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Editor's Corner

Plant Neurobiology as a Paradigm Shift Not Only in the Plant Sciences

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ABSTRACT

Plants are complex living beings, extremely sensitive to environmental factors, continuously adapting to the ever changing environment. Emerging research document that plants sense, memorize, and process experiences and use this information for their adaptive behavior and evolution. As any other living and evolving systems, plants act as knowledge accumulating systems. Neuronal informational systems are behind this concept of **organisms as knowledge accumulating systems** because they allow the most rapid and efficient adaptive responses to changes in environment. Therefore, it should not be surprising that neuronal computation is not limited to animal brains but is used also by bacteria and plants. The journal, *Plant Signaling & Behavior*, was launched as a platform for exchanging information and fostering research on plant neurobiology in order to allow our understanding of plants in their whole integrated, communicative, and behavioral complexity.

I always go by official statistics because they are very carefully compounded and, even if they are false, we have no others ...
~ Jaroslav Hašek, 1911

This quotation of writer and mystificator Jaroslav Hašek is from his electorial speech aimed to get a seat in the Austro-Hungarian parliament for his imaginary political party 'Moderate Progress within the Limits of the Law' in 1911. It indicates how statistics can be misused for manipulation of public opinion, sometimes allegedly for general good. This quotation is partially relevant also for recent biology which is passing through a critical cross-road from reductionist-mechanistic concepts and methodologies towards the post-genomic, holistic, systems-based analysis of integrated and communicative hierarchic networks known as life processes.

There is a message hidden in this Hašek's aphorism. All those mathematical models, scientific theories and concepts, however appealing, harmonious and long-standing … but which do not correspond to reality …; inevitably will be 'killed by ugly' facts generated by scientific progress, and finally replaced by new models, theories, and concepts.[1]

Despite the indisputable success of the reductionistic approach in providing many discoveries regarding single cells and their components, it is increasingly clear that promises of 'mechanistic' genocentric biology were just chimeras and that living organisms are much more complex than the sum of their constituents. Ernst Mayr, in his final opus, almost a testament published at his age of 100, strongly opposed the belief that the reductionism at the molecular level could help to explain the complexity of life. He stressed that the concept of biological "emergence", which deals with the occurrence of unexpected features in complex living systems, is not fully accessible using only physical and chemical approaches.[2]

Themes of hierarchy, continuity, and order dominated biology before the turn of the century, but these have in many cases been replaced by images of the workshop.

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Examples include such terms as 'machineries', 'mechanistic understanding', 'mechanistic explanation', 'motors', 'machines', 'clocks' etc. This shift may well reflect the characteristic style of our age. These concepts, although useful for mining of details, do not reveal the true complexity of life and can be misleading. Even a one-celled organism is made up of 'millions' of subcellular parts. Concerning the great complexity of unicellular creatures Ilya Prigogine (1973) wrote: "… but let us have no illusions, our research would still leave us quite unable to grasp the extreme complexity of the simplest of organism."[3] Moreover, eukaryotic cell proved to be, in fact, 'cells within cell',[4-8] while there are numerous supracellular situations, the most dramatic one is represented by plants when all cells are interconnected via plasmodesmata into supracellular organism.[6] All this collectively indicate that the currently valid 'Cell Theory' dogma is approaching its replacement with a new updated concept of a basic unit of eukaryotic life.[6-8]

Furthermore, genomes are much more complex and dynamic as we ever anticipated.[9,10] They often have as much as 99% of non-coding DNA sequences,[11] which is not 'junk DNA' but rather DNA which is part of multitask networks integrating coding DNA.[12] In genomes exposed to stress (like mutations), changes are scored preferentially in non-coding sequences which regain a new balance by complex changes in genome composition and activity.[9,10,13,14] There are several definitions regarding what is gene[11] and molecular biologists and genetics are learning to be careful not to make strong conclusions from under-expression, knocking-out, or overexpression of any particular gene. It is increasingly clear that mutations in single genes are accompanied with altered expressions of other genes and non-coding DNA sequences too, and even subtle re-arrangements of chromatin structure and genome architecture are possible. The dynamic genome actively regains the lost balance, also via extensive re-shufflings of non-coding DNA.

After complete sequencing of numerous genomes, it is clear that our understanding of what constitutes life and what distinguishes living biological systems from non-living chemical - biochemical systems is not much better than our understanding before the start of the genomics era some 60 years ago. Yet, it is also obvious that living systems, whether single cells or whole complex organisms like animals and plants, are not machines and automata which respond to external signals via a limited set of predefined responses and automatic reflexes. While humans and other animals, even insects, are already out of this 'mechanistic' trap[15,16] which can be traced back to Descartes,[17] plants are still considered to act only in predetermined automatic fashions, as mechanical devices devoid of any possibility for choice and planning of their activities. In contrast to machines, life systems are based on wet chemistry, being systems of hierarchical and dynamic integration, communication and emergence.[1,18]

Recently, a critical mass of data has accumulated demanding reconsideration of this mechanistic view of plants.[19,20] Plants are complex living beings, extremely sensitive to environmental factors and continuously adapting to the ever changing environment.[21] In addition, plants respond to environmental stimuli as integrated organisms. Often, plants make important decisions, such as onset or breakage of dormancy and onset of flowering, which implicate some central or decentralized command center. Moreover, roots and shoots act in an integrated manner allowing dynamic balance of above-ground and below-ground organs. The journal, *Plant Signaling & Behavior*, was launched as a platform for exchange of information about the integration of discrete processes, including subcellular signalling integrated with higher-level processes. Signal integration and communication results in adaptive behavior of whole supracellular organisms, encompassing also complex, and still elusive, plant-plant, plant-insect, and plant-animal communications. Coordinated behavior based on sensory perception is inherent for neurobiological systems.[22] Therefore, plants can be considered for neuronal individuals. Moreover, plants are also able to share knowledge perceived from environment with other plants, communicating both private and public messages.[23,24] This implicates social learning and behavioral inheritance in plants too.

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> **Behavior**
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> 1. An activity of a defined organism: observable activity when measurable in terms of quantitative effects of the environment whether arising from internal or external stimuli.
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> 2. Anything that an organism does that involves action and response to stimulation.
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> (Webster Third New International Dictionary 1961).

> Neuronal informational systems allow the most rapid and efficient adaptive responses. Therefore, it should not be surprising that neuronal computation is not limited to animal brains but is used also by bacteria and plants.

Some of our colleagues assert that plants do not exhibit any integrated neuronal principles.[25] They maintain that plants do not show complex experience- or learning-based behavior. Plants, they aver, act rather as machines manifesting predefined reflexes. Yet recent studies indicate that even prokaryotic bacteria exhibit cognitive behavior[26,27] and posses linguistic communication and rudimentary intelligence.[28-30] Therefore, it should not be too surprising that plants also show features of communication and even plant-specific cognition.[19,20,31,32-35] As any other living systems, plants act as 'knowledge accumulating systems'.[1] In fact, in order to adapt, all organisms continuously generate hypotheses about their environment via well formulated 'questions' which are solved by an increasing set of possible 'answers' in order to adapt.[1] Neuronal informational systems are behind this concept of organisms as 'knowledge accumulating systems' because they allow the most rapid and efficient adaptive responses.[22] As a consequence, neuronal computation is not limited to animal brains but is used also by bacteria and plants.

Reductionistic approaches will continue to "atomize" biological systems. Nevertheless, the avalanche of new data will be in need of functional integration, winning adherents to the idea that plants have integrated signaling and communicative systems that endowed them with complex and adaptive behaviour. We trust that *Plant Signaling & Behavior*, will become an important platform for exchange of

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these ideas. With progress of sciences, plants show more and more similarities to animals despite obviously plant-specific evolutionary origins, cellular basis, and multicellularity. We can just mention sexuality and sex organs, embryos, stem cells, immunity, circadian rhythms, hormonal and peptide signaling, sensory perception and bioelectricity including action potentials, communication and neurobiological aspects of signal integration. The whole picture strongly suggest that convergent evolution is much more important[36,37] than currently envisioned in evolutionary theories.

We have started with Jaroslav Hašek and we close with him as well. His quotation from 1911 is also a warning for future that we should stay open-minded. We should not slip into dogmatic 'traps' which have been so characteristic for the mechanistic and genocentric biology. Mathematics and computational biology are important tools, and surely will play decisive role in systems biology in the future. But they can be easily misinterpreted, and even misused. Plant systems biology, and the whole biology in general, must overcome dogmas of mechanistic genocentric biology. We hope that characterizing plants in their whole behavioral and communicative complexity will allow us to better understand what is life and how it emerged from chemical and biochemical complex systems.

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