Our Self-Organized Brains

Our Self-Organized Brains:

A Systemic View of Human and Social Learning

By

Osvaldo Agamennoni

Cambridge Scholars Publishing

Our Self-Organized Brains:
A Systemic View of Human and Social Learning

By Osvaldo Agamennoni

This book first published 2021

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-5275-7038-X
ISBN (13): 978-1-5275-7038-2

Dedicated to my grandchildren, Hugo, Lorenzo and Lena.

“Living systems are cognitive systems, and the process of living is a process of cognition”
[Humberto Maturana, Chilean biologist and philosopher].

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

PREFACE

All our actions, past and present, lead us to a future that is a consequence of them. This is an undeniable fact of our dynamic nature. To go from where we are to where we want to be, we must carry out specific actions. This reality applies to every aspect of our existence, from trivial to life-changing activities. Our brain is in command of those actions, and for doing so, it has developed a wide variety of “mechanisms” that, in general, are invisible to us, but have a significant impact on our lives.

During the evolutionary process, the human brain has developed, and continues to do so, learning prediction and adaptation strategies called “cognitive abilities”. Such capacities have arisen from the dynamics of innumerable feedback loops and self-organisation processes that are, in turn, a result of the interaction with the environment. What are the feedback loops and self-organisation processes? They are so important in our daily life, but we do not pay any attention to them whatsoever. For example, when driving a car, our brain perceives the position of the vehicle in the context of traffic through our sight. Our brain also controls it through our arms and feet while agreeing with other drivers on how to get around so as not to collide. This is a simple example of feedback and self-organisation. In this case, it is easy to appreciate if the brain is functioning properly or not, and how perception and learning affect it. We use the same mechanisms when doing all kinds of activities, such as studying, working, playing sports, interacting with peers, etc.

The graceful movement of a flock of birds crossing the skies has amazed us all. Surely, we have noticed that they perform a dance and that it is very unusual to see them collide. That beautiful dance composes a dynamic behaviour, based on feedback control and self-organisation. If only we could witness the electrical activity of neurons in the brain, we would find out that it has much in common with that magical movement of a flock of birds. Let´s imagine a huge tree filled with millions of small lights instead of leaves, as an analogue of our brain and its neurons. The lights turn on and off in different branches following a pattern that depends on the activity. On a night watching our tree full of lights, we could see that the transmission of neuronal activation (lighting of the lights) would resemble the flight of a flock of birds. How this dynamic activity of neuron activation is linked with our mental functions is an exciting puzzle that attracts many researchers. In this book, I intend to open some windows and have a look into the understanding of such events.

We have acquired vast knowledge about the structure and capabilities of the human brain. However, it is still unclear how they arise and are integrated into a functional and understandable whole. This book aims to take a step in that direction. Feedback control systems and self-organised systems are two basic natural processes necessary for the development of life. Organisms of all kinds use them, and because of them, we evolve. Keeping an individual and social awareness of them is crucial to understand our individual and social behaviours, and thus follow suitable evolutionary paths. We are aware of the importance of having basic notions of mathematics. How they allow us to perform better in our daily lives. Similarly, basic knowledge about the dynamics of feedback systems and self-organised systems will allow us to understand many human behaviours and to appreciate the key elements that influence the achievement of individual and social goals.

This book is organised to welcome the reader into a gentle journey, which can be started without prior knowledge about the tools we will use, and which is filled with examples that will facilitate your understanding.

ACKNOWLEDGMENTS

First, I want to thank my wife, Liliana, who accompanied me throughout the writing of the book in countless talks and joint works and through the revision of the Spanish version. In addition, she helped with the figures. I thank my children, Gabriel, Lucía and Melisa, for the suggestions and corrections in the Spanish and English manuscripts, especially Melisa, who did a careful reading with excellent ideas to improve the writing. I thank my daughter-in-law Laure Authenac for her contributions, especially for the books she provided me with.

Very special thanks to the memory of my great teacher, advisor, friend and inspiration Alfredo Desages. He taught me to enjoy science. Thanks to him and José Romagnoli, I entered the wonderful world of feedback dynamic systems. Thanks to José Romagnoli for showing me how to search beyond the next steps when pursuing scientific questions.

I also thank Mateo Niro for having motivated me to write the Spanish version and for his suggestions, ideas and revisions to it, together with Natalia Bengochea. Without Mateo's push, I would not have carried out the task of writing it.

Another special thanks to Gerardo Fernández. First, for having motivated me to enter into the neurosciences field; and most of all because, thanks to him, we have been able to carry out an incredible, utterly original research activity. Thanks to Pablo Mandolesi for having introduced me to Gerardo Fernández. Together, Pablo and Gerardo and I conceived the original idea of evaluating human cognitive capacity from the processing of eye movements.

I thank Marcela Schumacher for several comments after the first reading of the manuscript. I thank Silvana Sañudo, Ernesto Bjerg, Silvia Castro and Daniel Lapegrini for their feedback on the first draft. Thanks to Juan M. Trobbiani for his great work in correcting the first draft in English, and to Laurence Fenton for his excellent proofreading work.

I would also like to express my deep gratitude to the Universidad Nacional del Sur (National University of the South), the Departamento de Ingeniería Eléctrica y de Computadoras (Department of Electrical Engineering and Computers) and the Instituto de Investigaciones en Ingeniería Eléctrica (Institute for Research in Electrical Engineering) of Bahía Blanca (Argentina), where I have carried out my academic activity since 1979. In addition, my deep gratitude to the Comisión de Investigaciones Científicas (Scientific Research Commission, Province of Buenos Aires), in which I have served as a scientific researcher since the year 1986. Thanks to the Agencia Nacional de Promoción Científica y Técnica (National Agency for Scientific and Technical Promotion) for financing the vast majority of our scientific activities.

CHAPTER ONE

INTRODUCTION

We and our environment

“There is no favourable wind for the sailor who doesn’t know where to go” [Lucio Anneo Seneca, Spanish-Roman philosopher, politician and writer].

As we know, the brain is a system made up of a complex network of neurons. It is responsible for a large number of functions, from maintaining life to developing our human activity par excellence: thinking. However, its structure does not clearly reflect its functions, which emerge from the particular interconnection between neurons. In this network of neurons, information flows through electrical pulses, making our brain the most amazing dynamic system known on the planet. Thus, it is enlightening to begin its study from a perspective that allows us to look into this property. Besides, we must bear in mind that the brain´s operation expands from the interactions with other people´s brains.

Advances in neurosciences are, in general, the result of coordinated efforts from different disciplines. Medicine and biological sciences in general, physics, mathematics, computing, engineering, behavioural sciences, such as psychology and sociology, among others, are transversally involved in this field. Their continuous and permanent development allows us to study, from different points of view and with very different objectives, the structure and functional organisation of the nervous system, and particularly, the brain. Neurosciences constitute a relatively new area of work (just over a century) but, especially in recent years, they have made tremendous progress with the help of new technologies.

The different areas of study range from those focusing on the neuronal cell, to those focusing their attention on modelling and analysing the highest level of the brain functions. In the middle of the whole range of possibilities, a gap often makes interdisciplinary communication difficult. It could be said that this gap is similar to the one existing between the technician who studies the production of bricks and the architect who designs the building: both work on the same object, but with the first concentrating on the elementary blocks and the second on the functional whole. Fritjof Capra, a renowned Austrian theoretical physicist, has studied the philosophical and social consequences of modern science. He showed that:

> It is a tension between the study of substance and the study of form. The study of substance starts with the question, What is it made of? The study of form starts with the question, What is its pattern? Those are two very different approaches (Capra 1994, 4).

Throughout this book, we shall try to address both substance and form as an integrated and functional whole.

Fig. 1-1 aims to contextualise some concepts by showing a global framework of the different dynamic systems in which the brain is involved. A set diagram emphasises that neurons are the blocks that build up the brain. At the same time, the brain is part of our human body, which performs in an environment that constitutes a part of the world around us. This figure helps us to show that our brains, and the brains of the whole animal kingdom, have been and continue to be shaped by constant interactions with the environments where we live. In turn, these generate a succession of events that propagate over time, creating paths through which information flows, thus transforming our brain when trying to adapt to those events. It is then clear that an approach to brain functionalities requires delving into its systemic aspects; an approach that tries to take into account all the interrelating parts making up a whole. In this way, we can achieve a better understanding of the events and their causal chains.

As individual biological beings integrated into a network of similar beings, we continuously discern the environment and categorise it to simplify its internal representation. Our actions modify the environment in many ways and generate messages that others perceive of us. The ability to act appropriately in this context is known as cognitive ability. Within it, all the elements that make up the information processing circuit are involved: prediction, attention, perception, memory, and understanding, among others.

For example, revisiting the car driving example, we are attentive to both the traffic and the entire transit scenario. We use the long-term memory where we have stored the traffic signals' information and the short-term memory where we record, at every moment, the position of the other elements that could interact with us. We then make predictions about their future locations.

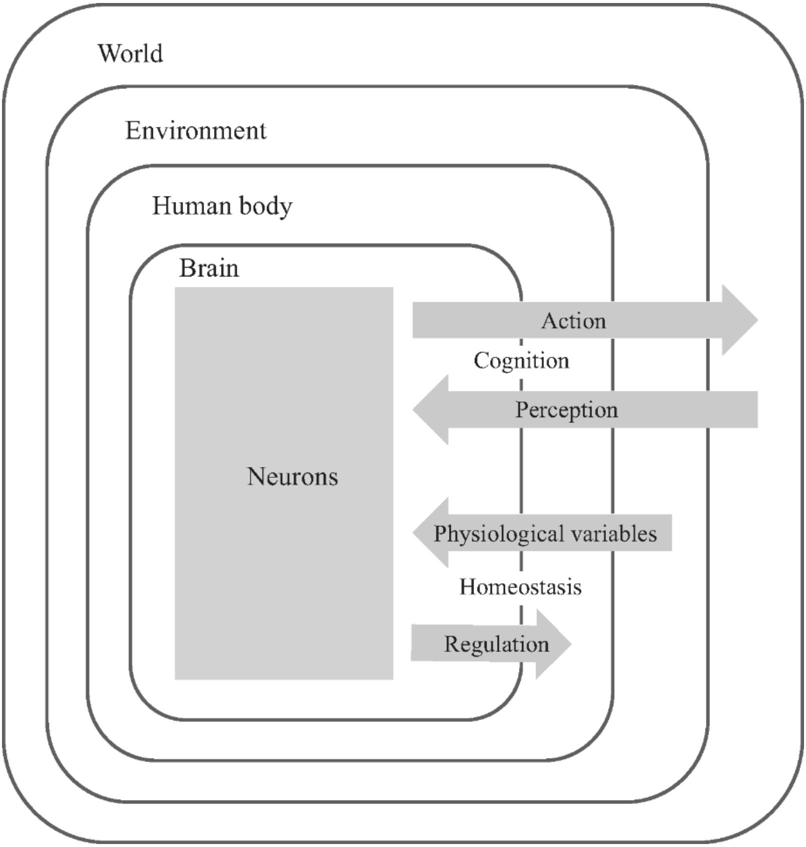

Fig. 1- 1: Information flow on our environment.
From neurons to the world and vice versa. The neurons of the brain are responsible for perceiving the events of the environment and the world that we live in and for performing the actions that make up our daily life. Cognitive capabilities are responsible for such performances. The homeostatic processes regulate physiological variables to guarantee a living condition for our body.

With all the available information, we take actions that translate into decisions about where and how to position the vehicle until we arrive at the destination. Fig. 1-2 illustrates the elements presented and the flow of information in a "cognitive cycle" that we will analyse in the chapter "The Brain Dynamic". The cognitive capacity that allows us to interact is accomplished through feedback loops where information flows from the environment towards us through perception, and from us to the environment through our actions (see Fig. 1-1).

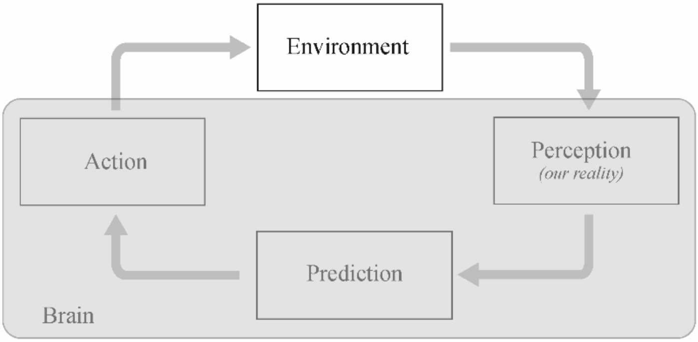

Fig. 1- 2: Information flow involved in the cognitive cycle.

Our brain is the most important organ because it is the only one that can give transforming nuances to the continuous loop of information; the only one that can introduce significant changes. Without feedback, there would be no brain since the brain's main capacity, *i.e.* cognition, has been developed to interact with the environment. We need to predict the behaviour of all its relevant actors. Prediction is the nervous system's ultimate goal because it allows a living being to control its future actions. For example, by anticipating where the prey and the predator go, our ancestors were able to hunt and flee, that is, survive.

Rodolfo Llinas, a Colombian neurophysiologist and professor of neuroscience at the School of Medicine of the University of New York who is internationally recognised for his contributions to the field of neuroscience, presents an original vision of the evolution and nature of the brain's predictive functions. According to Llinas, the brain in mobile creatures evolved to generate predictive interactions with their environment. Llinas shows the initial evolution of the mind through a primitive animal called "ascidia". The cerebral ganglion of the mobile larval form of this animal receives sensory information from its surroundings. When they reach adulthood, ascidians adhere to a stationary object and then digest most of their own brains. This suggests that the animals' nervous system evolved to allow their active control of movements. Then, the brain would have developed due to the need for organisms to have a resource to increase the probability of survival.

There would be little need for a nervous system in a stationary organism or in one that lives in a regular and completely predictable environment. In a partially chaotic environment, it is more difficult to predict the distribution and location of resources and hazards. Therefore, it becomes necessary to have a system for processing data coming from perception that allows predicting the performance of actions to achieve sustenance and avoid hazards.

The brain is also responsible for maintaining our biological functions through a process known as homeostasis. This self-regulated process enables keeping the physiological variables of an organism relatively constant, making life possible. This capacity for self-regulation is the result of feedback ties at the unconscious level. For example, the one that keeps our body temperature constant. However, many others can reach a conscious level.

It is clear that our brain constructs the sense of the information we perceive from the environment and continually contributes to the generation of new messages. These enrich and adapt as our interactive networks expand; in other words, the amount of feedback loops with other brains increases. These two sentences are intentionally expressed in the plural to emphasise that, in reality, we should talk about our brains rather than an individual brain, since our abilities have been developed and adapted through interaction with other people. We first developed oral languages, and then written ones; later we spread knowledge and ideas through books, until we reached the present time where we have a global network. Then it is worth asking: how much of our brain is nothing other than the result of the innumerable amount of other brains with which we have exchanged information? Our brain is currently supported by an immense amount of other brains and devices that store data information and procedures, which allow us to carry out our daily existence.

In addition, this adaptive characteristic comes from the development of the learning capacity that has allowed us to excel over the rest of the biological species. Professor Schultz and colleagues pointed out that:

> The capacity to predict future events permits a creature to detect, model, and manipulate the causal structure of its interactions with its environment. Behavioral experiments suggest that learning is driven by changes in the expectations about future salient events such as rewards and punishments (Schultz, Dayan and Montague 1997, 1593).

For example, in ancient times, the development of the calendar gave people the ability to predict when to sow. We have already learned to anticipate many more things. Learning is driven by changes in expectations about events of great future impact that bring rewards and punishments. In addition, these studies are ratified by the identification of dopaminergic neurons, whose fluctuating production indicates changes or differences in the predictions of future gratifying events that are relevant for learning (Glimcher 2010, 1). Dopamine neurons are responsible for the production and distribution of a neurotransmitter essential for the functioning of the brain known as dopamine. To those neurons we owe, in addition to a great diversity of motor and cognitive functions, the feelings of well-being and pleasure that enable the plastic adaptation of the brain. The plasticity of the brain can be understood through the theory of feedback control and adaptive optimisation (Schultz, Dayan and Montague 1997, 1595). We will return to this subject in the chapter "Feedback Systems".

In short, human beings are, or at least have been so far, the best living example of adaptation to the environment. The growing scientific evidence shows that one of the key factors of the human brain adaptation capability is its high degree of plasticity. Comparative studies with the great apes show that human brains are substantially more plastic (Gómez-Robles and Sherwood 2017, 41). Now, if we look forward, we will realise that we face very important and transcendent adaptation challenges. In a few decades, we have amazingly increased the amount of information readily available at our fingertips. It is difficult to glimpse the real meaning and all the implications of such availability as a whole. At first, it amazes us and makes us believe that it constitutes the best aspect of this era we are living in. However, that overabundance of information can also generate problems of different kinds. There are already terms to define the excess of information (informational excess, information glut, data smog, etc.) and the effects of such an excess on individuals (infobesity, infoxication, cognitive diabetes, etc.). It becomes difficult to understand a problem and make effective decisions when there is too much information about it. This fact is not new; the German philosopher and sociologist Georg Simmel (1858-1918) raised a long time ago the hypothesis that the overload of sensations in the modern urban world causes fatigue and interferes with the ability to react to new situations (Edmunds and Morris 2000, 20). Alvin Toffler has also considered this in 1970 in his book "The Shock of the Future." This problem has been progressively increasing (Pantzar 2010, 13).

Nowadays it is easy to appreciate the harmful effects of information overload, especially during some key periods of human development such as the transition from secondary school to university. We will not consider aspects related to criminal activities such as grooming, scams, etc. We will only refer to information that we could consider as well-intentioned. It is estimated that the average internet user receives 63,000 words of information every day (emails, tweets, Facebook messages, etc.), which is approximately the length of a novel. In this scenario, it is possible to observe that some people can easily adapt to it and take advantage of all the opportunities offered by that possibility, while others fail to do so and succumb to it, overwhelmed and affected by such excesses, unable to focus on their activities.

We live in the information age and we are facing the process of adaptation to it. We have to solve a very large diversity of problems and we have an immense amount of information to address. However, we have difficulties when it comes to using all that information properly. A systemic vision of how the feedback brain has adapted, trying to focus attention on the relevant aspects to learn to overcome the challenges of its environment, can be useful to understanding this new process of adaptation.

The approach to the systemic study of the brain has more than a century of history. Its main actors knew that the understanding of the outstanding functional characteristics of the human brain required analytical tools oriented to the study of the dynamic processes involved in its evolutionary development. That is, the adaptive capacity that is based on learning through a feedback process of interaction with the environment. The beginning of this period of the study of the brain during the twentieth century is quite fascinating. Some of the relevant approaches developed really deserve to be outlined.

To understand the adaptive capacity of the brain and its relationship with brain processes, it is necessary to pay attention to its evolutionary development. We have the current brain going through a series of stages, although many of them are now very distant in time to us. They are all part of our history, wired in the structure and reflected in the functioning of our brain. Adaptation is a feedback dynamic process. Consequently, addressing a systemic approach to the brain, from which its capacity to adapt to the environment can be studied, requires the use of a discipline that has been specifically developed to study the feedback systems. The feedback control theory allows us to appreciate the film of our most important adaptive processes. It is a theory that has made important contributions to psychology, as can be seen from a quick review of some academic publications that exhibit a large number of references to the term "control" (Skinner 1996, 550). The importance of control theory in the process of living and in the sciences that study it has long been recognised. However, this recognition is not deep enough. It is important to appreciate clearly all implications of the feedback process, to fully understand all its possible contributions to life sciences (Powers, Abbott, Carey, Goldstein *et al*. 2011, 1).

In this dynamic process of adaptation, the perception of the environment has played, and still plays, a fundamental role in the construction of our reality. Although it seems natural that for learning how to do something we should perceive it correctly, we are not always aware of doing it properly. Outstanding features of certain people are due to special characteristics of their perceptual system. On the other hand, distortions in the perception of the environment can cause multiple problems or difficulties, particularly in the learning process.

When we are learning something, we are building a mental model that allows us to carry out a course of action that is facilitated as we move forward. We gradually incorporate this model to perform the activity learned more automatically. Once achieved, we focus on the next learning objective. Let us return to the example of driving a car. During the first learning steps, we build a mental model to relate our actions (hands on the steering wheel and feet on the pedals) with the dynamic performance of the car. Once this model has been developed, we can control it adequately, almost automatically, and without focusing so much on how we carry out our actions, allowing us to focus more on the environment (traffic, pedestrians, etc.) around us to drive more safely.

The sensory structures of the peripheral nervous system continuously receive stimuli from the environment and send sensory signals to our brain. From these input stimuli, the brain produces a new signal as an output response, which is transformed into a command signal to carry out the corresponding action. For example, a tennis player perceives the image of the opponent hitting the ball and the brain predicts where it will go and immediately sends a control signal to the motor system in order to move the muscles accordingly. With a proper and practical instruction, the tennis player will be able to improve the performance to predict the ball trajectory as well as to control the muscles. To appreciate these types of processes, we will briefly describe the artificial neural networks. These networks are built up of a large number of artificial interconnected neurons. This kind of network is used to emulate the input-output behaviour (stimulus-response) of the brain. The internal structure of these artificial networks is, generally, uniform or at least easy to organise in order to facilitate their mathematical formulation and electronic implementation. They do not reproduce exactly the structure of the brain, but they have proved to mimic many human brain functionalities. Understanding how these artificial networks learn to perform various tasks sheds light on the way we humans do it. It is not exactly the same, but it is a model that allows us to glimpse some significant facts more clearly.

On the other hand, artificial neural networks allow engineers and computer experts to develop artificial intelligence tools for emulating certain brain capacities, particularly those related to the detection of some type of pattern or to modelling the behaviour of some complex dynamic system (for instance, predicting the future position of a vehicle in order to alert to a risk situation and avoid it). In this sense, we will briefly present various approaches to brain capacity modelling, which should not be confused with modelling the brain. The main idea is to reproduce some of its functionality, not its real structure. It is intended to emulate the ability to adapt through a learning process in the performance of a certain activity.

Learning processes require an adequate provision of knowledge and appropriate guidance. In the pre internet era, books and teachers were the knowledge providers. Teachers were also involved in the tutorial guide for a comprehensive reading. The students focused their activity on a few sources of information and could thus achieve an effective understanding of them. Today there are many sources of knowledge provision and even tutorials through the internet. Then, the directives of teachers or professors now compete with many others and students find it difficult to achieve the effective targeting and comprehensive perception of the knowledge they intend to acquire. This does not mean that the fact of having so much information is harmful per se. However, the effect that such excessive availability can cause should be taken into account.

In the book “The Art of Thinking Clearly” the Swiss writer and entrepreneur Rolf Dobelli argues that thinking clearly does not imply adopting another person’s rational point of view, but rather resolving conflicts between our own values and daily behaviour (Dobelli 2014, 2). In the aforementioned book, he defines the concept of the paradox of choice, which, in a nutshell, can be described as follows: the more options we have, the less founded our actions will be. If we had more alternatives we would need to have more time to study all of them properly. When we have to choose between many alternatives, we tend to use more emotional reasons than rational ones. Because of this, we will most likely not be sure that we have made a correct decision, thus affecting our attention on the perceived signals and the neural processing involved in the decision taken.

In this sense, the concept of self-regulated learning has been progressively growing in the academic community as a valuable tool for adaptation to these new realities facing humanity (Zimmerman 1990, 14). Nevertheless, the motivational aspects of activity focus and self-evaluation are essential for a thorough understanding and use of this learning paradigm that could be the key to facing the current adaptation process. Again, feedback control theory will not only allow us to observe some key aspects of such a paradigm, especially concerning the importance of perceptual qualities, but also to develop predictive strategies for navigating the fascinating and complex ocean of information.

Although feedback control theory could help us to understand many of our individual brain capacities, it does not suffice when dealing with interconnected brains, *i.e.* society. The problem is the great complexity of these systems. If the dynamics of a brain are complex, try to imagine the increasing complexity of the resulting system by connecting millions of brains. In this case, we have to address it with the theory of self-organised systems. Self-organisation is an adaptive dynamic process in which systems achieve and sustain the structure by themselves, without external control, but manage to reach a certain order.

In conclusion, in this book we shall try to provide the knowledge that will allow us to understand many aspects of individual and social behaviour arising from the interactive dynamics that we continuously maintain with our environment. Our particular ways of perceiving, constructing our reality and learning, among others, are developed from such feedback ties. We will also look at the way we interact with our peers and develop joint activities; in other words, how we organise ourselves. We will try to visualise some of our invisible mechanisms so that we become aware of the way they influence our behaviour.

CHAPTER TWO

A SYSTEMIC VISION

The system and its emerging dynamics

> "Cybernetics is the biggest bite out of the fruit of the Tree of Knowledge that mankind has taken in the last 2000 years" [Gregory Bateson, English anthropologist, 1904-1980].

Before entering this section, it is appropriate to clarify the use of the word "system" – its meaning and scope to unify and integrate concepts. The word system refers to a set of interrelated components that act in a coordinated way, trying to achieve a higher objective than the parts do at an individual level. An entity maintains its existence through the mutual interactions of its parts. The whole is more than the sum of its components because it is the whole that achieves the objective. For example, a soccer team is a system that tries to score goals. We know well that the presence of eleven players, even the best ones, does not necessarily guarantee a good team. However, if they do it in coordination, and if the interactions are adequate, they can develop a successful game system.

In principle, as we have already glimpsed, we use the systemic approach when the sum of the parts cannot explain the whole. If this were the case, there would be no point in undertaking a systemic analysis since it is easier to study each of its constituent parts separately. A systemic approach includes all elements of the system under study, as well as their interaction and interdependence. When we see in the sky a flock of birds flying or a documentary of a shoal of fish, we can discern that these dynamic movements could not be predicted from the sum of birds or fish, respectively; there is an emergent phenomenon. These actions of the system depend on its components and structure (links between elements) and the context that makes up its environment.

The relationships between the elements of the system generate paths that enable the communication of information. Such propagation can form closed feedback loops and favour the appearance of diverse collective behavioural patterns with properties at higher hierarchical levels. These systems with these properties are called self-organising systems, and we will discuss them later.

In the systemic approach, the limits of the system must be evident. What are the elements that are part of it, and consequently, what is the border between the system and its environment. It is important then to consider where the observer is. Whenever a system is analysed, we must examine whether or not we become a part of it. It is evident that, in the case at hand, we cannot avoid being part of the object of study. Real-world systems, unlike the laboratory cases, are not closed, isolated or controlled, but rather open, ever-changing and unpredictable.

It is essential to clarify that the systemic analysis allows us, in general, to analyse the behaviour of the system under study rather than to predict its evolution. We cannot anticipate where the birds in a flock will go, but we can understand the most critical characteristics of their movement patterns. We are far from being able to analyse the behaviour of the brain based on the exhaustive modelling of neurons in the same way that we cannot explain the movement patterns of a flock of birds from a thorough knowledge of them. Therefore, the systemic approach pays attention to both the links and the elements that make up the system and how such relationships are responsible for generating dynamic behaviours that cannot be inferred from the exhaustive knowledge of each component. In many cases, with elementary modelling of the component elements of a system and precise understanding of the links between each one, we can reasonably emulate the behaviour of very complex systems. Emulating behaviour does not mean reproducing its dynamics exactly, but its most relevant characteristics.

In living systems, it is possible to distinguish many structural levels according to how we address our vision and organise its approach. As an example, in our social and biological system, we can identify the following levels: country, states, municipality, neighbourhoods, families, human beings, organs, tissues, cells, etc. Consequently, living systems present a layered organisation with interconnections and interdependencies between all its levels. Each of them interacts and communicates with the environment surrounding such living systems. Besides, living systems are in continuous activity, and for this reason, they must maintain a permanent exchange of energy and matter with their environment. In the case of a biological organism, this process is called metabolism.

In short, the outstanding characteristic of living systems is the continuous production of themselves. This quality of a biological system of reproducing and maintaining itself is called autopoiesis. The Chilean biologists Humberto Maturana and Francisco Varela proposed this term, in 1972, as the condition of existence of living beings in the continuous production of themselves (Maturana 1995, 29). Originally, they applied it to the chemical processes by which living cells are self-supporting. According to Maturana:

> Living beings are networks of molecular productions in which the molecules produced generate, with their interactions, the same network that produces them.

The whole is more important than the sum of the parts because functionality as a system is implicit in it. Living dynamic systems can maintain their functionality (life) thanks to homeostasis, which is, as mentioned above, the process that allows them to adapt to changing environments while maintaining all physiological variables relatively constant. The interconnectivity between different elements enables the formation of information communication ties that generate feedback processes between the different components and are the basis for the appearance of complex patterns that evolve in time. There are two types of feedback processes: a negative one that favours the maintenance of the equilibrium point and a positive one that favours the occurrence of instabilities and the search for new equilibrium points. We will consider these issues again in the "Feedback Systems" chapter.

Instead of just concentrating on the essential elements, the systemic approach also studies the main characteristics of the structural organisation. All living systems (from bacteria to societies, through human beings) have a particular structure that links their different constituent elements. All of these systems are intrinsically dynamic, and their most relevant characteristics emerge from the processes related to the interactions that can change adaptively over time.

The different dynamic processes observed in a given system can present very different characteristics. Thus, on many occasions, it is difficult for us to understand that they are, in fact, distinct manifestations of the same system. Prigogine (Prigogine and Stengers 1985) describes the possible dynamic features in the following way:

> When the variations or oscillations caused by the disturbances that enter a system are kept within certain limits, the capacity for self-regulation allows it to maintain its operation and distinctive character. If the disturbances exceed a certain limit, the system may collapse, or it may lead to a new state of creative chaos. The system is forced to adapt to the new conditions. For the most part, the fluctuations are small and can be easily adjusted via negative feedback. However, occasionally the fluctuations can be so high that the system cannot be adjusted, and the positive feedback takes over. The fluctuations, then, are amplified. When this happens, the system can collapse

or reorganise itself.

This property of living organisms is essential to achieve adaptation to the environment in which they live and to escape from it on certain occasions in search of new states, which is essential for learning and creativity. In the words of Philippe Faure and Henri Korn (Faure and Korn 2001, 790):

> A major advantage of chaotic systems […] is that their extreme sensitivity can be used to direct them rapidly towards a desired state using minimal perturbations. Viewed in this context the unpredictable behaviour of chaotic systems becomes an advantage rather than an undesirable "noisy" disturbance. The basic idea is that a chaotic system explores a large region of a state space.

However, to advance the understanding of these dynamic processes, it is necessary to have some elementary notions of feedback control theory and the theory of self-organised systems, to which we will dedicate ourselves in subsequent chapters.

Surely, Norbert Wiener, with his works from the 1950s and 1960s, was one of the scientists who contributed the most to giving rigour to the systemic approach to the brain (McCulloch 1964, 1). A particular activity carried out by Wiener allows us to have a first approach to self-organised systems based on what he called the "pooling effect". One of Wiener's favourite occupations was meeting with close colleagues and discussing new ideas together towards and beyond the limits of man's understanding. The relaxed and calm atmosphere of a small group discussing these kinds of topics was for him a study laboratory. People achieved close collaborative communication with each other. With imagination and a clear understanding and scientific vision, such meetings could lead to very interesting conclusions when the participants showed a dynamic of mutual reinforcement, which Wiener called the rhythm of mutual participation. Wiener had been aware of this effect for a long time. Such a rhythmic phenomenon of self-organisation, or mutual aggregation, could be seen in very diverse systems of the natural world.

Wiener showed that randomly distributed objects or particles in a rhythmic oscillating state could affect each other through interactions between them, generally consisting of feedback of information or, generally speaking, self-organisation. He also found this same pattern in electrical generators, in the electrical circuits of computers, in biological organisms, etc. From such a conception and the application of the feedback control theory (in great development at that time due to the space race) to the analysis of the behaviour of animals and even of human beings, the aforementioned cybernetics emerged. These pioneering works by Wiener led to what became known as "Perceptual Control Theory" (PCT) growing in the 1970s from the works of William Powers (Mansell and Marken 2015, 425). William T. Powers (1926-2013) was a physicist and physician but, above all, an independent scholar of theoretical and experimental psychology. He developed a theoretical model of behaviour as a result of control over the perceived environment. Powers' approach provided a completely new perspective on psychological science by shaping what came to be called the third lane of great theories, after behavioural and cognitive theories. The PCT starts from the observation that living beings control the perceived environment through their behaviour that translates into actions, and therefore the phenomenon of feedback control occupies a central place. An organism does not control its own behaviour or external environmental variables, but rather its own perceptions of these variables. In other words, the PCT takes as a base the circular causality formed by a closed feedback loop through the environment, by which the behaviour emerges as a consequence of the control actions arising due to perception. This approach contradicts the classical notion of linear causality of stimulus behaviour, in which environmental stimuli are assumed to cause open-loop behavioural responses, modulated (according to cognitive psychology) by intervening cognitive processes. According to PCT, the behaviour is the externally visible aspect of a feedback process by which perceptual experiences are controlled. We control the perceived results and not the actions. Behaviour is the observable result in the process of controlling what we perceive. In this sense, it is extremely important to pay attention to the perception process that we will address later.

Charles Carver, a psychologist expert in behavioural sciences at the University of Miami, and Michael Scheier, a researcher in psychology at Carnegie Mellon University, argued in 1982 that the feedback control theory provides an adequate study model on human behaviour and clearly illustrated how feedback loops were manifested in people's psychological behaviour (Carver and Scheier 1982, 111). They also showed how the results they obtained were in accordance with the scientific evidence available in the area of psychology. They concluded by pointing out what could be achieved with the interdisciplinary integration of feedback control theory and human behavioural sciences.

Carver and Scheier also questioned the stereotypical conception of that time in relation to cybernetic systems, especially regarding their use in studies of human behaviour. The general idea about cybernetic systems, at that time, was a kind of programmed automaton advancing towards a predefined goal. Then, when it reaches it, it ends its programme and it remains stopped or working only to maintain stable, functional states. For this conception, feedback control theory does not constitute an adequate conceptual framework to study human behaviour, since it does not take into account its changing goals. Carver and Scheier raised the fallacies of such a conception. First, the belief that in control systems, the objectives are always static, just like homeostasis. The same does not happen when we drive a vehicle. We can change the goal of where to go at any time. The second great fallacy, in this stereotyped image of cybernetic systems and control processes, is their inability to deal with changing situations over time and with the events that occur in the meantime. On the contrary, control systems are designed to act in a changing environment and thus be able to cope with the disturbances that such an environment generates.

The stereotypical conception of cybernetics arose from non-academic reasons. In the 1950s, cybernetics began to take a significant prominence in the then Soviet Union. With the onset of the Cold War, the concept of Artificial Intelligence (AI) began to be used in the West. On the other hand, the British television science fiction series “Doctor Who”, aired between 1963 and 1989, installed an unsightly image of the term since the Cybermen, members of the fictional cyborg race, were some of Doctor Who’s enemies. Cybermen implanted artificial parts in the body with the aim of self-preserving the species.

Another cause of the loss of interest in the systemic approach by the scientific community related to neuroscience was, according to Fritjof Capra, the emergence of molecular biology. The spectacular advances made in the area of genetics, with the elucidation of the structure of DNA, led to the assumption that biological functions could be explained through molecular structures and mechanisms. In this way, Capra says, biologists became fervent reductionists concerned with molecular details (Capra 1996, 95).

In conclusion, a systemic vision is an approach that can contribute greatly to understanding brain function and its emerging behaviours; particularly, the learning processes needed for the adaptation to our increasingly complex environment.