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A Cognitive Revolution in Theoretical Biology?

Tiago Rama
Department of Philosophy
University of the Republic of Uruguay
Montevideo, Uruguay
trama.folco@gmail.com
https://orcid.org/0000-0002-1531-7233

Abstract: The foundations of biology have been a topic of debate for the past few decades. The traditional perspective of the Modern Synthesis, which portrays organisms as passive entities with limited role in evolutionary theory, is giving way to a new paradigm where organisms are recognized as active agents, actively shaping their own phenotypic traits for adaptive purposes. Within this context, this article raises the question of whether contemporary biological theory is undergoing a cognitive revolution. This inquiry can be approached in two ways: from a theoretical standpoint, exploring the centrality of the cognitive sciences in current theoretical biology; and from a historical perspective, examining the resemblance between the current state of theoretical biology and the Cognitive Revolution of the mid-20th century. Both inquiries yield affirmative answers, though important nuances will be emphasized. The cognitive sciences' explanatory framework is employed to elucidate the agentic characteristics of organisms, establishing a clear parallelism between the Cognitive Revolution and the present state of theoretical biology.

Keywords: Cognitive Revolution; Theoretical Biology; Conceptual Change; History and Philosophy of Biology; Cognitive Science; Behaviourism.

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Introduction

The title of this work raises a question that may be provocative. Is a cognitive revolution taking place in theoretical biology? Undoubtedly, the question itself needs to be clarified before an answer can be proposed. To this end, I will propose two possible interpretations.

The first interpretation I will call the *theoretical interpretatio*n. From this perspective, we want to know whether part of the explanatory apparatus of the cognitive sciences is beginning to play a central role in current theoretical biology. This means that a theory (from one discipline) influences or interferes with another theory (from another discipline). This entails an epistemic extension of the concepts and explanations we find in the cognitive sciences to biology. So the theoretical interpretation is tied to other questions: are concepts such as representation, perception, or memory central to biology? Is it necessary to introduce *intentional explanations* in biology?

On the other hand, there is a *historical interpretation*. According to this interpretation, we ask ourselves whether the events in the history of science from which cognitive science emerged are similar to the current situation in theoretical biology and the various controversies that have been on the table for several decades (which we will discuss in the next section). In this sense, the expression *Cognitive Revolution* (with capital letters) refers to a historical event in science that took place in the 1950s and that led to the emergence of the cognitive sciences and the abandonment of the behavioral model that had prevailed until then. It is therefore a question that is posed from the history and philosophy of science through a metatheoretical analysis of each individual discipline. The historical interpretation thus asks the following question: Is something similar to what caused the move away from behaviorism and the emergence of the cognitive sciences, i.e. the cognitive revolution, happening in theoretical biology?

We will analyze each interpretation separately, even though their connection will be clear. This analysis will be carried out in Sections 2 and 3. Before we embark on this task, however, we need to ask ourselves a question: What is all this about? On what grounds do we ask ourselves whether or not there is a cognitive revolution in theoretical biology? In this way, it is necessary to introduce the current panorama of theoretical biology.

1. What Is Going on in Contemporary Theoretical Biology?

The term *theoretical biology* was used at the beginning of the 20th century by various biologists who were inclined towards organicism. Apart from its specific use at various times and by different authors, we will speak here of *theoretical biology* to refer to the theoretical and philosophical foundations of biology, i.e. the field responsible for ordering and systematizing the concepts and modes of explanation in biology. Theoretical biology is thus intersected by various questions of the philosophy of science itself, as we will see throughout this paper.

It is generally known that the foundations of biology were systematized in a sub-discipline of biology itself: evolutionary biology. The other areas of knowledge in biology converge in a unified way in this field to give rise to an organized vision of the world of living beings. In this sense, the first solid and complete theory of evolution, which was developed in the first half of the last century, represents the theoretical foundations of biology itself. This theory is known as the Modern Synthesis or Neo-Darwinism and arises from the integration of Darwin's theory of evolution by natural selection with the theory of heredity proposed by Mendel. This synthesis took place within the framework of a mathematically rigorous model (developed by Fisher, Wright, and Haldane) capable of explaining the change in species composition over history as a consequence of heritable variation in the fitness of organisms in a population.

The conceptual apparatus of the Modern Synthesis is rich and sophisticated; at the same time it has several aspects that will not be explored in detail for this paper. Instead, I will focus on one particular phenomenon: the null explanatory function of organisms and their development in evolutionary theory, and consequently, in theoretical biology. As Goodwin (1994, 1) points out:

> Something very curious and interesting has happened to biology in recent years. Organisms have disappeared as the fundamental units of life. In their place we now have genes, which have taken over all the basic properties that used to characterize living organisms [...] Better organisms made by better genes are the survivors in the lottery of life.

As we can see, biology was able to dispense with organisms as explanatory units and replace them with *genes*. How was it that the Modern Synthesis was able to dispense with organisms themselves when explaining organisms and refer to genes instead? The concept of the gene has certainly changed throughout history (see Griffiths and Stotz (2013) for a critical introduction to the history of genetics). When interpreted as a material entity, it was initially understood as something found in inherited cells. Then, at the beginning of the 20th century, the gene was placed in the chromosomes. Later, in 1953, Crick and Watson, in a discovery unprecedented in the history of biology, defined the gene at the molecular level. However, the material nature of the gene is not decisive for its explanatory role. As we can see, beyond their physical nature, genes have always been central to the Modern Synthesis. As Ågren (2021, 52) points out, "[t]he key take-home message is that the gene's-eye view wants to talk about genes in an abstract way and happily accepts a bit of fuzziness regarding their physical basis." So what is this abstract use of the word gene that can replace the explanatory role of organisms?

The answer lies in the ability to reduce the three central elements of evolution by natural selection (i.e. the unifying discipline in theoretical biology) to the genetic level (Lewontin, 1974; Godfrey-Smith, 2009): heredity, variation, and fitness. This was the reduction made in the emergence of the Modern Synthesis. The first central step was taken by Weismann and Haeckel: heredity is considered to be purely genetic; neither can epigenetic factors influence the hereditary material nor can the epigenetic factors themselves be heritable. Second, phenotypic variation within a population is exclusively genetic -due to genetic drift and mutations. This position on variation is closely linked to the genetic theory of inheritance. If evolution requires that the most adaptively advantageous variations be maintained across generations, these variations must be heritable. Since what is heritable is what is genetic, epigenetic variation is outside the scope of evolutionary processes. In this way, natural selection chooses those heritable variations that are most advantageous. To the extent that heritable variations are caused and reduced to the genetic level, the fitness of organisms in a population can ultimately be defined at the genetic level. Over these pillars, Dobzhansky (1951, 16) concluded that "[e]volution is a change in the genetic composition of populations. The study of mechanisms of evolution falls within the province of population genetics." In the context of the Modern Synthesis, "'selfish genes' in 'gene pools' are taken to be more important than organisms" (Reid, 2009, 11).

This view of natural selection encloses a central commitment:[1] Genes must be able to explain the ontogenetic history of organisms. That is, to the extent that traits (and not genes) are the ones that confront the environment that determines the fitness of a species, there must be a link between what is inherited (genes) and what is selected (phenotypes). This link is called the Genotype-Phenotype map (GxE map), i.e. the development of organisms. The genetic material of an organism must explain its own structure. This was exactly what Crick (1970) postulated in his Central Dogma of Molecular Biology. According to Crick's version, the information is transferred from DNA to RNA to the production of proteins in the cells. Which proteins have to be built and thus which cell has to be created in an organism is determined solely at the DNA level. This is because information flows in one direction during development, namely from the DNA to the cell, but the reverse process never takes place: DNA is never influenced by epigenetic phenomena. There is therefore a correspondence between the genetic information and the constructed phenotypic trait, which is essential for the genetic theory of evolution.

Given this panorama, it is predictable that, when explaining evolution, organisms are considered as "*vehicles* in which replicators [genes] travel about" (Dawkins, 1982, 82; emphasis in the original), as "merely the *medium* by which the external forces of the environment confront the internal forces that produce variation" (Levins and Lewontin, 1985, 88; emphasis added), as the "*arena* in which this interaction [genome variations and natural selection] is played" (Michel and Moore, 1995, 127; emphasis added), as "mere *middlemen* in evolution, a sort of *interface* between the organism building activities of replicators and the selecting role of the environment" (Walsh, 2006b, 775; emphasis added), or as "the *superficial face* that genes show to the world" (Sober, 1984, 228; emphasis added). As Hamburger (1980) stated, organisms and their development were put into a black box that did not need to be looked into in order to understand evolutionary processes.

The reason that raises the question of the cognitive revolution, however, is that "the black box [of development] is now being opened to provide a more complete picture of what really happens" (Bateson and Gluckman, 2011, 17). Much of the philosophy of biology today revolves around the role of organisms and their development in evolution and the extent to which the inherited genocentric view is appropriate. A fundamental turning point that has led to the (re)emergence of the organism as a central explanatory element in evolution in recent years is precisely the fundamental empirical advances in developmental biology. In particular, the idea that the

[1] It is good to remember that Darwin did not postulate this genocentric view of natural selection (Darwin himself accepted Lamarkian inheritance) and that natural selection can be embedded in other positions on inheritance, variation, and fitness.

development of an organism can be explained solely by looking at its genetic basis was discarded when the Human Genome Project was completed and the true complexity of developmental systems began to be recognized -in the context of so-called *post-genomics* (cf. Griffiths and Stotz, 2013; Keller, 2002; Moss, 2003; Rheinberger and Müller-Wille, 2020). The idea that genes encode phenotypic traits is being replaced by a holistic view of development in which various genetic, epigenetic, and exogenous resources play a central role in the construction of phenotypes (Oyama et al., 2001). Likewise, the true role of epigenetic processes in the origin of phenotypic variation has begun to be recognized (Sultan, 2015; West-Eberhard, 2003) and epigenetic inheritance systems have been found in all living things (Jablonka and Lamb, 2020).

The aim of this article is not to revive this debate or to explain the various aspects of it. The moral is that the philosophy of contemporary biology is experiencing a moment of intense controversy in which various empirical advances invite us to rethink the foundations of biology, especially because in the reductionist model of the Modern Synthesis "an immense amount of biology was missing" (Lewontin, 2010). Today, organisms are once again at the center of theoretical biology (Baedke, 2018; Bateson, 2005; Nicholson, 2014; Gilbert and Sarkar, 2000). The role of organisms and their development is moving from the periphery to the center of evolutionary theory itself, as Walsh (2006, 438) points out:

> The picture that emerges from recent developmental biology is that the stability and the mutability of organisms that are pre-requisites for adaptive evolution are consequences of the distinctive capacities of organisms, particularly as they are manifested in their development.

In this article, I will use the term *new proposals in theoretical biology* to refer to the proposals that have generated new areas of knowledge in biology, which in turn aim to reconsider and reformulate some of the ideas inherited from the Modern Synthesis, such as Eco-Devo, Evo-Devo, Developmental Systems Theory, Niche Construction Theory, Autonomous Systems Theory, Extended Inheritance Systems Theory, Extended Evolutionary Synthesis, and Systems Biology, among others.

2. Interpretation 1: The Use of the Conceptual Apparatus of Cognitive Science

Organisms are once again the protagonists of their own history. They are once again the key to explaining their own existence and the producers of those central characteristics in evolution -such as heredity, variation, and fitness. The question we now face is whether or not the cognitivist apparatus in biology is necessary to explain the causal role of organisms in evolution. Once organisms are no longer passive systems controlled by genetic engineering that evolved over millennia, their role as active agents capable of adaptive action becomes more important. How do we explain this agency and the diverse processes it entails?

As a first approach to this question, we can note the recent growth and importance of *cognitive biology* (Auletta, 2011; Baluška and Levin, 2016). Cognitive biology combines different approaches in biology that take into account the cognitive abilities of organisms. Cognitive biology analyzes a wide variety of living systems and the various natural abilities that are characteristic of cognitive systems.

A central question within cognitive biology concerns the existence of cognition in unicellular organisms, both eukaryotes and prokaryotes (e.g. Lyon, 2015; Shapiro 2007; Kováč, 2006). The main task behind this question is to investigate the presence of various cognitive phenomena in cells, from memory, learning, movement, or perception (cf. special issue on basal cognition in Levin et al. (2021) and Lyon et al. (2021)). The central element is the recognition that cells can manipulate and process different types of information, both endogenous and exogenous, to produce behavior that corresponds to their living conditions. This ability appears to be a minimum requirement for cognition which many discuss under the term *minimal cognition*, and is present in every cognitive ability. Research into signaling systems, signal processing, and signal transmission in various information networks thus brings together research into cellular cognition.

Another area with a strong cognitive approach in biology is plant cognition. Here we find a variety of approaches to the cognitive abilities of plants, from their neurobiological basis (Brenner et al., 2006), their ability to feel (Calvo et al., 2017), to experience a specific ecological niche (Sultan, 2015), to behave adaptively (Calvo and Kijzer, 2011) or intelligently (Trewavas, 2014), or even to have consciousness (Segundo-Ortín and Calvo, 2021) or thoughts (Marder, 2013). Again, this involves information processing and signaling systems associated with the intrinsic ability of plants to regulate their interaction with the environment through various responses, be it through morphology, movement, behavior, and other physiological changes.

As we can see, there are various proposals in the field that defend and use the cognitivist apparatus, even to explain unicellular organisms. It is important to point out that the question of cognition in biology is an independent topic -or not necessarily related- to questions about the foundations of evolutionary biology (Section 1). Many of the proposals mentioned here simply ask about cognition in cells or plants, without assessing what consequences this has for evolutionary theory. Although there are different fields of knowledge devoted to the study of biological cognition in various kinds of organisms, there are also several nuances in the use of the explanatory apparatus of cognitivism in biology. Not all proposals agree on what we should transfer from cognitive science to biology. We will therefore present various proposals, their commonalities, and their inconsistencies below.

2.1 Which Theories Need to be Extended to Biology?

The panorama of cognitive sciences is diverse and there are different approaches to cognition with many ramifications. Consequently, different positions in biology arise depending on the model and framework adopted from cognitive science. Cognitive approaches to biology inherit the inherent pluralism of cognitive science.

In a strict terminological sense, *cognitivism* refers to the classical approach in cognitive science, which we will refer to here as *classical cognitivism*. A central pillar of classical cognitivism is the Representational Theory of Mind (RTM): the idea that cognition consists of the processing of information with semantic content, referred to as mental representations (see Schulte (2023) for a recent introduction to the topic). Processing mental representations about external features allows us to describe intentional states and to explain behavior as something caused by intentional states. Another pillar is the so-called Computational Theory of Mind (CTM): the idea that the processing of mental representations in cognitive processes can be described in terms of computational operations. If we rely on this classical view, the explanatory role of representational and computational explanations in theoretical biology becomes relevant (Prusinkiewicz and Runions, 2012; Lahoz-Beltr et al., 2014; Arnos, 2004)

While both pillars of cognitivism can lead to explanatory value that transcends cognitive science, some observations can guide this interdisciplinary dialogue. First, usually, the CTM goes hand in hand with RTM, but this need not be the case. There are different interpretations of the CTM as well as different representational theories of mental content. Each theory also has different ontological commitments: While some computationalists believe that the nervous system is a physical computer, others take an instrumentalist position and argue that computational explanations are only useful explanatory tools to understand the mind. This scenario also exists in theoretical biology. There is no doubt that computational science is ubiquitous in biological modelling, but that does not mean that organisms are computers. Second, specific representational or computational models could be constructed in theoretical biology. For example, it is not necessary to ascribe *mental* representations to plants, even though this view has some proponents (see Section 2.2). We can say that plants have some kind of representational abilities. Even if computational models based on language-like symbols are too far removed from, say, unicellular life, we can still find computational approaches suitable for unicellular organisms, such as those developed in the field of artificial life.

However, beyond the boundaries of classical cognitivism, other positions in cognitive science have had a major influence on biology. For example, *enactivism* is presented as a radical theory in cognitive science (Hutto and Myin, 2013; Thompson, 2010). According to this view, the classical representationalist model has serious foundational problems. Cognition is not the processing of representations in the brain, but an action that takes place in a particular environment and is distributed across the organism's body. In contrast to classical representationalism, enactive approaches generally assume an "intentional directedness that is not contentful" (Hutto and Myin, 2013, 82), i.e. intentional processes are based on the directedness of organic action. Without entering into the debates of the philosophy of cognitive science, the relevant point is that the conceptual apparatus of enactivism has been applied to biology (e.g. Di Paolo et al., 2017; de Jesus, 2016; Froese and Di Paolo, 2011). As expected, the non-contentful account of intentionality is easier to digest by biologists: It is not necessary to assume internal cognitive constructs with semantic properties to explain cognitive biology, but merely a kind of directedness in action. Enactivists can indeed accept the existence of *some* mental representations; the main claim is that *some* cognitive abilities do not require representations to be explained. In particular, enactive explanations of cognition are associated with non-linguistic cognitive abilities. In this way, enactive approaches to cognition are more seductive for biological explanations: There is no need to assume complex mental phenomena inherent in higher cognitive functions such as language.

Moreover, other positions in biology adopt, for example, the apparatus of Ecological Psychology, a non-classical theory of cognitive science developed by James Gibson in 1979. The central idea in this case is that the information available to cognitive systems should not be understood as something internal to the system and detached from the environment. Instead of appealing to the internal manipulation of mental representations, they use the term *affordance* (cf. Heras-Escribano (2019) for a recent critical introduction to ecological psychology). An affordance is always defined as a relationship between the environment and the organism: affordances are opportunities to act in a particular environment. A clear example of the use of this cognitivist apparatus in biology can be found in the work of Walsh (2013; 2015), who probably represents the most integrated vision between evolutionary theory and the use of the apparatus of cognitive science in biology, which he calls *Situated Darwinism*. Moreover, Richard Lewnotin, a forerunner of the developmental turn embraces a similar position to ogranismic activities that the one developed by Gibson. Lewnotin's famous quote "[t]here is no organism without an environment, but there is no environment without an organism" could be attributed to Gibson (Levis and Lewontin 1997, 76). In this sense, ecological psychology is offered to the new trends in theoretical biology as a well-developed and philosophically founded approach to organism-environmental relationships, central phenomena in the attempt to construct a context-sensitive view of organismic development (Sultan 2015).

Besides the different approaches in cognitive biology, in all these cases -classical cognitivism, enactivism, and ecological psychology- cognitive science overlaps with biology. This is partly because in some cases it has been biology itself that has inspired various theories in cognitive science, sharing philosophical foundations and ways of understanding the living sciences. Von Uexkull's work in ethology and his concept of *Umwelt* influenced post-cognitivist approaches in ecological psychology (Heras-Escribano and DeJesus, 2018; Feiten, 2020)[2] and today von Uexküll is called to play a central role in theoretical biology (Rama, 2021, forthcoming). Similarly, the work of Maturana and Varela in cybernetics were cornerstones of enactivism, and today enactivism is useful in theoretical biology. In this sense, an exchange between cognitive science and biology has been taking place for decades, sharing philosophical foundations and ways of understanding the living sciences.

The aim here is not to defend a particular cognitivist theory. Each of them can have its advantages and disadvantages, both in cognitive science itself and in biology. The discussion about which theories need to be extended to biology runs parallel to the "explanatory turn" in cognitive science (Schulte 2020, chapter 7). The explanatory turn consists of evaluating different theoretical approaches in terms of the explanatory power gained. The role of cognitivist theories in theoretical biology is therefore relative to their explanatory value. As expected, the requirements of each

[2] The contentions surrounding the parallels between *affordances* and the *Umwelt* concept are analyzed by Fultot and Turvey (2019), among others. While affordances underscore the direct nature of the organism-environment relationship, emphasizing that they are not internal, representational constructs, the *Umwelt* concept posits that the connection between an organism and its environment is never immediate or automatic. Thus, the anti-representationalist essence inherent in affordances is not necessarily found in the Umwelt concept. Beyond this debate, there are several points of connection between both concepts.

discipline are different: the adequacy of a cognitive theory is evaluated on different grounds in biology than in cognitive science. One clear difference is that certain explanations appear to be at odds with biological explanations. While it is not radical to assume explanations for complex human behavior through representations, it seems that the assumption of representations must have relevant explanatory value in all biological taxa. In other words: If we pay a high price (e.g., accepting counterintuitive representationalist claims), we expect a valuable explanatory *quid pro quo*. Not surprisingly, post-cognitivist theories are more "biology-friendly" since they can achieve similar explanatory gains without involving single-celled organisms in "mental puzzles". However, this also requires some thought. Representational theories take different formats and can be adapted to different cognitive capacities. So the debate is completely open and the land is fertile for future interdisciplinary research.

2.2 Which Concepts Need to be Extended to Biology?

Aside from the various theories that exist about cognition and its nature, a variety of approaches to biology arise when we ask which phenomena associated with cognition are present (and which are not) in all living systems. Do all organisms have a mind? Is an organism with memory functions a cognitive system? Does context sensitivity include perception? Is all learning a cognitive process?

When we ask ourselves what it is that is transferred from the cognitive sciences to biology, it is useful to make some distinctions. The question that heads this Section (2.2) is linked to various theses about the *continuity* between organisms and cognitive systems. The best-known and at the same time most radical thesis is the *life-mind continuity thesis* (e.g. Dennett, 2017; Godfrey-Smith, 2016; Thompson, 2010; Wheeler, 2011; Wiese and Friston, 2021). According to this thesis, the mental and the living are coextensive; every living system has a mind, and every system with a mind has life. However, there are other theses about the continuity of properties in the organic world, for example, the *cognition-life continuity thesis* (e.g. Bechtel and Bich, 2021; Kováč, 2006; Lyon, 2015; Maturana and Varela, 1991). This thesis does not assume that mental states must be attributed to every living system, but rather that every living system has cognitive abilities (which can be diverse, of greater or lesser complexity, such as memory, learning, communication, or perception) and vice versa; i.e. that the living and the cognitive are co-extensional. An even weaker thesis could be categorized as a continuity thesis between sensorimotor systems and the living systems, i.e. a coextension between living systems and those systems that adapt their actions to what is perceived in the environment, without this in itself implying the attribution of any mental or cognitive capacity to living systems (e.g. Van Diujn et al., 2006).

Furthermore, the question that is the title of Section 2.2 also requires a distinction between different cognitive phenomena. Perhaps the use of the cognitivist apparatus in biology does not mean that every organism has thoughts or engages in reasoning, but rather that every living system performs tasks that require, for example, memory, learning, or complex communicative systems with their environment. In this sense, only some properties of the cognitive sciences can be extended to biology, without implying continuity between the paradigmatic organisms of the cognitive sciences (animals) and the rest of the living realm. For example, as already mentioned (see references above), the field of plant cognition is very diverse. While some limit themselves to postulating the sensorimotor abilities of plants, others emphasize that plants are able to think and have consciousness. While some are dedicated to understanding the physiological basis of perception in plants, others summarise this study under the term *plant neurobiology.* When it comes to extending cognitive abilities beyond organisms with a nervous system, the situation is undoubtedly no different from other non-cognitive traits; not all traits that we find in human cognition need to be extended, and those that are extended need not have the same complexity as in the case of human cognition.

The endorsement of some of these theses and the rejection of others is largely related to a semantic question inherent in epistemological debates, namely what we mean by cognition, perception, or mind. The various answers to the question of a cognitive revolution are intersected by a particular position on the semantic value of the categories used in cognitive science. This does not mean that it is a purely terminological question, but theoretical biology inherits from cognitive science various conceptualizations that are in themselves complex and controversial. Again, the explanatory turn is a metatheoretical frame of reference: Whether or not the existence of a cognitive concept in biology is accepted depends on the explanatory power gained. Even if it may seem dubious to attribute consciousness to bacteria, we can achieve an explanatory benefit that justifies our controversial commitment.

2.3 The Point of Convergence: Agentivity

The aim of this article is not to argue for or against any of the various positions described in this section. I have merely limited myself to pointing out various positive answers to the question of the cognitive revolution in theoretical biology (under its theoretical interpretation). All of the proposals mentioned in this section would more or less accept that at least some elements of cognitive science have important epistemic value for understanding organisms. Undoubtedly, some positions are more radical than others. It is more controversial to say that our immune system has a mind than to claim that it has memory.

Despite the variety of connections that may exist between theoretical biology and the cognitive sciences, it is possible to find a point of convergence within this pluralism. In all cases, the goal is to justify the role of organisms as *agentive* entities. As Dennett and Levin (2020) point out: "Biology's next great horizon is to understand cells, tissues and organisms as agents with agendas" It is precisely this idea that contrasts with the vision of the Modern Synthesis, in which organisms are not active agents but passive objects when it comes to explaining evolution (Sultan et al., 2021). Generalizing, we can claim that all applications of the cognitive science apparatus aim to capture or are related to the agentive dimension of organisms. In other words, the thesis that unites the various applications of cognitivism can be called the *agency-life continuity thesis:* Every living system is an agent, and every agent has life (no doubt the notion of agent is also complex, and although there is an entire discipline devoted to artificial agents, there have been various efforts to clarify what characterizes the agentivity of living systems (e.g., Barandiaran et al, 2009; Kauffman y Clayton, 2006; Okasha, 2023)).

We can therefore draw a first conclusion regarding the theoretical question: Theoretical biology is undergoing a cognitive revolution in which the explanatory apparatus and conceptual models of the cognitive sciences are beginning to play a central epistemic role in theoretical biology, especially in developmental biology. However, this conclusion requires several considerations. On the one hand, the use of the cognitivist apparatus in biology is not a task undertaken with great systematicity or with a consensus on how to do it. Rather, it is a matter of new proposals used to deal with the agentive nature of organisms, with no predominant approach when it comes to integrating it into evolutionary biology. The use of the cognitivist apparatus is partly due to the fact that the cognitive sciences explain what the new proposals in theoretical biology begin to deal with: agents. On the other hand, a scientific discipline that reviews its foundations, such as theoretical biology, is also expected to draw on conceptualizations from other scientific disciplines. In developing a new conceptual framework, one scientific discipline may involve another in the process of consolidation, especially when it comes to disciplines as closely related as biology and cognitive science. Cognitive science, therefore, can be expected to play an explanatory role in understanding the adaptability of an organism's internal processes. If adaptability is not just a question of population genetics, we need to explain how organisms adapt to their environment. This is where different cognitive abilities come into play.

3. Interpretation 2: The Parallelism With the Cognitive Revolution

The analysis in the previous section has given us an overview of the current landscape in relation to the theoretical question. Now it is time to look at the historical interpretation. In this case, we are not concerned with potential conceptual shifts, the expansion of epistemic domains, or the adoption of theories from one discipline (cognitive science) to another (biology). Nevertheless, these issues have an impact on the assessment of the historical question. If the explanatory framework of cognitive science is applied to biology -whatever this framework and application may entail- then the historical question becomes more important; a certain similarity between the approaches to cognition and the approaches to living systems becomes clear. Our task now is to situate these approaches within the historical context of their respective disciplines: the role of the cognitive sciences in the history of behavioral sciences and the position of current proposals in theoretical biology within the history of biology itself. We will first present the case of the cognitive sciences and then assess the parallels with theoretical biology. The result of the analysis is that the current landscape of theoretical biology can indeed be compared to the Cognitive Revolution.

3.1 Whitin the Mind: Cognitive Science Opening the Black Box

The expression *Cognitive Revolution* usually refers to the emergence of the cognitive sciences and the move away from prevailing behaviorist theories. This event took place in the middle of the 20th century as a result of various experimental and theoretical advances (the beginning is usually dated to 1956 when various innovative papers were disseminated; see Miller (2003)). The interdisciplinary character of the cognitive sciences is already evident in their beginnings. Cognitive psychology, neuroscience, linguistics, artificial intelligence, and philosophy, among other disciplines, played a crucial role in the critique of behaviorism and later became key figures in the development and advancement of the cognitive sciences. Chomsky's work in linguistics, the neural network models of McCulloch and Pitts, the mouse experiments of Tolman and Honzik, the insights into the limits of information processing by Miller, and the advances in computing made by Turing (extended by influential figures in artificial intelligence such as Minsky, McCarthy, Newell, and Simon) are generally recognized as catalysts for the field of cognitive science (see Bermudez (2014) for a classical textbook in cognitive science).

These advances paved the way for a new way of understanding mind and behavior. The element that brings these advances together is precisely the idea that runs counter to the behaviorist model: that the processes *internal* to the system that generate behavior can be studied scientifically. In other words, there can be a science of mental processes and mental states, that not only behavior is observable, but also mental states. All that is needed is an appropriate theory to make them visible. The acceptance of this idea is referred to as "opening the black box" in which behaviorism had put the mind.

Behaviorism has put the mind and the internal processes of the organism into a black box for historical, philosophical, and experimental reasons. First, behaviorism was defended in a context in which the technological infrastructure for studying cognition had not yet been developed. Second, the mind was considered a purely subjective and speculative field, far removed from any possibility of understanding the underlying causes of mental processes. The Cartesian legacy proclaimed a vision in which the mind could not enter the reach of science. And finally, the experimental model of behaviorism itself did not depend at all on how the mind worked. The behaviorist model was simply based on the relationships between stimuli, responses, and reinforcement, while "the mind, contained in the organism, is not depicted. It is treated as a 'black box,' meaning that it is unfathomable and unexplainable. The mind becomes simply an entity that serves to convert stimuli to responses" (Friedenberg y Silverman, 2006, 86).

The question of the cognitive sciences consists of "how to analyze the behavior of a complex network, instead of treating it as an unintelligible black box" (Boden, 2008, 957). The conceptual and experimental apparatus of the cognitive sciences emerged from this question. As we have already seen, various more or less orthodox positions in the cognitive sciences accept the ideas of classical cognitivism in whole, in part, or not at all. Despite this plurality of views exposed in Section 2, it is possible to emphasize the central proposal developed during the Cognitive Revolution: Mental processes can be understood as information processes that represent internal states of the cognitive system. Such states and processes are the causal bases that produce the behavior that links the input to the output of a system.

This core tenet built during the Cognitive Revolution deals with three central concepts: information, intentional-internal states, and causation. First, mental processes perceive *information* from the environment, manipulate it, and produce it to perform adaptive behavior (Fresco, 2022). Second, we can conceptualize the system's internal states as states of an agent with intentions. We can explain why a system performs a behavior by invoking a mentalistic language without implying dualism or anti-scientificity (Braddon-Mitchell and Jackson, 2007). *Perceptions, intentions, desires,* *thoughts, or goals* are different mental categories that can be understood as informational states of a system. Finally, the psychological explanation derived from this points to the *causes* of behavior.

Undoubtedly, the sketch presented in the previous paragraph is extremely schematic and reflects the classical vision developed at the beginning of cognitive science -and not the variety and depths that nowadays we find in the discipline. The aim, however, is to show how the box of the mind was opened. In this way, we can draw a direct parallel with current theoretical biology. Moreover, if we stress that the main idea of all cognitivist theories is the agentive explanation of behavior (Section 2.3), the main moral of the Cognitive Revolution (CR) is as follows:

> *(CR) The adaptability of the system must be explained in terms of what happens within the system. To abandon the internal processes of a system is to abandon the causes that give rise to interaction with its environment.*

3.2 Within Organisms: Developmental Biology Opening the Black Box

What parallels are there between the Cognitive Revolution and the current disputes about the foundations of biology? This also means that we need to ask ourselves about the parallels between behaviorism and the Modern Synthesis, and the parallels between the cognitive sciences and the new proposals in theoretical biology.

Apart from the fact that both theories were forged in the first half of the 20th century and developed mainly in the Anglo-Saxon world, the most remarkable parallelism between behaviorism and the Modern Synthesis occurs when we consider their explanatory models. Here we find the fact that in both cases a black box is postulated into which we do not need to look in order to achieve our scientific goals. The behavioral model is based on three variables: a perceptual input, a behavioral output, and a reinforcement -positive or negative- of the link between input and output. We also find these three elements in the evolutionary model of the Modern Synthesis: a genetic input (inheritance), a phenotypic output (variation), and selection -positive or negative- of traits (fitness). This is how Amundson (1990, 578) summarizes the similarity between the two models:

> Natural selection explains phylogenetic adaptation by positing a nondirected ("random") source of heritable variation within the lineage, together with selection by the environment of those variants which happen by chance to be better suited to survival and reproduction. The Law of Effect [of behaviorism] ... explains the ontogenetic adaptation of individual behavior by positing nondirected ("spontaneous") variations in behavior, together with some form of selection by the environment which allows successful behavior to persist and the unsuccessful to die out ...[Both models are] virtually identical in its structure to that used to explain the phylogenetic adaptation of the evolving species.

As we see, the mind and the development of organisms are conspicuous by their absence. We can explain behavior and evolution without paying attention to the processes that take place inside the mind and organisms. It is not a matter of explaining the causal process that leads from an input to an output. That is, it is not necessary to explain the developmental process that links the inherited genetic material of an organism to the constructed phenotype (the GxP map), nor is it necessary to understand the mental processes that produce behavior in the face of particular perceptual inputs. The development of organisms and mental processes are transparent (Rama, 2022): The Modern Synthesis can see phenotypes through the genetic material, just as behaviorism is able to see behavior through the input the system receives. Given the similarities between these models, we can argue with Fodor and Piattelli-Palmarini that (2010, xvi) "Skinner's account of learning and Darwin's account of evolution are identical in all but name."

The central historical note is that both black boxes were opened with the same key. In this sense, the parallelism between behaviorism and the Modern Synthesis is not only to be found in their models, but they are also similar in their rejections. That is, the Modern Synthesis is criticized for the same reasons that behaviorism was criticized in the last century. This is due to the parallelism that exists between the theories that oppose the Modern Synthesis and behaviorism, i.e. between the new proposals in theoretical biology and the cognitive sciences. Both disciplines, cognitive science, and current theoretical biology, have used *the same key* to open the black boxes of mind and development respectively.

As mentioned in Section 1, the new proposals in theoretical biology categorically reject the idea that an organism's phenotypes are fully encoded in its genome. On the contrary, organisms are active agents that can adaptively regulate their own development and living conditions. In this context, various phenomena play a central role, such as phenotypic plasticity, niche construction, or self-organization processes, to name but a few. So when it comes to understanding development as something that is controlled and produced by the organism itself, we find the same central components that triggered the Cognitive Revolution (see Section 3.1): Developmental processes can be understood as *information processes* that represent *internal states* of the organism. These states are the *causes* of the emergence of a phenotypic product.

In this way, we can first find the idea that developmental processes can be understood as *informational processes*. This idea emerged at the same time as the molecular genocentric view described by Crick in Central Dogma in Molecular Biology. Instead, the current proposal is situated in post-genomics: the idea is that different elements in development, genetic, epigenetic, and exogenous, provide crucial information throughout ontogeny (Rama, 2023). As we saw in Section 2, much of cognitive biology is based on the ability of organisms to process information. When it comes to explaining how organisms adapt to their environment as they develop, the focus is on the study of signaling systems that inform the system about its internal and external conditions so that it achieves an appropriate coupling to its environment. Nor can the organism be regarded as an inert object at the mercy of the chance of mutation and the vicissitudes of the environment. The central idea mentioned in section 2.3 is to conceive of originators as agents capable of regulating their own living conditions in order to achieve adaptive outcomes. The internal states of an agent can be viewed as informational states. Agents process information from different channels (whether internal or external to the organism itself) and give a response that is consistent with that information. In this way, we can understand the development of organisms as an activity directed towards an adaptive goal. The goals of developmental systems "consist in the capacity of a system as a whole to enlist the causal capacities of its parts and direct them toward the attainment of a robustly stable end-point" (Walsh, 2015, 195). As in the cognitive sciences, it is internal processes that promote an adaptive explanation between organisms and the environment. And just as the cognitive sciences have allowed us to understand how behavior is caused by states internal to the system, current theoretical biology emphasizes that a true explanation of development requires explaining the different stages of a developmental system, rather than summarizing it to a genetic code. In other words, the causes of development do not precede development; they are distributed throughout ontogeny. A true explanation of development is to understand the interaction between the different causes and how organisms regulate their own development; or as Robert (2004, 22) says: "To take development seriously is to take development as our primary explanandum, to resist the substitution of genetic metaphors for developmental mechanisms."

The parallelism between CR and the new proposals in theoretical biology (NPTB) is easy to recognize since theoretical biology advocates the same morality as the cognitive sciences:

> *(NPTB) The adaptability of the system must be explained in terms of the processes within the system. To abandon the internal processes of a system is to abandon the causes that give rise to interaction with its environment.*

In this way, we can summarize the analysis of this section by answering in the affirmative the question that is posed to us: Yes, the current panorama of theoretical biology can be seen as parallel to the Cognitive Revolution of the last century. Such a conclusion arises from the analysis of three points:

1. The similarity between the behaviorist model and the evolutionary model of the Modern Synthesis.
2. The transition from behaviorism to the cognitive sciences and the (current and incomplete) transition from the Modern Synthesis to the new proposals in theoretical biology are due to the same reasons: mental processes and developmental processes have been put in a black box.
3. The similarity between the explanatory model of cognitive science and the explanatory model of the new proposals in theoretical biology: the same key was used for both black boxes (CR = NPTB).

However, like the answer to the theoretical question, the answer to the historical question also requires a certain amount of nuance. In particular, it is noteworthy that he does not claim that theoretical biology is undergoing a scientific revolution. The term *scientific revolution* has a strong connotation and usually implies the abandonment of old theories and their incompatibility with new theories. The debate on how to view the relationship between the Modern Synthesis and the new proposals in theoretical biology is open and on the table (Gefaell and Saborido, 2023). Again, there is a gradient of more or less radical possibilities, from those who believe that nothing new poses a problem for the old (Futuyma, 2017), to those who think that new proposals require an extension of the Modern Synthesis (Pigliucci and Muller, 2010), to those who point to certain points of the Modern Synthesis that need to be abandoned and completely reconstructed (Noble, 2021). In any case, the current panorama of theoretical biology shows no signs that a revolution has taken place. In this episode of the history of biology, we find ourselves *in media res.* The Modern Synthesis needs to be rethought, but there is not yet a consolidated and accepted vision to replace it. The claim of a scientific revolution taking place in biology does not seem to be justified given the fact that, as Laland et al. (2013, 807) say, “it is probably fair to say that these various lobbies [the new trends in theoretical biology] currently more resemble a disorganized protest movement than a viable alternative government.” In this sense, there could be a scientific revolution in biology, but there definitely is not one, at least at the moment.

4. Conclusions

This paper aims to systematize the connection between the cognitive sciences and contemporary theoretical biology. Undoubtedly, various interesting elements have not been taken into account, and the analysis carried out does not intend to emphasize any particular proposal. Moreover, we dealt with *cognitive biology,* not *biological cognition* (Huebner and Schulkin 2022). Certainly, the two fields may be related or overlap, but they differ in which discipline feeds the other. If biology is the input for cognitive studies, we are pursuing biological cognition. Our aims fall within cognitive biology: to provide, in a schematic way, a synthesis of the role played by the conceptual apparatus of cognitive science (together with its own history) in theoretical biology. The emphasis on the connection between disciplines was analyzed in a unidirectional way, i.e. without taking into account the role that theoretical biology plays in cognitive science (which is undoubtedly ubiquitous; for example, we find it in teleosemantics, evolutionary psychology, generative linguistics, bioethics, and other approaches to cognition).

The analysis began in the second section with the theoretical question. This section concludes that the cognitive sciences do indeed provide central conceptualizations and experimental frameworks for understanding the cognitive capacities of organisms. However, this conclusion requires different nuances due to the different positions that can be taken. First, we can ask which theories of cognitive science should be applied to biology. There are several possibilities related to the different propositions of cognitive science -from classical cognitivism to radical post-cognitivism. At the same time, there are also discrepancies regarding the concepts that should be applied to cognitive science. While some defend that all living organisms have mental properties, other, less radical positions claim that some paradigmatic properties of cognitive systems, such as memory, perception, or learning can be found in unicellular organisms. The current panorama is therefore diverse. As already mentioned, there is a core idea in all positions: that organisms are active agents in their own existence and not passive systems controlled by their genetic engineering. In this way, we can understand the multiple uses of the apparatus of cognitive science in biology as an attempt to explain the agency of organisms.

As we have argued, the historical question can also be answered affirmatively. The situation in the mid-20th century in mental and behavioral science resembles the current panorama in theoretical biology. We have highlighted three relevant parallels: (i) between behaviorism and the Modern

Synthesis, (ii) between the cognitive sciences and the current proposals in theoretical biology, and, above all, (iii) the fact that the reasons for the change from one theory to another -from behaviorism to cognitive sciences and from the Modern Synthesis to the new proposals in theoretical biology- are the same. There is an attempt to open a black box that left many natural phenomena -mental processes and developmental processes- unconsidered. Opening the box required a conceptual and experimental advance that makes it possible to understand the internal states of the system and how the information is processed in order to obtain an adaptive response according to the goals of the system. In the case of the cognitive sciences, progress was made through different fields of knowledge that emerged in the second half of the 20th century. In theoretical biology, in this 21st century, we are on the way to a new understanding of developmental processes, motivated by a rethinking of the functioning and structure of genetics and the ability of organisms to be agents of their own development.

However, the positive response described in the previous paragraph also requires a caveat. The role of cognitive science in contemporary theoretical biology was presented as a possible Cognitive Revolution in biology. In the context of the philosophy of science, the term revolution has a strong connotation. This is not to claim that a scientific revolution is taking place in theoretical biology; as already mentioned, there are various positions in the review of the foundations of the Modern Synthesis. The main reason for using the term Cognitive Revolution is heuristic and is to represent and understand the current situation in theoretical biology through a historical comparison with the Cognitive Revolution of the 1950s. So say Jablonka and Lamb (2020, 76):

> We find it very difficult to assess the significance and nature of the change in evolutionary thinking that we are in the midst of, but we can see similarities to another scientific change, one that occurred in the mid-twentieth century ... it seems to us that the consensus around the EES [Extended Evolutionary Synthesis] is growing for reasons similar to those that drove the cognitive revolution.

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