Developmental Biology 357 (2011) 13–16

Contents lists available at ScienceDirect

Developmental Biology

journal homepage: www.elsevier.com/developmentalbiology

Evolutionary developmental biology its roots and characteristics

Michel Morange

Centre Cavaillès, USR 3308, Ecole normale supérieure, 29 rue d'Ulm, 75230 Paris Cedex 05, France

ARTICLE INFO

Article history:
Received for publication 10 December 2010
Revised 8 March 2011
Accepted 10 March 2011
Available online 5 April 2011

Keywords:
Regulatory gene
Developmental gene
Epistemological obstacle
Actualism
History

ABSTRACT

The rise of evolutionary developmental biology was not the progressive isolation and characterization of developmental genes and gene networks. Many obstacles had to be overcome: the idea that all genes were more or less involved in development; the evidence that developmental processes in insects had nothing in common with those of vertebrates.
Different lines of research converged toward the creation of evolutionary developmental biology, giving this field of research its present heterogeneity. This does not prevent all those working in the field from sharing the conviction that a precise characterization of evolutionary variations is required to fully understand the evolutionary process.
Some evolutionary developmental biologists directly challenge the Modern Synthesis. I propose some ways to reconcile these apparently opposed visions of evolution. The turbulence seen in evolutionary developmental biology reflects the present entry of history into biology.

The rise of evolutionary developmental biology was one of the major events in biology at the end of the XXth century.

Although many historical descriptions and interpretations of the development of this new discipline have already been provided (Laubichler and Maienschein, 2007; Pigliucci and Müller, 2010), the direct involvement of most of their authors in this development has frequently biased their accounts. In this contribution, I will consider once more the emergence of this discipline, outline some of its new characteristics, and position its development in a wider historical context.

The emergence of evolutionary developmental biology

In 1942, Julian Huxley published *Evolution: The Modern Synthesis*, a fundamental book that not only described the recent convergence of disciplines toward the explanation of evolution, but also gave its name to this new approach to evolutionary phenomena (Huxley, 1942). For Huxley “a study of the effects of genes during development is as essential for an understanding of evolution as are the study of mutation and that of selection”. But Julian Huxley considered that these effects were poorly known at the time he was writing, preventing the incorporation of embryology into the synthesis.

The delayed development of evolutionary developmental biology would have been the direct consequence of the slow characterization of the role of genes in development.

The early discovery of mutations (and genes) affecting development by Thomas Morgan's group in the early decades of the XXth century (done in particular by Calvin Bridges) was followed by the progressive description of their action and organization on the chromosomes by Ed Lewis. The first description of mechanisms controlling gene expression in microorganisms by François Jacob and Jacques Monod in 1961 (Jacob and Monod, 1961) led immediately to the hypothesis that embryological development was controlled by an ensemble of gene regulatory networks. In parallel, from observations made on the early development of sea urchins, Eric Davidson postulated the existence of complex gene circuits controlling development, the modification of which guided evolution (Britten and Davidson, 1969, 1971).

Thanks to the tools of genetic engineering, the isolation of developmental genes and the characterization of gene regulatory pathways and networks involved in development became possible at the beginning of the 1980s. The isolation and characterization of the first homeobox-containing genes in 1984 somehow constituted the birth date of evolutionary developmental biology (Gehring, 1998).

Such an historical reconstruction is not incorrect, but masks some of the obstacles which had to be overcome, and the existence of different alternative approaches which also contributed to the rise of evolutionary developmental biology and explain its present heterogeneity.

The obstacles were what the French philosopher of science Gaston Bachelard has described as ideas that seemed obvious but were in fact false and which had to be abandoned to allow the new vision to emerge (Bachelard, 1938). What was apparently evident in that case was that all genes contributed more or less directly to development. Before the 1970s, there was no such thing as a category of “developmental genes”.

E-mail address: morange@biologie.ens.fr.

0012-1606/$ – see front matter
doi:10.1016/j.ydbio.2011.03.013

Another seemingly obvious idea was that the genetic mechanisms of development of highly different organisms, following different developmental pathways, were unrelated to one another.

The notion of developmental gene took form progressively (Morange, 1996, 2000). A decisive step was the distinction between structural and regulatory genes introduced by Jacob and Monod in 1959 (Jacob and Monod, 1959). This distinction opened the way to the existence of different categories of genes with different functional roles. It surreptitiously established a hierarchy among genes, a hierarchy important in terms not only of functional but also evolutionary explanations.

The Spanish *Drosophila* geneticist Antonio Garcia Bellido was the first to explicitly link the observations made on the genetic control of development in insects and the models elaborated by Monod and Jacob (Garcia Bellido et al., 1973). For Garcia Bellido, a selector gene was a regulatory gene controlling the formation of a cellular compartment during insect development.

Peter Lawrence and Francis Crick developed this new vision of the genetic control of development (Crick and Lawrence, 1975), and these ideas became widely accepted among biologists working on *Drosophila* (and more generally insect) development (Baker, 1978). It paved the way to the systematic search for early developmental genes in *Drosophila* by Christiane Nüsslein-Volhard and Eric Wieschaus in their laboratory at EMBL, and their classification of these genes.

Allan Wilson also played a crucial role in exploring the relation between regulatory genes and evolution. Jacob and Monod were very cautious in addressing the evolutionary consequences of their distinction between structural and regulatory genes—in sharp contrast with the rapid examination of the evolutionary consequences of their model by Roy Britten and Eric Davidson (Britten and Davidson, 1971). Jacob and Monod only admitted that mutations in the regulatory systems might have important consequences in a cryptic publication of the Pontifical Academy of Sciences (Jacob and Monod, 1962). This cautious attitude was probably due to the fact that, at that time, neither Monod nor Jacob had worked in embryology, and the only organism they had so far studied was the bacterium *Escherichia coli*. In addition, they did not want to directly challenge the Modern Synthesis. In the French context, such an attitude might have been interpreted as an attack against Darwinism, and a support to the Lamarckian views still adopted by most French biologists. In contrast, Allan Wilson immediately initiated a research program to estimate the consequences of mutations of the regulatory systems in microorganisms. He then turned to the study of higher organisms, with the same conviction that regulatory mutations were central to evolution. In 1975, he published a famous paper with Mary-Claire King demonstrating the small genetic distance between humans and chimpanzees (1–1.5%) (King and Wilson, 1975). This result, obtained through a comparison of protein sequences, has been amply confirmed since with more powerful molecular techniques. But the conclusion of the study was highly different from that which is presently given to this work. Allan Wilson and Mary-Claire King considered that the contrast between this small genetic distance and the huge differences between human beings and chimpanzees only meant that biologists were not looking at the right genes. Only a small fraction of the genomes significantly contributed to these differences: the genes controlling development, which had not yet been characterized.

Stephen Jay Gould hypothesized about the relation between developmental genes and evolution by suggesting that mutations affecting the rhythm of development played a major role in evolution (Gould, 1977). He saw this as a way to reinterpret the observations of Ernst Haeckel who wrongly saw them as evidence of the law of recapitulation, according to which ontogeny recapitulates phylogeny. These mutations, called heterochronic, affect genes controlling the rate of developmental processes. The existence of heterochronic genes and mutations has since been confirmed, but their importance in present-day biology remains limited.

The unexpected result which boosted the rise of evolutionary developmental biology was the discovery that developmental genes have been conserved during evolution. Such a result was totally unexpected: the developmental processes differ so greatly between organisms such as insects and mammals! In addition, evolution was seen as the result of an addition of genetic information. The complexity of organisms was directly related to how many genes they had. It was believed that the human genome contained at least 100,000 genes, two thirds of which were involved in the formation of the brain. Today, it is considered that evolution tinkered with a limited group of developmental genes, to build all organisms, extinct and extant.

When François Jacob introduced this notion of bricolage (tinkering) at the end of the 1970s (Jacob, 1977), a notion already used by Darwin, he did not contrast this tinkering action of evolution with the necessary addition of genetic information. In 1982, in *The Possible and the Actual*, he wrote (p. 41) that "the few really big steps in evolution clearly required the acquisition of new information. But specialization and diversification took place by using differently the same structural information" (Jacob, 1982). Twelve years later, he confirmed that, at the beginning of the 1980s, the tinkering action of evolution did not extend to the master genes controlling development: "While it was known that cell constituents had been conserved throughout evolution, there were no reasons to consider that it was the same for regulatory genes" (Jacob, 1994).

The conviction that developmental processes differed greatly from one organism to another, and required different regulatory genes, was shared by all pioneers in developmental genetics. In 1978, Ed Lewis wrote an important article in *Nature* in which he emphasized the role and organization of homeotic genes in insects (Lewis, 1978). Nothing in the article suggested that the developmental rules established for insects might be valid for other organisms.

What really changed the picture was the surprising discovery in 1984 of the structural and functional conservation of the homeobox-containing genes. Since this result was totally unexpected, it is difficult to understand what motivated the experiments. One possible interpretation would be that samples from organisms distant from insects were used as negative controls, and surprisingly proved to be positive. But this does not tally with the authors' own account (Gehring, 1998).

This conservation was not limited to isolated genes, but concerned complex signaling pathways, including not only transcription factors, but also signaling molecules, receptors and effectors. The evidence obtained in 2000 that the human genome contains no more than 25,000 genes supported the idea that the tinkering action of evolution is not limited to structural genes and components, but includes the genes involved in regulation and control (Davidson and Levine, 2008; Shubin et al., 2009).

But the rise of evolutionary developmental biology was also made possible by other contributions, foreign to the direct search for genes involved in development. The first was the notion of punctuated equilibria introduced by Niles Eldredge and Stephen Jay Gould (Eldredge and Gould, 1972), and supported by the precise stratigraphic observations made by Williamson (Williamson, 1981). There are different interpretations of the observed alternating periods of stasis and of rapid evolution. These may reflect irregular modifications in the environment or be the result of rapid migrations. They may also result from the fact that the genetic mechanisms of development are so precisely controlled and buffered against variations that mutations leading to a deep and viable change are rare. This interpretation of punctuated equilibria was not in the end adopted, but was voiced in the discussions which immediately followed the publication of Eldredge and Gould's article.

The contributions of Pere Alberch were also very influential (Alberch, 1980; Rasskin-Gutman and De Renzi, 2009). He positioned himself in a tradition of morphology, where researchers are interested