Phenotypic Range of Gene Expression: Environmental Influence

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Obviously, genes are not the only factors that determine phenotype - after all, even identical twins are not exactly alike. But what can armadillos teach us about being an individual?

Each individual organism is exactly that—an individual. In humans, individuality is reflected in many ways, such as through variations in height, hair color, and personality. Understanding the variation between individual organisms is a common goal of geneticists. Even laboratory organisms, which have a high degree of genetic similarity because they have been inbred for many generations, behave differently under the same conditions. For example, perhaps one mouse has eight pups and her sister has six, or one fruit fly lives for 31 days while another lives for just 13. Similarly, among humans, even "identical" twins who are raised together in nearly the same environment are never truly identical (Newman *et al*., 1937). Even though such twins are indeed the same at the genetic sequence level, people who know them can easily tell them apart. This is because the individuality and variation we observe in each organism is generated through a complex interaction between the organism's "complete genetic endowment" and its environment from conception onward (Hirsch, 1963).

Looking for Answers in Armadillos

One way to examine the role of the environment in variation among organisms is to compare the phenotypes of various traits in genetically identical organisms, like twins or, even better for research purposes, quadruplets. Armadillos are thus ideal animals to use in such research, because they are born as quadruplets derived from a single fertilized egg. This means that all four armadillo pups share the same genetic sequence.

During the 1960s, researcher Roger Williams decided to study armadillos after completing extensive experimentation with rats. In these experiments, Williams noted that even after being inbred for 101 generations, the rats continued to show significant metabolic differences (Storrs & Williams, 1968; Culliton, 1968). Williams's results were compelling, because after inbreeding animals for this many generations, scientists generally assume that the animals are nearly genetically identical. Moreover, Williams had housed the animals in controlled environments with the same diet. Why, then, did the rats' phenotypes differ so greatly? Williams grew increasingly curious about this issue, and he surmised that the genetic contribution alone was not enough to generate the observed phenotypic differences. Williams thus decided to take a closer look at the role of the environment. Before beginning his research, however, Williams knew he must do as much as possible to remove genetic variation from the equation. Thus, he and his student Eleanor Storrs turned to armadillos and looked at a variety of phenotypes in sets of quadruplets. After collecting data for 20 phenotypic characteristics, such as metabolic activity and organ weight, Williams and Storrs observed that some phenotypes had variations up to 140-fold among the monozygotic quadruplets (Storrs & Williams, 1968). In contrast, other heritable traits had very little variation at all.

In their research, Storrs and Williams focused on the "norm of reaction" for various phenotypes in armadillos. The norm of reaction is the theoretical concept that a specific phenotype may have a range of manifestations. In some cases, like human blood type, the range of phenotypes is strictly related to genotype, and the environment has little effect. For other phenotypes, like height in humans, the norms of reaction are much wider. The norm of reaction also depends on the level of organization under study, and it can be used to describe the various ways in which related organisms respond to their environment. Organisms of the same species with different genotypes can show differing norms of reaction when different phenotypes are measured or when environmental variables are altered. Therefore, a different norm of reaction exists for every combination of genotype, phenotypic trait, and environmental variable studied.

In Williams and Storrs's research, how might four embryos that developed in the same mother armadillo have been exposed to different environments? One possibility is that the intrauterine environment is slightly different for each developing embryo. For example, the position of the armadillo fetus in the uterus may play a role (Culliton, 1968), causing one fetus to be exposed to a different amount of light or a slightly different temperature than its siblings. The blood supply from the mother may also vary between armadillo siblings (Culliton, 1968). Similarly, researchers Herbert Hauser and Ron Gandelman wondered if the in utero positioning of a fetus with respect to the sex of neighboring fetuses influenced phenotype. They found that female mice that had been situated between two female fetuses in utero showed behavioral responses that were dramatically different than those in females that had developed between two male fetuses (Hauser & Gandelman, 1983). Uterine position could therefore partially explain the phenotypic differences in the sets of armadillo siblings.

Another possibility is that the four individual armadillo embryos shared identical genetic sequences, but not the same intracellular environment. After all, the initial fertilized egg is not a uniform cell with an equal distribution of cytoplasmic components. Rather, the cytoplasm and intracellular proteins, mitochondria, and ribosomes are unequally distributed, which may cause variation. Differences in the number of mitochondria, for example, may produce variations in energy production in different animals during development (Culliton, 1968). In armadillos, the fertilized egg develops to the blastocyst stage, and then four primordial buds form in two stages, which results in the development of quadruplets. Storrs and Williams noticed that, in a set of four siblings, there were two pairs of similar armadillos, with each pair corresponding to one of the two primordial bud stages (Storrs & Williams, 1968). Thus, while the primordial buds formed four genetically identical embryos, the cytoplasmic contents were divided unequally. This too may account for the phenotypic differences between the armadillo siblings.

Gene-Environment Interactions

Environmental factors are certainly critical in defining phenotypes during early development, as in the armadillos, and they continue to influence phenotypes throughout an organism's life cycle. Nearly every aspect of our development and behavior is affected by both the personal experiences we gain through our environment and our genetic makeup. For example, we obtain necessary amino acids through our diets, and the incorporation of these nutrients into our bodies is determined by our genes. It is also important to remember that genes are not a steadfast blueprint for heredity. Genes are actually quite active throughout our lives, switching their expression on and off in response to the environment and experience. Environmental factors can affect and alter gene expression, while our genes can define how we respond to different environments.

In an age in which scientists and the public are excited about the sequencing of the entire human genome, we need to temper that excitement, at least a little, and be careful not to believe all the hype surrounding genes' involvement in determining development and behavior. While an organism's genetic makeup plays a critical role in its development, there is also a rich and complex interplay between the genome and cues from the environment. It is not a question of which one affects us more, nature (heredity) or nurture (environment); instead, it is a question of how signals that are not hard-coded interact with our genetics to make us complex individuals. Indeed, it is actually superficial to debate whether nature or nurture is more important. In truth, the relationship between genetic determinants and the environment is so completely entwined that you cannot look at an individual and judge which contribution is more valuable. Together, the continual interplay of both genes and ever-changing environmental factors determines who we are.

References and Recommended Reading

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