when applied to the

- 18 This concept has a great salience in contemporary biological sciences: recent scientific literature, especially in immunological and neurobiological fields, has paid increasing attention to Degeneracy as an organizing principle for describing the properties and the dynamics of complex biological networks. Shifting from its original physico-chemical meaning (in quantum theory, to define different stationary states with different wave-functions corresponding to the same energy level), today it defines any class of objects in which different elements (i.e. inputs) could perform the same function (i.e. output). Degeneracy entered the Biological field for the first time thanks to Crick, in 1955 (on the relations between DNA and proteins). Immunology is the discipline that gave it a fundamental and wide-ranging explanatory role. Edelman proposes two different operative dimensions: 1) at the level of antibody-gene repertoire, 2) at the organism's level (assuming an analogy between somatic and natural selection mechanisms, Degeneracy is also a general evolutionary strategy to produce adaptability to unforeseen environments). The formation of a repertoire of degenerate neuronal circuits could then explain the brain as a modular system, giving it an evolutionary resilience ('robustness') to damage via the substitution of the damaged structure by others performing the same function (cfr. G. TONONI, O. SPORNS, G.M. EDELMAN, «Measures of Degeneracy and redundancy in biological networks», *Proceedings of the National Academy Sciences of USA*, p. 3257-3262). It is possible to make various examples of Degeneracy at different levels of biological organization: the genetic code, the protein folding process, metabolism, immune responses, connectivity in neural networks and neural dynamics.
- 19 «A complex system may be considered as one in which smaller parts are functionally segregated or differentiated across a diversity of functions but also as one that shows increasing degrees of integration when more and more of its parts interact. ... Unlike redundant elements, degenerate elements can produce new and different outputs under different constraints. A degenerate system, which has many ways to generate the same output in a given context, is thus extremely adaptable in response to unpredictable changes in context and output requirements. The relevance to natural selection is obvious», in : G.M. EDELMAN, and J. GALLY, «Degeneracy and complexity in biological systems», *Proceedings of the National Academy of Sciences of USA*, p. 13767.

nervous system it means that different populations of neurons can produce similar behavioural responses to identical external stimuli.

In a degenerate system, there is a partial functional overlap of elements already capable of non-rigid, flexible and versatile functionality: it is a “redundant functionality” that confers robustness, i.e. the ability to cope with variations in an operating environment with minimal damage, alteration or loss of functionality²⁰. In this light, degeneracy makes it possible to substitute—or vicariate—impaired functions, since degenerate networks allow for widespread, compensatory adjustment: many neurological lesions that appear to have little effect upon behaviour within familiar contexts reveal the presence of degeneracy in the brain. The redundant functioning of a system composed of heterogeneous elements, therefore, requires degeneracy.

The difference between redundancy and degeneracy is clear: unlike functional redundancy, which occurs when the same function is performed by identical elements, Degeneracy, which involves structurally different elements, may yield the same or different functions depending on the context in which it is expressed.

«Evolution and natural selection necessarily are accompanied by degeneracy. It is a prerequisite of natural selection because natural selection can only operate among a population of genetically dissimilar organisms»²¹.

The classical engineering concept of redundancy is opposite to that of degeneracy: the first refers to the “one-to-one”, or “one structure-one function” paradigm, the second to the ‘many structures-one function’ paradigm. A structural advantage of degeneracy in comparison to redundancy, lies in the evolvability of the degenerate element and of the whole system: degenerate structures are functionally overlapping and versatile, and rearrange their configuration to meet internal or external (environmental) changes thanks to their interchangeable task capabilities. Degenerate systems, then, show a flexibility that makes them capable to produce unforeseen functionalities (on a longer evolutionary time scale, this outcome coincides with the Gouldian concept of ex-aptation).

20 Robustness can be defined as the ability to produce a non-catastrophic response to perturbation/noise in the system.

21 G. EDELMAN and J. GALLY, *op. cit.*, p. 13763.

Neural Phenomenology?

In the correlation between the phenomenological analysis of behaviour, as grounded in the dynamical and experiential dimension of the individual, and cognitive neurosciences, a sort of “neural phenomenology” can be identified, deeply dynamical and integrated.

On the basis of many complex population dynamics, different populations of neurons and synapses organize themselves on different levels to produce different functionally equivalent choices²². In this context action is the cornerstone: its dynamical link with perception makes it planned and modulated in an ever-changing complex environment. Action and cognition are deeply linked and the motor organization of behaviour needs, and produces, complex cognitive functions and consciousness. Complexity and consciousness are also strictly linked, and complexity is in the brain. Neuronal dynamical integration occurs along with the integration of consciousness.

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22 The different functional aggregations of neurons can act as “functional systems”—in the words of Lurija—induced in the brain by the organism’s interaction with environment and culture.

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