2 The Study of Human Adaptation

A. Roberto Frisancho

INTRODUCTION

Ever since hominids left Africa, they have expanded throughout the world and have adapted to diverse environments, and acquired specific biological and cultural traits that have enabled them to survive in a given area. The conceptual framework of research in biological anthropology is that evolutionary selection processes have produced the human species and that these processes have produced a set of genetic characteristics, which adapted our evolving species to their environment. Current investigations have demonstrated that the phenotype measured morphologically, physiologically, or biochemically is the product of genetic plasticity operating during development. Within this framework, it is assumed that some of the biological adjustments or adaptations people made to their natural and social environments have also modified how they adjusted to subsequent environments. The adjustments we have made to improve our adaptations to a given environment have produced a new environment to which we, in turn, adapt in an ongoing process of new stress and new adaptation.

HOMEOSTASIS AND ENVIRONMENTAL STRESS

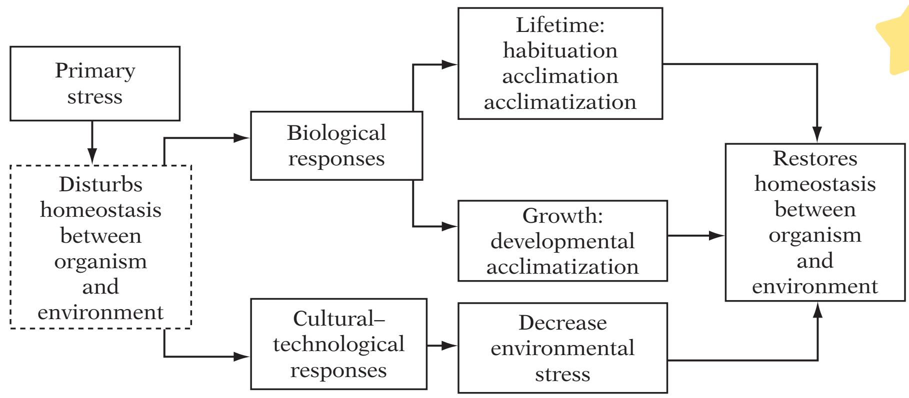
Central to the study of adaptation is the concept of homeostasis and environmental stress. Environmental stress is defined as any condition that disturbs the normal functioning of the organism. Such interference eventually causes a disturbance of internal homeostasis. Homeostasis means the ability of the organism to maintain a stable internal environment despite diverse, disruptive, external environmental influence (Proser, 1964). On a functional level, all adaptive responses of the organism or the individual are made to restore internal homeostasis. These controls operate in a hierarchy at all levels of biological organization, from a single biochemical pathway, to the mitochondria of a cell, to cells organized into tissues, tissues into organs and systems of organs, to entire organisms. For example, the lungs provide oxygen to the extracellular fluid to continually replenish the oxygen that is being used by the cells, the kidneys maintain constant ion concentrations, and the gastrointestinal system provides nutrients.

Humans living in hot or cold climates must undergo additional functional adjustments to maintain thermal balance; these may comprise adjustments to the rate of metabolism, avenues of heat loss, heat conservation, respiration, blood circulation, fluid and electrolyte transport, and exchange. In the same manner, persons exposed to high altitudes must adjust through physiological, chemical, and morphological mechanisms, such as increase in ventilation, increase in the oxygen-carrying capacity of the blood resulting from an increased concentration of red blood cells, and increased ability of tissues to utilize oxygen at low pressures. Failure to activate the functional adaptive processes may result in failure to restore homeostasis; which in turn results in the maladaptation of the organism and eventual incapacitation of the individual. Therefore homeostasis is a part and function of survival. The continued existence of a biological system implies that the system possesses mechanisms that enable it to maintain its identity, despite the endless pressures of environmental stresses (Proser, 1964). The complementary concepts of homeostasis and adaptation are valid at all levels of biological organization; they apply to social groups as well as to unicellular or multicellular organisms (Proser, 1964).

Homeostasis is a function of a dynamic interaction of feedback mechanisms whereby a given stimulus elicits a response aimed at restoring the original equilibrium. Several mathematical models of homeostasis have been proposed. In general, they show (as schematized in Figure 2.1) that when a primary stress disturbs the homeostasis that exists between the organism and the environment the organism must resort either to biological or cultural–technological responses in order to function normally. For example, when faced with heat stress, the organism may simply reduce its metabolic activity so all heat-producing processes are slowed down, or may increase the activity of the

Human Evolutionary Biology, ed. Michael P. Muehlenbein. Published by Cambridge University Press.

https://doi.org/10.1017/CBO9780511781193.004 Published online by Cambridge University Press



2.1. Schematization of adaptation process and mechanisms that enable individual or population to maintain homeostasis in the face of primary environmental disturbing stress. From Frisancho (1993).

heat-loss mechanisms. In either case, the organism may maintain homeostasis, but the physiological processes will occur at a different set point. The attainment of full homeostasis or full functional adaptation, depending on the nature of the stress, may require short-term responses, such as those acquired during acclimation or acclimatization, or may require exposure during the period of growth and development as in developmental acclimatization.

In theory, the respective contributions of genetic and environmental factors vary with the developmental stage of the organism – the earlier the stage, the greater the influence of the environment and the greater the plasticity of the organism (Proser, 1964; Timiras, 1972; Frisancho, 1975, 1993). However, as will be shown, the principle does not apply to all biological parameters; it depends on the nature of the stress, the developmental stage of the organism, the type of organism, and the particular functional process that is affected. For example, an adult individual exposed to high-altitude hypoxia through prolonged residence may attain a level of adaptation that permits normal functioning in all daily activities and as such we may consider him adapted. However, when exposed to stress that requires increased energy, such as strenuous exercise, this individual may not prove to be fully adapted. On the other hand, through cultural and technological adaptation, humans may actually modify and thus decrease the nature of the environmental stresses so that a new microenvironment is created to which the organism does not need to make any physiological responses. For example, cultural and technological responses permit humans to live under extreme conditions of cold stress with the result that some of the physiological processes are not altered. However, on rare occasions, humans have been able to completely avoid an environmental stress. Witness the fact that the Eskimos, despite their advanced technological adaptation to cold in their everyday hunting activities, are exposed to periods of cold stress and in response have developed biological processes that enable them to function and to be adapted to their environment.

Not all responses made by the organism can be considered adaptive. Although a given response might not be adaptive per se, through its effect on another structure or function it may prove beneficial to the organism's function. Conversely, a given adaptive response may aid the organism in one function, but actually have negative effects on other functions or structures. Thus, within all areas of human endeavor a given trait is considered adaptive when its beneficial effects outweigh the negative ones. In theory, this is a valid assumption, but in practice, due to the relative nature of adaptation, it is quite difficult to determine the true adaptive value of a given response. Every response must be considered in the context of the environmental conditions in which the response was measured and within the perspective of the length of time of the study and the subject population.

ADAPTIVE PROCESSES

The term adaptation is used in the broad generic sense of functional adaptation, and it is applied to all levels of biological organization from individuals to populations. A basic premise of this approach is that adaptation is a process whereby the organism has attained a beneficial adjustment to the environment (Lewontin, 1957; Mayr, 1963; Proser, 1964; Dubos, 1965; Baker, 1966; Lasker, 1969; Mazess, 1973; Frisancho, 1975, 1993). This adjustment can be either temporary or permanent, acquired either through short-term or lifetime processes, and may involve physiological, structural, behavioral, or cultural changes aimed at improving the organism's functional performance in the face of environmental stresses. If environmental stresses are conducive to differential mortality and fertility, then adaptive changes may become established in the population through changes in genetic composition and thus attain a level of

https://doi.org/10.1017/CBO9780511781193.004 Published online by Cambridge University Press

genetic adaptation. In this context, functional adaptation, along with cultural and genetic adaptation, is viewed as part of a continuum in an adaptive process that enables individuals and populations to maintain both internal and external environmental homeostasis. Therefore the concept of adaptation is applicable to all levels of biological organization from unicellular organisms to the largest mammals and from individuals to populations. This broad use of the concept of adaptation is justified not only in theory but also because it is currently applied to all areas of human endeavor so that no discipline can claim priority or exclusivity in the use of the term (Dubos, 1965). Functional adaptation involves changes in organ system function, histology, morphology, biochemical composition, anatomical relationships, and body composition; either independently or integrated in the organism as a whole. These changes can occur through acclimation, habituation, acclimatization or genetic adaptation.

ACCLIMATION

Acclimation refers to the adaptive biological changes that occur in response to a single experimentally induced stress (Eagan, 1963; Folk, 1974) rather than to multiple stresses as occurring in acclimatization. As with acclimatization, changes occurring during the process of growth may also be referred to as developmental acclimation (Timiras, 1972; Frisancho, 1975, 1993).

HABITUATION

Habituation implies a gradual reduction of responses to, or perception of, repeated stimulation (Eagan, 1963; Folk, 1974). By extension, habituation refers to the diminution of normal neural responses, for example, the decrease of sensations such as pain. Such changes can be generalized for the whole organism (general habituation) or can be specific for a given part of the organism (specific habituation). Habituation necessarily depends on learning and conditioning; which enable the organism to transfer an existing response to a new stimulus. A common confusion is that habituation can lead to adaptation. However, the extent to which these physiological responses are important in maintaining homeostasis depends on the severity of environmental stress. For example, with severe cold stress or low oxygen availability, failure to respond physiologically may endanger the well-being and survival of the organism. Likewise, getting used to tolerating high levels of noise implies ignoring the stress, which eventually can lead to deafness. In other words, habituation is a process that in the long run produces negative side effects.

trade offs

ACCLIMATIZATION

Acclimatization refers to changes occurring within the lifetime of an organism that reduce the strain caused by stressful changes in the natural climate or by complex environmental stresses (Eagan, 1963; Bligh and Johnson, 1973; Folk, 1974). If the adaptive traits are acquired during the growth period of the organism, the process is referred to as either developmental adaptation or developmental acclimatization (Timiras, 1972; Frisancho, 1975, 1993). Studies on acclimatization are done with reference to both major environmental stresses and several related secondary stresses. For example, any difference in the physiological and structural characteristics of subjects prior to and after residence in a tropical environment is interpreted as a result of acclimatization to heat stress. In addition, because tropical climates are also associated with nutritional and disease stresses, individual or population differences in function and structure may also be related to these factors. On the other hand, in studies of acclimation any possible differences are easily attributed to the major stress to which the experimental subject has been exposed in the laboratory. For understanding the basic physiological processes of adaptation, studies on acclimation are certainly better than those of acclimatization. However, since all organisms are never exposed to a single stress, but instead to multiple stresses, a more realistic approach is that of studying acclimatization responses. Thus, studies on both acclimation and acclimatization are essential for understanding the processes whereby the organism adapts to a given environmental condition. This rationale becomes even more important when the aim is to understand the mechanisms whereby humans adapt to a given climatic area, since humans in a given area are not only exposed to diverse stresses but have also modified the nature and intensity of these stresses, as well as created new stresses for themselves and for generations to come.

DEVELOPMENTAL ACCLIMATIZATION

The concept of developmental acclimatization (also referred to as developmental adaptation) is based upon the fact that the organism's plasticity and susceptibility to environmental influence is inversely related to developmental states of the organism, so that the younger the individual the greater is the influence of the environment and the greater the organism's plasticity (Frisancho, 1975, 1993; Frisancho and Schechter, 1997). Hence, variability in physiological traits can be traced to the developmental history of the individual.

https://doi.org/10.1017/CBO9780511781193.004 Published online by Cambridge University Press

ACCOMMODATION AND ADAPTATION

Trade offs

The term accommodation is used to describe responses to environmental stresses that are not wholly successful because, even though they favor survival of the individual, they also result in significant losses in some important functions (Waterlow, 1990). For example, subjects when exposed to a low intake of leucine for three weeks can achieve body leucine balance at the expense of reducing protein synthesis and protein turnover (Young and Marchini, 1990). Since low protein synthesis and protein turnover diminishes the individual's capacity to successfully withstand major stresses, such as infectious diseases (Frenk, 1986), under conditions of low-dietary protein intake achieving body leucine balance represents only a temporary accommodation, which in the long run is not adaptive. In other words, accommodation is a stopgap that ultimately produces negative side effects.

INDIVIDUALS VERSUS POPULATIONS

Whatever the method employed, geographical or experimental research in human adaptation is concerned with populations, not with individuals; although the research itself is based on individuals. There are two related reasons for this.

The first is a practical consideration. Studying all members of a given population, unless its size is small enough, is too difficult to be attempted by any research team. Therefore, according to the objectives of the investigation, the research centers on a sample that is considered representative of the entire population. Based on these studies, the researchers present a picture of the population as a whole, with respect to the problem being investigated.

The second reason is a theoretical one. In the study of adaptation, we usually focus on populations rather than on individuals because it is the population that survives and perpetuates itself. In the investigation of biological evolution, the relevant population is the breeding population because it is a vehicle for the gene pool, which is the means for change and hence evolution. The study of an individual phenomenon is only a means to understand the process. The adaptation of any individual or individuals merely reflects the adaptation that has been achieved by the population of which he is a member.

CULTURAL AND TECHNOLOGICAL ADAPTATION

Cultural adaptation refers to the nonbiological responses of the individual or population to modify or ameliorate an environmental stress. As such, cultural adaptation is an important mechanism that facilitates human biological adaptation (Thomas, 1975; Rappaport, 1976; Moran, 1979). It may be said that cultural adaptation during both contemporary times and in an evolutionary perspective, represents humanity's most important tool. It is through cultural adaptation that humans have been able to survive and colonize far into the zones of extreme environmental conditions. Humans have adapted to cold environments by inventing fire and clothing, building houses, and harnessing new sources of energy. The construction of houses, use of clothing in diverse climates, certain behavioral patterns, and work habits, represent biological and cultural adaptations to climatic stress. The development of medicine, from its primitive manifestations to its high levels in the present era, and the increase of energy production associated with agricultural and industrial revolutions are representative of human cultural adaptation to the physical environment.

Culture and technology have facilitated biological adaptation, yet they have also created, and continue to create, new stressful conditions that require new adaptive responses. A modification of one environmental condition may result in the change of another, and such a change may eventually result in the creation of a new stressful condition. Advances in the medical sciences have successfully reduced infant and adult mortality to the extent that the world population is growing at an explosive rate, and unless world food resources are increased, the twenty-first century will witness a world famine. Western technology, although upgrading living standards, has also created a polluted environment that may become unfit for good health and life. If this process continues unchecked, environmental pollution will eventually become another selective force to which humans must adapt through biological or cultural processes, or else face extinction. Likewise, cultural and technological adaptation has resulted in the rapid increase of energy availability and has decreased energy expenditure; causing a disproportionate increase in the development of degenerative diseases associated with metabolic syndrome. This mismatch between biology and lifestyle threatens our survival as human species (Eaton et al., 2002). Therefore, adaptation to the world of today may be incompatible with survival in the world of tomorrow unless humans learn to adjust their cultural and biological capacities.

GENETIC ADAPTATION AND ADAPTABILITY

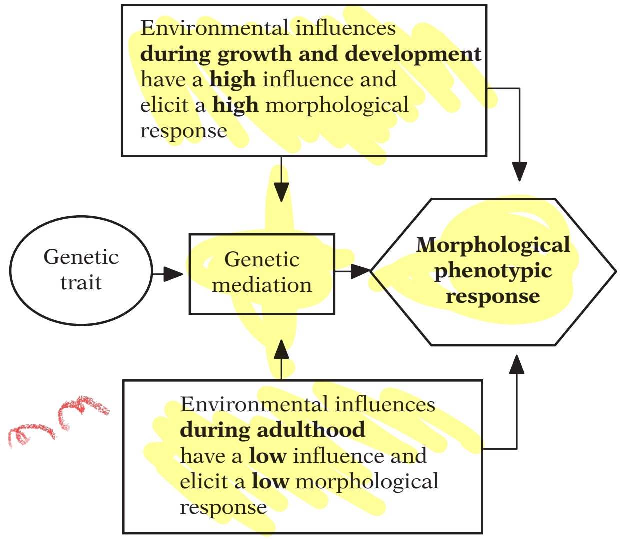
Genetic adaptation refers to specific heritable characteristics that favor tolerance and survival of an individual or a population in a particular total environment. A given biological trait is considered genetic

https://doi.org/10.1017/CBO9780511781193.004 Published online by Cambridge University Press

when it is unique to the individual or population and when it can be shown that it is acquired through biological inheritance. A genetic adaptation becomes established through the action of natural selection (Livingstone, 1958; Neel, 1962; Mayr, 1997; Neel et al., 1998). Natural selection refers to the mechanisms whereby the genotypes of those individuals showing the greatest adaptation or "fitness" (leaving the most descendents through reduced mortality and increased fertility) will be perpetuated, and those less adapted to the environment will contribute fewer genes to the population gene pool. Natural selection favors the features of an organism that bring it into a more efficient relationship with its environment. hmm Those gene combinations fostering the best-adapted phenotypes will be "selected for," and inferior genotypes will be eliminated.

The selective forces for humans, as for other mammals, include the sum total of factors in the natural environment. All the natural conditions, such as hot and cold climates and oxygen-poor environments, are potential selective forces. Food is a selective force by its own abundance, eliminating those susceptible to obesity and cardiac failures, or by its very scarcity, favoring smaller size and slower growth. In the same manner, disease is a powerful selective agent, favoring in each generation those with better immunity. The natural world is full of forces that make some individuals, and by inference some populations, better adapted than others because no two individuals or populations have the same capacity of adaptation. The maladapted population will tend to have lower fertility and/or higher mortality than that of the adapted population.

The capacity for adaptation (adaptability) to environmental stress varies between populations and even between individuals. The fitness of an individual or population is determined by its total adaptation to the environment – genetic, physiological, and behavioral (or cultural). Fitness, in genetic terms, includes more than just the ability to survive and reproduce in a given environment; it must include the capacity for future survival in future environments. The long-range fitness of a population depends on its genetic stability and variability. The greater the adaptation, the longer the individual or population will survive, and the greater the advantage in leaving progeny resembling the parents. In a fixed environment, all characteristics could be under rigid genetic control with maximum adaptation to the environment. On the other hand, in a changing environment a certain amount of variability is necessary to ensure that the population will survive environmental change. This requirement for variability can be fulfilled either genetically or phenotypically or both. In most populations a compromise exists between the production of a variety of genotypes and individual flexibility. Extinct populations are those which were unable to meet the challenges of new conditions. Thus, contemporary fitness requires both genetic uniformity and genetic variability.



2.2. Schematization of interaction of genetic trait and environment and the phenotypic morphological outcome. Morphological and physiological diversity reflects the responses and adaptations that the organism makes to a particular environment during and after development. From Frisancho (1993).

Contemporary adaptation of human beings is both the result of their past and their present adaptability (Lasker, 1969; Frisancho, 1993). It is this capacity to adapt that enables them to be in a dynamic equilibrium in their biological niche. It is the nature of the living organism to be part of an ecosystem whereby it modifies the environment and, in turn, is also affected by such modification. The maintenance of this dynamic equilibrium represents homeostasis; which, in essence, reflects the ability to survive in varying environments (Dubos, 1965; Proser, 1964). The ecosystem is the fundamental biological entity – the living individual satisfying its needs in a dynamic relation to its habitat. In Darwinian terms, the ecosystem is the setting for the struggle for existence, efficiency and survival are the measures of fitness, and natural selection is the process underlying all products (Proser, 1964).

In general, the morphological and functional features reflect the adaptability or capacity of the organism to respond and adapt to a particular environment (Figure 2.2). The effect and responses to a given environmental condition are directly related to the developmental stage of the organism; so that the younger the age, the greater the effect and the greater the flexibility to respond and adapt. Conversely, the later the age and, especially during adulthood, the effect of the environment is less likely to be permanent and the capacity to respond and adapt is also diminished when compared to a developing organism.

https://doi.org/10.1017/CBO9780511781193.004 Published online by Cambridge University Press

MULTILEVEL SELECTION AND EVOLUTION OF CO-OPERATION

Ever since Darwin (1871) indicated that the competition between groups can lead to selection of cooperative behavior, the concept of multilevel selection has been developed. He stated that, "there can be no doubt that a tribe including many members who were always ready to give aid to each other and to sacrifice themselves for the common good, would be victorious over other tribes; and this would be natural selection" (Darwin, 1871, p. 166). Over many years, Wilson and colleagues have been the main proponent of the idea of group selection (Wilson, 1975; Sober and Wilson, 1998; Traulsen and Nowak, 2006). It is assumed that group selection is an important organizing principle that permeates evolutionary processes from the emergence of the first cells to development of nations. According to multilevel selection, groups consist of genetically unrelated individuals, and successful groups attract new individuals, which learn the strategies of others in the same group. A population can be subdivided into groups, and the individuals interact with other members of the group, and depending on their reproductive fitness, individuals can lead to larger groups that split more often. In other words, higher-level or group selection emerges as a by-product of individual reproduction.

A fundamental condition for the success of the group, therefore, must be co-operation among individuals, and thus group selection favors co-operative altruistic behavior and opposes defectors. The fitness of an individual, and the group at large, also depends on the altruistic behavior of nonrelatives. When an altruist gives an alarm call, it benefits not only his or her relatives, but also other unrelated members of the group because a primate troop does not only include relatives. Thus, altruism can be selected if these nonrelated individuals can be counted on to reciprocate the favor when the need arises. A recipient of an altruistic behavior who fails to reciprocate is a cheater. Studies of nonhuman primates indicate that a cheater may gain in the short run by receiving aid without any costs to their own fitness (Strier, 2000). However, reciprocity is necessary for future support in the long run because the cheater's fitness is lower when compared to the individual who reciprocated. In view of the fact that primates constantly need to protect themselves from neighboring communities and predators, one can assume that reciprocal altruism must have been selected for because it enhanced their fitness, not because the animals are conscious of their motives or the reproductive consequences of their behavior. Mathematical models indicate that a single co-operator has a greater fixation probability than a single defector (Traulsen and Nowawk, 2006). Hence, this simple condition ensures that selection favors co-operators and opposes defectors.

The concept of group selection has been a major tenet of behavioral ecology. The major premise of behavioral evolutionary ecology is that genetic and behavioral traits are two distinct expressions of a single evolutionary process (Trivers, 1971; Cronk, 1991; Strier, 2000; Silk, 2001). In behavioral ecology, behaviors are treated like any other biological trait and are potentially subject to natural selection. The processes involved in behavioral evolution are equivalent to those in genetic evolution: natural selection influences the frequency of a trait transmitted from parent to offspring through differential fertility and mortality. In the evolutionary perspective, biological structures have been custom tailored to motivate behaviors that are likely to enhance individual fitness. Therefore, behavioral variants with a high fitness have been favored and these perpetuate the evolutionary origin of fitness-enhancing biological traits. It follows then, that the behavioral traits that enhance fitness also accentuate biological fitness. In other words, a change occurring in one system entails a change in the fitness governing evolution in the other system. Therefore, both genetic and behavioral selection tend to favor those existing variants whose net effect is to increase the average fitness of the individual and population to the prevailing conditions. Studies of primates indicate that they use a diversity of behaviors that increase the likelihood of gaining access to mates and guarantee the survival of their offspring; which, in turn, insures the passing of their traits to the next generation. In this context, behavioral actions that lead to a higher reproductive success will become adaptive and the genes associated with such behavior will be transferred to the next generation faster than those that are less adaptive. Therefore, the differences in fitness between individuals and populations will determine the behavioral pattern of a given primate group. In other words, a specific behavioral strategy that contributes to the survival and reproductive fitness of the individual – and eventually the population – becomes part of the genetic milieu of the species.

In summary, co-operation and altruism evolve by group selection or multilevel selection. Human behavioral ecology rests upon a foundation of evolutionary theory, which include sexual selection, whereby individuals within one sex secure mates and produce offspring at the expense of other individuals within the same sex, which can cause changes in gene frequency across generations that are driven at least in part by interactions between related individuals referred to as kin selection, and be expressed as the sum of an individual's own reproductive success.

https://doi.org/10.1017/CBO9780511781193.004 Published online by Cambridge University Press

CURRENT DIRECTIONS IN ADAPTATION RESEARCH

In the 1970s I postulated the hypothesis of developmental adaptation to explain the enlarged lung volume and enhanced aerobic capacity that characterize the Andean high altitude natives. According to the developmental adaptation hypothesis, "adult biological traits are the result of the effects of the environment and the physiological responses that the organism makes during the developmental state" (Frisancho, 1970, 1975, 1977). This concept is based upon the fact that the organism's plasticity and susceptibility to environmental influence is inversely related to developmental states of the organism, so that the younger the individual the greater is the influence of the environment and the greater the organism's plasticity (Frisancho, 1975, 1977, 1993). Hence, variability in physiological traits can be traced to the developmental history of the individual (Figure 2.2). Currently this concept has been applied to explain the variability in adult behavioral traits such as in learning and crime and delinquency (Yueh-Au Chien, 1994; Sroufe et al., 2005; Kruger et al., 2008), in sensory inputs and auditory spatial processing (Martin and Martin, 2002), in tolerance to surgical intervention (Faury et al., 2003), in variability in oxygen consumption and mitochondrial membrane potential in energy metabolism of rat cortical neurons (Schuchmann et al., 2005), and in variability in increased risk of adult obesity and cardiovascular problems associated with the metabolic syndrome (Barker, 1994). A common denominator of all these studies is that humans and many other organisms are conditioned by experiences during development and a developmental experiences is an important contributor to variability in adult phenotypic behavioral and biological traits.

In this section I will summarize the evidence supporting the applicability of the concept of developmental adaptation to account for the origins of the high risk of the adult metabolic syndrome incorporating information derived from a thrifty gene, thrifty phenotype, and epigenetics. The evolution of the metabolic syndrome is also discussed at length in Chapter 30 of this volume.

DEVELOPMENTAL ADAPTATION AND THE THRIFTY GENOTYPE

Neel and colleagues (Neel, 1962; Neel et al., 1998) attempted to explain the epidemic proportions of diabetes in Native American populations, such as the Pima Native Americans, by postulating the existence of a "thrifty gene" that increased the risk of type II diabetes. According to this hypothesis, the basic defect in diabetes mellitus was a quick insulin trigger. Insulin's main function is to assist in the homeostasis of glucose in the blood. Specifically, when blood glucose levels are too high, the pancreas releases insulin to increase tissue uptake of glucose, thus reducing blood glucose levels. Conversely, when blood glucose levels are low, the organism secretes glucagon and growth hormone, which in turn, induce the release of stored glucose and fatty acids into the blood stream raising serum glucose levels. The insulin response is to activate an uptake of glucose into the muscle cells for storage, and in liver cells it influences the conversion of glucose to fatty acids for storage in fat (adipose) tissue. This response was an asset during times of abundance because it would allow an individual to build-up energy reserves more quickly and thus better survive times of food scarcity. Under these conditions, the thrifty gene was selected to regulate efficient intake and utilization of fuel stores. In other words, during periods of food shortage and famine, those with the thrifty genotype would have a selective advantage because they relied on larger, previously stored energy to maintain homeostasis; whereas those without "thrifty" genotypes would be at a disadvantage and less likely to survive and reproduce. However, under modern conditions of abundant food and sedentary lifestyle, this genotype becomes perversely disadvantageous. With a constant abundance of food, insulin levels remain high, resulting in tissues becoming less sensitive to the effects of insulin. This reduced sensitivity to the effects of insulin results in chronically elevated blood glucose levels type II diabetes and related chronic health problems (e.g., obesity).

A test of the genetic predisposition to type II diabetes involved a comparative study of the Pima Indians of southern Arizona and the Pima Indians of the Sierra Madre mountains of northern Mexico (Knowler et al., 1990; Price et al., 1992). These two groups, which were separated 700 to 1000 years ago, differ in their lifestyle. The Arizona Pima live under conditions of access to a high fat, highly refined diet and low energy expenditure. In contrast, the Mexican Pima still pursue a much more traditional lifestyle and have a diet based on the occasional intake of lamb and poultry, but mainly on beans, corn, and potatoes, grown by traditional, and physically very energy-demanding, techniques. These two groups differ significantly in the frequency of obesity and diabetes. The Arizona Pima adults have a body mass index (BMI) of 33.4 kg/m^2; compared to a BMI of 24.9 kg/m^2 in the Mexican Pima (Ravussin et al., 1994). Likewise, in the Arizona Pima 37% of men and 54% of women were diabetic, while in the Mexican Pima only 2 of 19 women and 1 of 16 men were diabetic (Knowler et al., 1990; Price et al., 1992). In other words, although the Mexican Pima share the "thrifty gene" with Arizona Pima, their increased frequency of

https://doi.org/10.1017/CBO9780511781193.004 Published online by Cambridge University Press

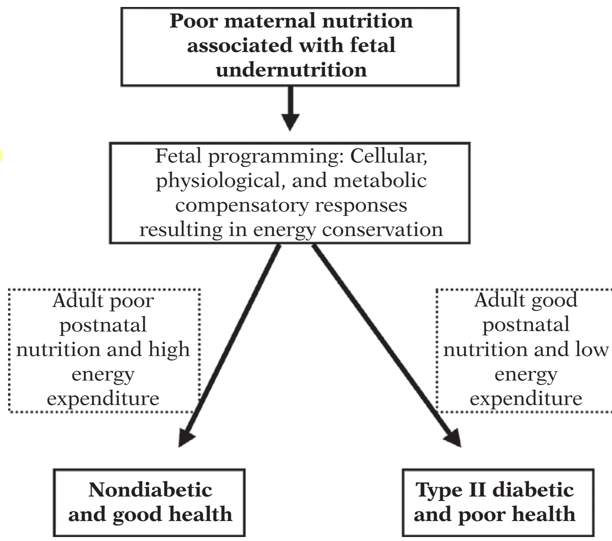
obesity and diabetes is more evidence that an abundance of fatty foods and modern sedentary lifestyles are the real culprits. Thus, it is not the presence of a "thrifty gene" alone that results in increased rates of diabetes, but rather the interaction with modern dietary and lifestyle conditions that results in increased rates of the chronic health problems.

In summary, the thrifty genotype hypothesis has been used to explain the epidemic levels of obesity and diabetes among non-Western populations, such as South Pacific Islanders, sub-Saharan Africans, Native Americans in the southwestern United States, Inuit, Australian aborigines, etc. (Eaton et al., 1988; O'Dea, 1991); all of whom were newly introduced to industrialized diets and environments. The fact that the frequency of type II diabetes has recently increased among Europeans that were not subjected to periodic famines cannot be attributed to the action of a so-called "thrifty" gene.

DEVELOPMENTAL ADAPTATION AND THE THRIFTY PHENOTYPE

Recently, Barker and colleagues (Barker, 2007; Hales and Barker, 1992) have reported an inverse relationship between birthweight and the risk of hypertension, cardiovascular disease, and type II diabetes in adulthood when the individual is well nourished postnatally. To account for these observations, Barker and colleagues proposed that adverse effects in utero induce cellular, physiological, and metabolic compensatory responses, such as insulin resistance, high blood plasma levels of fatty acids, which result in energy conservation and reduced somatic growth that enable the fetus to survive undernutrition. This response is referred to as the thrifty phenotype hypothesis (Armitage et al., 2005). These responses that were adaptive under poor prenatal conditions become a problem if food becomes abundant. In this view, thrifty physiological mechanisms are adaptive in nutritionally poor environments, but in rich environments are maladaptive. That is, what was positive under reduced availability of nutrients, particularly during periods of rapid development, becomes negative in rich environments because it facilitates nutrient absorption and hence increases the risk of adult obesity and the suite of risk factors for cardiovascular disease known as the metabolic syndrome (Figure 2.3).

In summary, it appears that nutrition and other environmental factors during prenatal and early postnatal development influence cellular plasticity; thereby altering susceptibility to adult cardiovascular disease, type II diabetes, obesity, and other chronic diseases referred as the adult metabolic syndrome. This hypothesis is supported by the finding that the offspring of women who were starved and became pregnant during



2.3. The thrifty phenotype. The risk of type II diabetes and metabolic syndrome in adulthood is associated with prenatal undernutrition resulting in efficient physiological adaptation that becomes detrimental when food is abundant and energy expenditure is low.

the Dutch famine of World War II were found to have impaired glucose tolerance and increased adiposity in adulthood (Stein et al., 1975, 2007).

DEVELOPMENTAL ADAPTATION AND EPIGENETICS

Epigenetics refers to the transmission of phenotypic traits from one generation to the next that do not depend on differences in DNA sequence (Waddington, 1952; Jablonka, 2004; Holliday, 2006). During the last two decades, there has been an accumulation of observations indicating that the expression of DNA traits can be affected by environmental factors acting during development. Specifically, experimental studies showed that identical twin mice differ in the color of fur; one has brown fur and will grow up to be lean and healthy, while the other has yellow fur and becomes obese and prone to cardiovascular disease. The different phenotypes are due to the addition of a methyl group (-CH_3); which is referred to as methylation.

Methylation

Methylation refers to the altering of the genetic environment through the addition of a methyl group (-CH_3) to the fifth position of cytosine, which is largely confined to CpG dinucleotides. This addition, by modifying the CpG islands, prevents signaling molecules from reaching the promoter site to turn the gene on and prevent the expression of the dark coat color. In other words, the additional methyl group attaches

https://doi.org/10.1017/CBO9780511781193.004 Published online by Cambridge University Press

to and shuts off the gene that controls dark fur color and allows the yellow color to be expressed. Thus, the process of methylation works as a kind epigenome that dictates which genes in the genome are turned on and which are not. This process can differ even between identical twins.

Recently, experimental studies indicate that bisphenol A (BPA) can alter gene expression and affect adult phenotype by modifying CpG methylation at critical epigenetically labile genomic regions (Waterland and Jirtle, 2004). Bisphenol A is used in the production of polycarbonate and plastic containers and in the organism acts like the body's own hormones. Thus, there is concern that long-term exposure to BPA may induce chronic toxicity in humans (vom Saal and Hughes, 2005). Fortunately, the effects of methylation are not permanent but reversible, as shown by the fact that the yellow agouti (Avy), whose diet was supplemented with folic acid, vitamin B_{12}, choline, betaine, and zinc, counteracted the DNA methylation and changed coat color from yellow to dark brown (Dolinoy and Jirtle, 2008), which is associated with a low risk of cardiovascular disease.

Transgenerational epigenetic effects

It has been suggested that the epigenetic modifications brought about by parental conditions may be expressed even in grandchildren. Extensive records of a population in Overkalix cohorts, northern Sweden, found an association between grandparental prepubertal slow growth periods (SGP) or rapid growth periods (RGP), and parental periods of low or high food availability, with grandchildren's mortality and disease risk (Kaati et al., 2007). If the SGP of the grandparent was during a period of high food availability, then the male grandchild had reduced longevity but an increased mortality. The extent to which these associations represent multigenerational epigenetic effects is unwarranted, in part because ruling out genetic and societal confounders, and in the absence of molecular evidence, is extremely difficult. Hence, future research must be focused on long-term transgenerational studies whereby many birth cohorts are studied using intensive prenatal and perinatal genotyping across generations. Only then can variability in the expression of phenotypic traits can be attributed to epigenetic changes.

In summary, epigenetic effects exist that are not necessarily adaptive, and in many of these cases, the inherited phenotype is actually detrimental to the organism. Environmental exposure to nutritional, chemical, and physical factors can alter gene expression and affect adult phenotype: a process known as epigenetics. In all of these studies, the extent of DNA methylation depends on and is inversely related to the developmental state of the organism; so that the younger the individual, the greater the epigenetic marks, including CpG methylation. Despite the great interest in molecular genetics, there is scant incontrovertible evidence indicating epigenetic effects in humans. Considering society's increased concern about environmental pollutants, this area of research should be a good direction for human biologists.

OVERVIEW

The term *adaptation* encompasses the physiological, cultural, and genetic adaptations that permit individuals and populations to adjust to the environment in which they live. These adjustments are complex, and the concept of adaptation cannot be reduced to a simple rigid definition without oversimplification. The functional approach in using the adaptation concept permits its application to all levels of biological organization from unicellular to multicellular organisms, from early embryonic to adult stages, and from individuals to populations. In this context, human biological responses to environmental stress can be considered as part of a continuous process whereby past adaptations are modified and developed to permit the organism to function and maintain equilibrium within the environment to which it is daily exposed.

The mechanisms for attaining full functional adaptation include acclimation, acclimatization, habituation, and accommodation. The role played by each of these processes depends on the nature of the stress or stresses, the organ system involved, and the developmental stage of the organism. It is emphasized that the goal of the organism's responses to a given stress is to maintain homeostasis within an acceptable normal range with itself and with respect to other organisms and the environment (as schematized in Figure 2.1). Such adaptations are usually reversible, but the reversibility depends on the developmental stage of the organism at which the adaptive response occurs and the nature of the environmental stress. This characteristic allows organisms to adapt to a wide range of environmental conditions. Furthermore, an adaptation is always a compromise between positive and negative effects. Every adaptation involves a cost. The process of adaptation is always positively beneficial; without which the organism would be worse off, however the organism has to pay a price for the benefit. The benefit derived from a given response depends on the circumstances and the conditions where it occurs. As recently pointed out (Young and Marchini, 1990), every adaptation involves a choice. For example, a man has 6 hours in which to walk 11 km. If he walks slowly, he saves energy expenditure, and therefore it may be adaptive if the energy resources are limited; however

https://doi.org/10.1017/CBO9780511781193.004 Published online by Cambridge University Press

he has no time left to do anything else. On the other hand, if he walks fast, he saves time at the cost of using more energy. Thus, the adaptive importance of a given type of response depends on the conditions.

The concept of developmental adaptation has become a major focus for studying the origins of human diversity (Figure 2.2). The applicability of this research strategy is based upon the premise that human biological responses to environmental stress represent a continuous process whereby past adaptations are modified and developed to permit the organism to function and maintain equilibrium within the environment to which it is daily exposed. From the studies of the thrifty genotype and thrifty phenotype, and their relationship to the etiology of metabolic syndrome, it is evident that what was positive under reduced availability of nutrients, particularly during periods of rapid prenatal development, becomes negative in rich environments. Research in epigenetics may provide the bridge between the thrifty genotype and thrifty phenotype to unravel the interrelations of how the impact of early diet helps how the organism adapts to a given environmental condition that differs in nutritional resources; resulting in the diverse phenotypic expression of physiology, body size, and health risk of contemporary and past populations. The study of individuals exposed to stressful conditions in natural and laboratory environments is one of the most important approaches for understanding the mechanisms whereby human populations adapt to a given environment. Knowledge of human adaptation is basic in our endeavors to understand past and present human variation in morphology and physiological performance. The insights we have gained during the last decade have stimulated new approaches to study human adaptation, not only for understanding behavior, but of how ecology shapes function both in the present and in the past, and for understanding variability in the immune system, thermo-regulation, coping with limited and excessive amounts of foods, low oxygen pressure, and high and low solar radiation.

DISCUSSION POINTS

1. What are the four processes of functional adaptation?
2. Why does the organism have to respond to environmental stimuli? Give examples.
3. When does a given functional adaptation become a genetic adaptation?
4. Discuss the role of multiple-level selection in the expression of biological and behavioral traits.
5. Compare accommodation and adaptation. Give specific examples.
6. Discuss how technological and cultural adaptations have created new environmental stresses. Give examples.
7. Compare developmental and adult adaptation. Which is more likely to be reversible and why?
8. Discuss the applicability of the concept of developmental adaptation to the hypothesis of thrifty genotype and thrifty phenotype that account for the increased frequency of the adult metabolic syndrome among native and nonnative populations.
9. Discuss the relationship of the concept of developmental adaptation to the field of epigenetics.

REFERENCES

Armitage, J. A., Taylor, P. D. and Poston, L. (2005). Experimental models of developmental programming: consequences of exposure to an energy rich diet during development. *Journal of Physiology*, **565**, 3–8.

Baker, P. T. (1966). Human biological variation as an adaptive response to the environment. *Eugenics Quarterly*, **13**, 81–91.

Barker, D. J. P. (1994). *Mothers, Babies, and Disease in Later Life*. London: BMJ Publishing.

Barker, D. J. P. (2007). The origins of the Developmental Origins Theory. *Journal of Internal Medicine*, **261**, 412–417.

Bligh, J. and Johnson, K. G. (1973). Glossary of terms for thermal physiology. *Journal of Applied Physiology*, **35**, 941–961.

Cronk, L. (1991). Human behavioral ecology. *Annual Review of Anthropology*, **20**, 25–53.

Darwin, C. (1871). *The Descent of Man and Selection in Relation to Sex*, 2nd edn. London: Murray.

Dolinoy, D. C. and Jirtle, R. L. (2008). Environmental epigenomics in human health and disease. *Environmental and Molecular Mutagenesis*, **49**, 4–8.

Dubos, R. (1965). *Man Adapting*. New Haven, CT: Yale University Press.

Eagan, C. J. (1963). Introduction and terminology. *Federation Proceedings*, **22**, 930–932.

Eaton, S. B., Konner, M. and Shostak, M. (1988). Stone agers in the fast lane: chronic degenerative diseases in evolutionary perspective. *American Journal of Medicine*, **84**, 739–749.

Eaton, S. B., Strassman, B. I., Nesse, R. M., et al. (2002). Evolutionary health promotion. *Preventative Medicine*, **34**, 109–118.

Faury, G., Pezet, M., Knutsen, R. H., et al. (2003). Developmental adaptation of the mouse cardiovascular system to elastin haplo insufficiency. *Journal of Clinical Investigation*, **112**, 1419–1428.

Folk, G. E. Jr (1974). *Textbook of Environmental Physiology*. Philadelphia: Lea and Febiger.

Frenk, S. (1986). Metabolic adaptation in protein-energy malnutrition. *Journal of the American College of Nutrition*, **5**, 371–381.

Frisancho, A. R. (1970). Developmental responses to high altitude hypoxia. *American Journal of Physical Anthropology*, **32**, 401–407.

Frisancho, A. R. (1975). Functional adaptation to high altitude hypoxia. *Science*, **187**, 313–319.

Frisancho, A. R. (1977). Developmental adaptation to high altitude hypoxia. *International Journal of Biometeorology*, **21**, 135–146.

Frisancho, A. R. (1993). *Human Adaptation and Accommodation*. Ann Arbor, MI: University of Michigan Press.

Frisancho, A. R. and Schechter, D. E. (1997). Adaptation. In *History of Physical Anthropology: an Encyclopedia*, vol. 1. Garland, TX: Garland Press, pp. 6–12.

Hales, C. N. and Barker, D. J. (1992). Type 2 (non-insulin-dependent) diabetes mellitus: the thrifty phenotype hypothesis. *Diabetologia*, **35**, 595–601.

Holliday, R. (2006). Epigenetics: a historical overview. *Epigenetics*, **1**, 76–80.

Jablonka, E. (2004). Epigenetic epidemiology. *International Journal of Epidemiology*, **33**, 929–935.

Kaati, G., Bygren, L. O., Pembrey, M., et al. (2007). Transgenerational response to nutrition, early life circumstances and longevity. *European Journal of Human Genetics*, **15**, 784–790.

Knowler, W. C., Pettitt, D. J., Saad, M. F., et al. (1990). Diabetes mellitus in the Pima Indians: Incident, risk factors and pathogenesis. *Diabetes/Metabolism Research and Reviews*, **6**, 1–27.

Kruger, D. J., Reisch, T. and Zimmerman, M. A. (2008).Time perspective as a mechanism for functional developmental adaptation. *Journal of Social, Evolutionary, and Cultural Psychology*, **2**, 1–22.

Lasker, G. W. (1969). Human biological adaptability. *Science*, **166**, 1480–1486.

Lewontin, R. C. (1957). The adaptations of populations to varying environments. In *Cold Spring Harbor Symposia on Quantitative Biology*, vol. 22. Boston, MA: Cold Spring Harbor Laboratory of Quantitative Biology.

Livingstone, F. B. (1958). Anthropological implications of sickle-cell gene distribution in West Africa. *American Anthropologist*, **60**, 533–562.

Martin, P. and Martin, M. (2002). Proximal and distal influences on development: The model of developmental adaptation. *Developmental Review*, **22**, 78–96.

Mayr, E. (1963). *Animal Species and Evolution*. Cambridge, MA: The Belknap Press of Harvard University Press.

Mayr, E. (1997). The objects of selection. *Proceedings of the National Academy of Sciences of the United States of America*, **94**, 2091–2094.

Mazess, R. B. (1973). Biological adaptation: aptitudes and acclimatization. In *Biosocial Interrelations in Population Adaptation*, E. S. Watts, F. E. Johnson and G. W. Lasker (eds). The Hague: Mouton, pp. 9–18.

Moran, E. F. (1979). *Human Adaptability: an Introduction to Ecological Anthropology*. North Scituate, MA: Duxbury Press.

Neel, J. V. (1962). Diabetes mellitus: A "thrifty" genotype rendered detrimental by "progress"? *American Journal of Human Genetics*, **14**, 353–362.

Neel, J. V., Weder, A. B. and Julius, S. (1998). Type II diabetes, essential hypertension, and obesity as "syndromes of impaired genetic homeostasis": the "thrifty genotype" hypothesis enters the twenty-first century. *Perspectives in Biology and Medicine*, **42**, 44–74.

O'Dea, K. (1991). Traditional diet and food preferences of Australian aboriginal hunter-gatherers. *Philosophical Transactions of the Royal Society of London. Series B*, **334**, 233–240.

Price, R. A., Lunetta, K., Ness, R., et al. (1992). Obesity in Pima Indians. Distribution characteristics and possible thresholds for genetic studies. *International Journal of Obesity and Related Metabolic Disorders*, **16**, 851–857.

Proser, C. L. (1964). Perspectives of adaptation: theoretical aspects. In *Handbook of Physiology*, vol. 4, D. B. Dill, E. F. Adolph and C. G. Wilber (eds). Washington, DC: American Physiological Society, pp. 11–26.

Rappaport, R. A. (1976). Maladaptation in social systems. In *Evolution in Social Systems*, J. Friedman and M. Rowlands (eds). London: Gerald Duckworth, pp. 49–71.

Ravussin, E., Valencia, M. E., Esparza, J., et al. (1994). Effects of a traditional lifestyle on obesity in Pima Indians. *Diabetes Care*, **17**, 1067–1074.

Schuchmann, S., Buchheim, K., Heinemann, U., et al. (2005). Oxygen consumption and mitochondrial membrane potential indicate developmental adaptation in energy metabolism of rat cortical neurons. *European Journal of Neuroscience*, **21**, 2721–2732.

Silk, J. (2001). Ties that bind: the role of kinship in primate societies. In *New Directions in Anthropological Kinship*, L. Stone (ed.). Lanham, MD: Rowman and Littlefield Publishers, pp. 71–92.

Sober, E. and Wilson, D. S. (1998). *Unto Others: the Evolution and Psychology of Unselfish Behavior*. Cambridge, MA: Harvard University Press.

Sroufe, L. A., Egeland, B., Carlson, E., et al. (2005). *The Development of the Person: the Minnesota Study of Risk and Adaptation from Birth to Adulthood*. New York: Guilford Press.

Stein, Z., Susser, M., Saenger, G., et al. (1975). *Famine and Human Development. The Dutch Hunger Winter of 1944–45*. New York: Oxford University Press.

Stein, A. D., Kahn, H. S., Rundle, A., et al. (2007). Anthropometric measures in middle age after exposure to famine during gestation: Evidence from the Dutch famine. *American Journal of Clinical Nutrition*, **85**, 869–876.

Strier, K. B. (2000). *Primate Behavioral Ecology*. Boston: Allyn and Bacon.

Thomas, R. B. (1975). The ecology of work. In *Physiological Anthropology*, A. Damon (ed.). New York: Oxford University Press, pp. 59–79.

Timiras, P. S. (1972). *Developmental Physiology and Aging*. New York: Macmillan.

Traulsen, A. and Nowak, M. A. (2006). Evolution of cooperation by multilevel selection. *Proceedings of the National Academy of Sciences of the United States of America*, **103**, 10952–10955.

Trivers, R. L. (1971). The evolution of reciprocal altruism. *Quarterly Review of Biology*, **46**, 35–57.

Vom Saal, F. S. and Hughes, C. (2005). An extensive new literature concerning low-dose effects of bisphenol A shows the need for a new risk assessment. *Environmental Health Perspectives*, **113**, 926–933.

Waddington, C. H. (1952). *Epigenetics of Birds*. Cambridge: Cambridge University Press.

Waterland, R. and Jirtle, R. (2004). Early nutrition, epigenetic changes at transposons and imprinted genes, and enhanced susceptibility to adult chronic diseases. *Nutrition*, **20**, 63–68.

Waterlow, J. C. (1990). Nutritional adaptation in man: General introduction and concepts. *American Journal of Clinical Nutrition*, **51**, 259–263.

Wilson, D. S. (1975). A theory of group selection. *Proceedings of the National Academy of Sciences of the United States of America*, **72**, 143–146.

Young, V. R. and Marchini, J. S. (1990). Mechanisms and nutritional significance of metabolic responses to altered intakes of protein and amino acids, with reference to nutritional adaptation in humans. *American Journal of Clinical Nutrition*, **51**, 270–289.

Yueh-Au Chien, C. (1994). *Developmental Adaptation of Social Learning Theory: the Etiology of Crime and Delinquency*. Denver, CO: University of Colorado Press.