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Report on my 2017 stay at the Yukawa Institute for Theoretical Physics, Kyoto, Japan

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Abstract. In this report, I summarize my research activities and some of the outcomes of the discussions during my one-month stay as Distinguished Visiting Professor at the Yukawa Institute for Theoretical Physics in October 2017. This visit was supported by the International Research Unit of Advanced Future Studies, Kyoto University, Japan.

Keywords: cognitive information processing, complex systems, creativity, interdisciplinary and transdisciplinary science

Personal Note

I wish to express my deep gratitude to Professor Masatoshi Murase for his wonderful hospitality, his kindness, inspiration and support during my stay at YITP as a Distinguished Visiting Professor. I consider Prof. Murase's efforts towards providing broad insights to the work of other researchers coming from different backgrounds and disciplines, including the sciences and the humanities, very stimulating.

I would like to thank the YITP and the International Research Unit of Advanced Future Studies for their support of my visiting professorship.

Moreover, I would like to thank the director Prof. Sinya Aoki and the colleagues at YITP and the International Research Unit of Advanced Future Studies for their hospitality and inspiring discussions.

Finally, I would like to thank the YITP staff, in particular Ms. Miyuki Nakamura and Mrs. Sachiko Mochidome, for their kindness and all their administrative help.

It has been a real pleasure to work at YITP and to interact with its faculty and staff, and a very inspiring and fruitful period for me personally and professionally. Working in this excellent place of science, embedded in such a beautiful city with its incredible historic heritage and its kind people, made it an unforgettable experience.

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1. Scientific Activity

My research as a Distinguished Visiting Professor at the International Research Unit of Advanced Future Studies was conducted during the month of October 2017 in collaboration with Professor Masatoshi Murase.

During my stay, I had the opportunity to conduct many fruitful discussions with Prof. Murase on the scope of his and our own work on the topics of interdisciplinary and transdisciplinary research and complex systems in general and cognitive processes involving information processing and creativity in particular. Moreover, I contributed to a transdisciplinary seminar at the Yukawa Institute, gave a seminar at Saitama University, and provided tutorials at a Nonlinear Dynamics Workshop at Tokyo University of Science.

1.1. Context

Neuro-inspired information processing and cognitive computing have been gaining renewed interest in recent years due to the development of novel computing concepts and insights from neurophysiological experiments into information processing in or by the brain, and in particular the implementation of cognitive computing using novel analog hardware.

Artificial intelligence and machine learning are important drivers behind this development. We are currently witnessing their success in performing tasks deemed human or at least very difficult to achieve before (Silver, 2017). In fact, tools developed in these fields are entering our everyday lives more and more. But even the most popular and successful methods like deep learning only employ very simplified and reduced network and learning concepts and cannot be regarded to mimic human information processing and creativity or to represent Artificial General Intelligence (AGI).

From a wider perspective, major aspects of how the brain is capable of performing so many different kinds of tasks in an ever-changing environment and to learn so efficiently at a very low power consumption of only 20-25W still evade our current understanding. We do not understand many aspects of how the brain encodes information, routes information, stores and retrieves (memorizes) information, connects information, and how these abilities are linked to certain properties of individual neurons, cortical structures, connectivity and emerging dynamical properties. The so-called inner workings of our mind still remain one of the largest scientific mysteries. The maxim “γνῶθι σεαυτόν”, meaning “know thyself”, which had been inscribed at the Temple of Apollo at Delphi, continues to be driving our curiosity and scientific efforts.

We feel that qualitative advances might benefit from a truly multidisciplinary and ultimately transdisciplinary approach. Some motivations and justifications for these thoughts, although highlighting only few particular aspects, will be discussed in the following section.

1.2. Cognitive information processing and creative processes

The following thoughts on cognitive and creative processes are themselves the result of a creative and very dynamical process: the discussions I have had with Professor Masatoshi Murase and colleagues during my stay at the Yukawa Institute of Kyoto University in October 2017. They should be considered a work in progress. The aim of our research is to gain an extended understanding of cognitive processes in general, to support a paradigm shift towards a perspective of cognition and creativity as a dynamical process and finally, in a practical sense, to apply and test the gained ideas and identified minimal requirements for the implementations of cognitive computing systems. In this report, I will restrict myself to rather general considerations and will leave more technical aspects and explicit modeling to future publications.

Our considerations emerged in the tension field of several ideas and thoughts. First, there were the works of Prof. Murase on the nature of life and of cognitive processes (Murase, 2000; Murase, 2018); and second, our work at IFISC on minimal analog complex dynamical systems, and performing neuro-inspired information processing based on nonlinear transient responses (Soriano, 2015). And third, there was our common understanding that complex hierarchical, potentially self-similar, dynamical processes are key for the understanding of cognitive processes.

1.3. Neuroscientific perspective

From a neuroscience perspective, the brain exhibits, both in structure and neural activity, features of scale-invariant behavior. With respect to structure, the branching of the brain's vascular and neural systems shows self-similar features in the brain's architecture. With respect to neural activity, avalanches of electrochemical activity, both in vitro and in vivo, have been reported to exhibit scale-invariant behavior in brain networks (Petermann, 2009; Shriki, 2013) (for a recent discussion and overview see (Martinello, 2017)). Currently, there is an active debate in the scientific community, in how far these properties are relevant or even key to the understanding of information processing abilities in the brain.

Although our insights into many aspects of the brain's structure and activity are still quite restricted, and we do not know first principles governing the dynamics of neural system, it is justified to consider the brain as a complex, self-organized dynamical system. With respect to information processing, distributed, parallel processing, as well as serial operations coexist within highly interconnected networks (Singer, 2013). Even (or maybe in particular) in its resting state, the brain exhibits highly complex dynamics (Shriki, 2013). This is not surprising given the large size of the cortical network that spans an extremely high-dimensional state space in which huge amounts of information, both genetically, ontogenetically and learned, can coexist. More surprising is how fast (~200ms) and reliable the brain is capable of accessing large parts of this information, extracting it from the high-dimensional state space, or even connecting it with other information. (Singer, 2013). The processing of information, like the recognition of a pattern, induced by a stimulus is, in this context, rather a reduction in dynamical complexity than a stimulus-induced increase.

Yet, it is often assumed that the neural mechanisms underlying perception and cognition can be well approximated by steady-states. Consequently, in many models, the behavior of the network is assumed to be extremely simple, often described by steady states or periodic states. This is a conceptual reduction in which, in fact, the key aspects of the cognitive processing might get lost (Rabinovich, 2008).

Moreover, in most concepts and models, like in the Hopfield model, information processing in the brain is assumed to be based on attractors in state space. This is a concept also being widely supported by the neural networks community. In this perspective, an input signal gradually changes the pattern of activated nodes (neurons) of a neural network, resulting in a new pattern represented by an attractor state (Rabinovich, 2008). There are a number of problems with this idea. First, in order to be able to react sufficiently fast to threats and dangers, it is a question of survival that the neural activity does not have to settle in an attractor state before a decision can be made. Moreover, given the incredible size of the state space, the convergence to the correct attractor corresponding to the stimulus/input signal becomes an immense problem. There are neurophysiological experiments that indicate the existence and functional relevance of deterministic dynamics that is not requiring classical attractor states (Rabinovich, 2008). The concept of Liquid-state machines that was introduced by Wolfgang Maass in 2002, suggests that the cerebral cortex is a nonequilibrium system, and that information processing in the brain is based on unique patterns of transient activity, induced by incoming inputs (Maass, 2002). Indeed, such computations can fulfill the requirement of being consistent, robust against noise, and easily decoded. (Rabinovich, 2008). Recently, complex networks of dynamically connected saddle states have been shown to be capable of performing information processing, like, e.g., arbitrary logic operations in a controled way (Timme, 2012). The corresponding dynamics allows for computation based on switching along complex networks of states. (Rabinovich, 2006, Timme, 2012).

These are only a few examples of questions stimulating ideas for novel concepts and, at the same time, illustrating the huge gaps that exist to model or understand even the most fundamental processes in the brain. These limitations also have as a consequence that technical implementations of artificial intelligence, machine learning or cognitive computing so far only mimic very limited aspects and few mechanisms that might be 'at work' in our brains. But some of the mentioned neuroscientific properties also provide clues to where one might start or advance existing approaches.

1.4. Minimal information processing concepts and implementations

At IFISC we have been following a minimal design approach that picks up upon some of the discussed complex dynamical features. With minimal design, we mean that we start with simple concepts, reducing them as much as possible in terms of ingredients, constraints and hardware requirements, and then exploring their capabilities. This suggests that we do not aim at making as close a copy of the brain (or small parts of it) in electronic or photonic hardware as possible, but to learn about the fundamental properties of information processing concepts. This is in clear contrast to the approaches chosen, e.g., in one of the European Flagship projects, the Human Brain Project. Our approach is motivated by the thought that we simply do not know which properties of neurons, synapses, plasticity mechanisms etc. are owed to constraints, determined, e.g., by the biological substrate, and which ones are key for the cognitive information processing concepts in general. We feel that this is paramount to explore, in order to avoid potential significant overheads and restrictions when building cognitive computing systems on other hardware platforms. Even the rather simple question regarding the exact role and requirement of excitable action potentials for neural information processing has not yet been satisfactorily answered.

For our minimal information processing concept, we have chosen a few components of the previously discussed features found in the brain. These are first the use of a recursive network, in contrast to feedforward networks, that are often employed in common artificial neural network methods; second, computation based on nonlinear transient responses rather than attractors; and third, the utilization of large state space dimensions to allow for linear separation of distinct states and the flexibility to approximate a large set of nonlinear transformations. Our approach is based on methods developed independently as Echo State Networks by Herbert Jaeger (Jaeger, 2001) and Liquid State Machines by Wolfgang Maass (Maass, 2002). Today, they are being mostly sub-summized under the name Reservoir Computing. The appeal of these methods is that they combine the properties of fading memory for contextual information processing with low constraints on the network and easy training methods based on linear regression.

Starting from their methods, which are still based on networks with a large number of nodes with nonlinear properties that mimic neurons and random connectivity patterns, we simplified the concept further. Instead of using a large recurrent network with many nodes, we used the simplest possible dynamical system allowing us to map the input onto a high-dimensional state space: a delay- dynamical system comprised of a single nonlinear node and a delayed feedback loop. We induced nonlinear transients, instead of using fixed mappings, by modulating the input information during one delay time with a defined random mask on time scales faster than the inverse characteristic frequency of the nonlinear node. And instead of using sigmoid nonlinearities, we used various kinds of nonlinearities depending on the hardware substrate we employed to realize the nonlinear node. These included a Mackey-Glass type nonlinearity (Appeltant, 2011), an Ikeda-type nonlinearity (Larger, 2012), and the nonlinear optical response of semiconductor lasers (Brunner, 2013).

Some of the remarkable findings of these studies were that the ring-like topology of the delay-dynamical system for several tested tasks worked similarly well, and sometimes even better, than the large random networks with many nodes, that many nonlinearities worked even better than the sigmoid one, and that no thresholding or spiking dynamical behavior was required at this point to achieve high-performance information processing. The tasks that were demonstrated included, among others, nonlinear prediction, utilizing only the inherent memory of the system, and dynamical pattern classification tasks. High-speed, high-performance information processing has been demonstrated by us and several other groups. (Brunner, 2013a; Brunner, 2013b; Bueno, 2017).

While we have been able to demonstrate the use of nonlinear transients to compute, we still started from systems that converged to a stable state as attractor without input. This has been so far considered a requirement to achieve the so-called consistency property. Consistency means that similar input stimuli result in similar outputs. This is demanded to have reliability of responses. Assuming a stable state without input is in clear contrast to the endogenously active brain which exhibits a highly complex state without external stimuli. We recently showed that even for autonomously dynamical systems exhibiting high-dimensional chaotic dynamics, consistency can be achieved under some conditions, managing another small step towards mimicking the above-mentioned features found in the brain (Oliver, 2016).

1.5. Towards creative processes

To extend these approaches towards more general and powerful neuromorphic computing concepts, and potentially even towards understanding and mimicking creative processes, the identification of crucial mechanisms is key. The discussions with Prof. Murase were very fruitful in this context and provided first clues.

Usually, creativity is defined as a process in which something new is formed that has value or meaning. The created item may be a physical object, like a piece of arts or an idea, a scientific theory or a music piece. Creativity is such a general concept that one can find many definitions depending on the discipline. The disciplines which are concerned with creativity range from arts and education to philosophy and science.

The idea of creativity is mostly associated with human activity. We usually associate it with the creation of something fundamentally new or the discovery of novel connections between before unconnected concepts and ideas. It is thus the generation of new information based on combining diverse types of information in novel ways, usually crossing intra-disciplinary or intra-modal boundaries.

The interplay of divergent and convergent thinking has been identified as an important mechanism of creativity. Convergent thinking is the cognitive ability or the logical process to arrive to the same (correct) answer when confronted with the same question or problem repeatedly. With what has been discussed before, convergent thinking might be associated with the property of consistency. Divergent thinking, in contrast, is the process of exploring many coexisting ideas that are being generated in a spontaneous emergent manner. Therefore, many ideas are explored in a short amount of time or even simultaneously, and unexpected connections are drawn. This process could be associated with the generation of information and conceptually even with chaotic processes. In a creative process, often, a period of divergent thinking is followed by a period of convergent thinking, in which ideas and information are being organized and structured.

From a psychological and neuroscientific perspective, divergent thinking has been linked in humans to semantic memory and, recently, also to episodic memory (Madore, 2017). From a functional connectivity perspective, creative thinking ability has been associated with a distinct brain connectivity profile. fMRI studies reveal that highly creative people show the ability to simultaneously engage large-scale brain networks comprised of cortical hubs within default, salience, and executive systems (Beaty, 2018). Moreover, it has been found that highly creative individuals are more likely to exhibit cognitive disinhibition compared to less creative individuals, which might allow more information to pass into conscious awareness (Carson, 2003).

An abstraction of the requirements for creative processes is, however, lacking so far. A starting point might be the ideas suggested by Prof. Murase, involving five major principles relating to essential, recursive aspects of life (Murase, 2008; Murase, 2011) and aspects of cognitive processes and information processing in complex systems in general (Murase, 2018). These five principles are: expansion, contraction, negation (deletion), connection, and emergence.

From the discussion in the previous paragraphs, the link of some of these principles to the requirements for and properties of cognitive processes is clear. Expansion and contraction relate to divergence and consistency. Negation and connection describe the changes in a physiological, functional or dynamical network. Finally, emergence describes that these processes occur in a self-organized manner, and that emergent complex behavior is at the heart of the self-similar endogenous activity and the responses of the brain to external stimuli.

It is a challenge for the coming years to identify the role and importance of these principles in cognitive and creative processes, to perform the abstraction into concrete complex systems models, and to verify or falsify their assumed role in the processes. It will be particularly interesting and crucial to explore the balance between the different mechanisms qualitatively and quantitatively. We might gain insights from psychological, medical and neuroscientific studies regarding the delicate balance. Imbalances result in disorders, diseases and pathologies that might give important clues to the balanced conditions that we consider the healthy one. How delicate these balances are might be illustrated by the finding that the frequency and intensity of certain psychopathic symptoms are noticeably higher in creative persons than in the rest of the population. Moreover, creative thinkers have been found to come more likely from family lines exhibiting a higher risk for psychopathologies even if the creative thinker or genius is herself/himself not suffering from these conditions.

In general, we are convinced that in order to gain a more thorough understanding of cognitive information processing and creative processes, we will need to extend the approach from the originally discipline-centric methods, via cross-disciplinary and inter-disciplinary collaborations, towards a truly transdisciplinary approach, comprising and combining insights, perspectives and synergetic methods, and not only from neuroscience, physics, mathematics, engineering, computer science, psychology and medicine, but also from philosophy. It is, in a nutshell, the whole spectrum from scientific reductionism to holistic Eastern philosophies brought together that might bring us closer to understanding the most complex system we know, our brain. Moreover, it will allow us to recognize the commonalities, but also to differentiate the different balance and qualitative differences with other creative processes in nature. These insights will not only enable technological advances, but bring us closer to understanding our own nature in the sense of the maxim “γνῶθι σεαυτόν”.

2. Presentations in affiliation with the International Research Unit of Advanced Future Studies

During my stay, I contributed to several seminars and workshops, as follows:

- Transdisciplinary Meeting at the Yukawa Institute for Theoretical Physics, Kyoto, Japan, 19. October 2017. I gave an invited talk with the title “Do we need a new information processing paradigm?”.
- Seminar at Saitama University in Saitama, 20. October 2017. I gave a one-hour presentation on “Photonic reservoir computing in telecommunication systems”, and also visited the labs and had discussions with Professor Atsushi Uchida and members of his group.
- Nonlinear Dynamics Workshop organized by Professor Tohru Ikeguchi at Tokyo University of Science with colleagues and students from many Japanese Universities. I contributed with two invited one-hour tutorials on “The surprising properties of delay-dynamical systems and how you can exploit them” and on “Using delay-coupled lasers for non-algorithmic photonic information processing”.

3. Conclusion

During my stay, I had the opportunity to interact intensively with Prof Masatoshi Murase on many topics including the fundamental requirements for advances in neuro-inspired cognitive information processing, recursive aspects of cognitive processes, the role of nonlinear transient and attractor dynamics for information processing, and the fundamental requirements for creative processes. Based on these discussions, we will continue to explore a minimal system approach that includes the necessary requirements and the related complex emergent behavior, nevertheless allowing for the desired information processing or creative properties. Exploring the consequences of changing the balance between the involved mechanisms will be one of the approaches by which we aim at gaining a better understanding of how cognitive processes work and how to realize cognitive computing systems. A key goal is to learn about the robustness of such systems and how we can influence and adapt their behavior. Ultimately, we aim at a truly transdisciplinary approach for gaining a more thorough understanding of cognitive information processing and creative processes that might go beyond the more restricted perspectives of individual disciplines alone. Considering that the brain is the most complex system we know, this might be the most promising path.

Besides the interaction with Prof. Masatoshi Murase, I had the great pleasure also to interact and discuss with Prof. Sinya Aoki about possible applications of cognitive computing in elementary particle physics, with Prof. Kazunari Shibata about complex phenomena related to the generation of solar flares and with visiting professor Richard Karban on plant-to-plant communication.

Moreover, it has been a great honor and pleasure having been invited by the president of Kyoto University, Prof. Juichi Yamagiwa, to a reception for foreign scientists at Kyoto University. To hear his enthusiastic call for international and interdisciplinary collaborations, for diversity in science and society, for curiosity-driven research and cross-disciplinary inspiration, for original thinking and plurality of ideas, for more women in academia and simply for open-mindedness was inspiring and confirmed my own impression of the spirit of this University. I wished there were more voices like his and more Universities like this one!

The work and discussions at Kyoto University were complemented by lively and inspiring discussions on more short-term advances with colleagues and friends outside Kyoto University, in particular with Dr. Peter Davis (Kyoto), who hosted me as a postdoctoral researcher 18 years ago, and Prof. Atsushi Uchida (Saitama) on neuro-inspired information processing systems, addressing aspects such as analog versus digital information processing, energy efficiency, decision making and reinforcement learning.

4. Future collaboration possibilities with Kyoto University

It would be a very worthwhile venture to explore a longer-term collaboration between the YITP and the IFISC in physics in the areas of Complex Systems and Advanced Future Studies. This could manifest itself in the exchange of research staff, graduate students, and post-doctoral fellows, joint research activities and the joint organization of seminars, workshops, conferences, academic meetings and other related activities.

I have myself benefited greatly from Professor Murase's generosity and hospitality, and the sharing of ideas. I would be delighted to have the opportunity to continue these insightful discussions and to build a strong and fruitful collaboration.

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