Human adaptations to the physical environment

During human evolution, people have settled in all the climatic zones of the world. They have had to adjust to very different environments – to extremes of temperature, of solar radiation, of humidity and of seasonal fluctuations in climate, and even to atmospheric pressure less than half that at sea level. Considering that our precursors were confined to the tropics or subtropics and, for the early forms at least, to wooded or open savannas, this global spread involved some remarkable adaptations. Still more remarkable is the fact that modern human populations still belong to a single, fully interbreeding species.

Early European explorers and settlers often found it very difficult to survive in new parts of the world and believed that the native people they met possessed special inherited characteristics that accounted for their survival. However, many of them later discovered that if they adopted the clothing, housing, food and behaviour of the indigenous inhabitants their chances of survival were greatly enhanced – a reflection of the basic mechanisms that allow humans to survive in a variety of environments. In a new environment, humans have the ability to invent and transmit ways of recreating part of the physical environment lived in by our ancestors. For example, although the Inuit (Eskimos) live in the Arctic, their combination of clothing, habitation and behaviour make the air temperature next to any individual's body generally comparable to that in the tropics. The principal exception occurs in the hands and feet, as even the best-insulated gloves and boots cannot prevent severe cooling under arctic winter conditions unless the individual is constantly active.

Despite human ingenuity in recreating a tropical environment, artificial microenvironments are seldom perfect replicas of our ancestral habitats. Until recently, no one could reproduce the year-round ultraviolet levels of tropical savannas, the sea-level atmospheric pressures in high mountains, or the low levels of air moisture in savannas. For populations to cope with new and challenging habitats there must be an interaction between their genetic structure and their physiological response to allow them to survive a variety of environmental stresses. Both natural selection and physiological plasticity contribute to our ability to cope with environmental stress, and their interaction is so close that it is meaningless to attempt to disentangle the two mechanisms. The science of human adaptability involves the study of such adjustments, which may involve variability in disease susceptibility, food preference and social system. Specifically biological responses to the physical environment are the subject of this chapter.

Anatomy and climate

An association between human physical characteristics and the environment was first noticed in ancient Greece. People from the interior of Africa were discovered to have dark skins and it was assumed that this difference was caused by the intensity of the tropical sun. Despite these early observations on humans, associations between climate and morphology were first measured in other animals. In 1847, the Swedish anatomist C. Bergmann formulated a rule that within a polytypic warm-blooded species, the body size of the subspecies usually increases with the decreasing mean temperature of its habitat. In 1877, another rule was formulated by J.A. Allen: 'In warm-blooded species, the relative size of exposed portions of the body decreases with the decrease of mean temperature.'

Body size

These rules were not applied to humans until the middle of the twentieth century, when large surveys showed that there was a strong association between human body size and average annual temperature. Bergmann's and Allen's rules can hence be applied to the human species. However, the cause of such relationships is still debated.

Climate affects disease patterns and food availability. Some of the associations may arise from stunting of growth in modern tropical populations, an explanation that excludes genetic differences between populations as a cause of differences in size and shape. Adequate diet and the control of infectious disease have indeed led to an increase in adult height and weight in some populations. However, there is no evidence that human populations from different parts of the world would be nearly identical in size if given the same food and exposure to disease. Furthermore, diet and disease do not affect body proportions in adults. If population differences are indeed genetic, then they probably reflect the action of natural selection.

Differences in food, survival behaviour and disease arising from climatic differences may each have contributed to selection on size and shape. Climate also has an important direct effect: in all warm-blooded species (mammals and birds), large-bodied animals with shorter extremities tolerate cold climates better because heat loss is reduced in relation to energy production and the storage of heat. In addition, in humans and other species that use sweat for cooling, a high ratio of skin surface to body mass is advantageous in heat regulation if sufficient water is available.
People living in cold areas of the world characteristically have a heavier build than those in warmer areas, as this distribution map shows (the weights are averages for indigenous males). Some Polynesian populations are an exception. They live in a hot and humid environment yet have the heaviest body weights of any population in the world. Key: ■, very high (69.5 kg and above); □, high (44.5—69.4 kg); ○, fairly high (69.5—84.4 kg); ×, medium (54.5—69.4 kg); ○, fairly low (49.5—64.4 kg); □, low (44.5—49.4 kg); ▼, very low (44.4 kg and below).

There are some more specific associations of morphology with climate. Broad, short noses tend to be characteristic of hot tropical environments, while long thin noses are found in cold climates. The amount of water vapour in the air is the climatic factor most strongly associated with nose shape, possibly because long thin noses aid in moistening dry air before it reaches the lungs.

**Skin colour**

Skin colour is the best understood of all the associations between external characteristics and climate. Many factors contribute to individual differences in this character, but the most important is the amount of the black and brown pigment called melanin in the dermal layer. Melanin levels are primarily under genetic control, and differences in skin colour between populations may largely be attributed to three to five allelic pairs of genes. Exposure to ultraviolet light will increase the amount of melanin in the skin of all populations, and, for unknown reasons, sunbathing appears to increase skin melanin by about the same degree in all groups. We do not notice this in dark-skinned individuals, because there is only a small absolute change in light reflectance.

As the Greeks suspected, there is a close relationship between skin colour and solar radiation throughout the world. Some populations, such as the American Indians and the Mongoloid peoples in Asia, do not show much geographic variation in relation to radiation intensity. In contrast, the relationship is so close in European populations that skin colour is lightest in people from the Baltic, which has the cloudiest weather in Europe.

The most convincing selective mechanism is associated with the capacity of melanin to block ultraviolet light. Light-
SWEATING – THE HUMAN RESPONSE TO HEAT

Many mammals sweat, but the human system is the most effective. For at least three reasons:

1. The heat produced is produced by evaporation of sweat on the skin, thereby reducing the temperature of the body. Most other mammals cool by sweating through sweat glands located on specific parts of the body, such as the tail, which are not as effective.

2. Human skin is composed of more than 300 sweat glands, which do not vary significantly among human populations, and differences appear to be the result of acclimatization rather than genetics.

3. Our lack of body hair and the fact that sweat glands are confined to the skin, which evaporates from the heated skin, means that the skin is not as effective in cooling as it is for other mammals, which have more body hair.

The efficiency of the human cooling system means that we are more likely to be affected by heat stress, especially in hot and humid climates. People have adapted by developing various strategies to mitigate heat stress, such as wearing lighter clothing, seeking shade, and using fans or air conditioning. In some cultures, people also consume cold drinks and use cooling techniques such as spraying water or using wet cloths to cool down.

Regarding evolutionary adaptations, humans in hot and arid environments have developed strategies such as wearing protective clothing and seeking shade to reduce heat stress. Additionally, some cultures have developed social norms and practices to help individuals cope with heat stress, such as communal bathing or sharing cool drinks.

The case of skin melanin shows how difficult it is to identify the details of human adaptive responses to climate. It is no doubt true that in other, more obscure adaptations, the mechanisms that allowed people to become established in all parts of the world have been at least as complex as this.

Skinned individuals may suffer from skin damage in very sunny areas and often develop potential skin cancer if exposed to ultraviolet rays for long periods. Shorter exposures can lead to possibly serious skin damage and infection in spite of tanning. As discussed in Chapter 7.6, dense layers of melanin in the skin can be disadvantageous in places with low ultraviolet radiation because they inhibit the synthesis of vitamin D, which takes place when ultraviolet radiation penetrates the skin. Deficiency in this vitamin can lead to poor ossification of bone and permanent skeletal deformation or rickets.

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SKIN TEMPERATURE

All humans can acclimatize to heat stress, as shown in this experiment. When men walk at a speed of 30 km/h for 60 to 90 minutes in a temperature of 40°C and relative humidity 23%, pulse rate falls, and body and skin temperatures fall.

Levels of heat produced through running provide a different kind of heat load. Although sweating is an efficient means of cooling, it becomes less effective at higher temperatures and humidity. The most stressful heat climates in the world are probably those of the deserts of the Western United States and the Middle East, where temperatures can reach 50°C or higher. In such environments, people rely on shade and water to stay cool.

Heat tolerance

As most early human evolution occurred in the tropics or subtropics and our fossil ancestors occupied semi-arid environments, it is not surprising that modern humans are well adapted to rather hot and dry conditions. Although camels exceed our abilities, humans are one of the few mammals that can survive moderately active during the day in the hottest regions of the world. This ability results primarily from an efficient sweating mechanism (see Box). Humans are genetically well adapted to hot, dry conditions, and, with the possible exception of a decrease in body size in tropical forests, there is no evidence of differing genetic adaptations to heat in different populations. In spite of this, most groups have developed behavioural specialisations that reduce exposure to uncomfortable heat.

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Cold tolerance

Although early human populations were established in quite cold climates long before the evolutionary appearance of Homo sapiens, modern humans have a very low tolerance of cold. Because we lack insulation such as fur and hair, nude exposure to still air temperatures as high as 26 °C causes constriction of blood vessels in the skin. At around 20 °C, increased heat production, manifest as shivering, begins, and at 6 °C inactive young adults may suffer such a reduction in brain temperature that they become unconscious in a few hours.

Most non-human primates have relatively poor cold tolerance but some bear cold better than humans do. For example, colonies of Japanese macaques (Macaca fuscata) successfully inhabit the cold wintry environments of central Japan. In contrast, without the culture that produced clothing and fire and without access to some kind of shelter, our predecessors were limited to places where it never became colder than about 10 °C.

Subcutaneous fat, which is more uniformly distributed in infants than in adults, has a low thermal conductivity and reduces loss of central body heat to the skin in cold conditions. The extent of cold protection provided by this layer of fat is directly related to its thickness, so that temperatures that cause violent shivering and a drop in core temperatures in thin individuals may cause only mild skin discomfort in those who are fat. Fat is particularly beneficial in cold water, because neither fur nor clothing provides significant insulation in these conditions. It is not surprising that all successful swimmers of the English Channel have heavy fat layers and that many of them are women (who tend to have markedly more fat than men do).

Because the skin is the primary agent of heat loss and body mass is the main agent of heat production, a small skin area in relation to body mass improves tolerance to cold.

Our relatively large adult size, therefore, aids cold tolerance, but it also follows that infants and young children require more protection against cold.

Although humans have the ability to acclimatise to heat, there is no evidence that short-term exposure to cold improves cold tolerance. Intermittent exposure for several months or years to conditions that produce shivering may reduce the intensity of this muscular response, but this does not reduce heat loss. Although most people suffer less discomfort from cold after long-term exposure, this appears to be a product of psychological habituation rather than a significant change in cold tolerance. The most important adaptations that allowed humans to inhabit temperate zones were the cultural adjustments that led to the creation of an artificial microenvironment like that of the tropics. Nevertheless, there are real population differences in the physiological responses of individuals to cold stress on hands and feet.

Adaptations to cold

If an adult immerses a finger in freezing water, there is an immediate stoppage of blood flow to the affected part. Among Europeans the subsequent response varies. For some, finger temperature will quickly drop to near water temperature and stay there. For others, it will drop to near water temperature but then rise and fall in short cycles; still others have a finger temperature that stays substantially above 0 °C and shows little cycling. These differences are associated with the degree and timing of the constriction of arteries to the hand.

Similar responses occur when the whole hand or foot is exposed to cold. A continuous constriction of the blood vessels might appear to be highly adaptive, as it keeps heat loss to a minimum. However, when temperatures are below freezing, the affected part would freeze without heat from the general circulation. Even in temperatures above freezing, a few days of cold-induced vasoconstriction will kill the skin cells. The most adaptive response for each individual depends on the length and severity of exposure to cold.

There are also real differences among populations exposed to cooling of this kind. Men of African black origin have a much lower average finger temperature in cold water than do European men and show less temperature cycling. Europeans in their turn have a less effective response than do the Inuit and highland Peruvian American Indians. During cold nights in central Australia, the blood vessels of the Aborigines constrict so that blood flow into the arms and legs is reduced to an extent sufficient to decrease total heat loss from the body significantly. This means that, while sleeping in conditions cold enough to raise the metabolic heat production of Europeans by 15 per cent, Australian Aborigines remain at basal metabolic levels. Their extreme vasoconstriction allows skin temperature to fall to 2.5 °C lower than that of Europeans, so reducing heat loss.
vapour decline in a nearly linear fashion. Radiation increases, and, perhaps most important, atmospheric pressure declines. Within the altitudinal range of human habitation, the decline in pressure is nearly linear and the proportions of nitrogen and oxygen in the air remain constant. At 5000 metres, atmospheric pressure is only half that at sea level, so that each breath fills the lungs with only half as many oxygen atoms.

Some lowlanders can stay conscious for a few hours at altitudes just above 8000 metres, but a rapid ascent to only 3000 metres produces mental distress and even loss of consciousness for many people. Professional mountaineers find that a few days at intermediate altitudes improve their performance, but a stay of several months above 5000 metres leads to a rapid decline in fitness. Although some permanent human settlements in the tropics reach this height, attempts to establish yet higher permanent settlements have failed, even when the residents have normally lived above 4000 metres.

Although the decline in air pressure is linear with altitude, its physiological influence is not. At 1000 metres, there is no discernible effect. By 1500 metres, the major effect is a slight diminution in the birth weight of infants born to mothers who spent their pregnancy at that altitude. At 2500 metres, there is a reduction in athletic performance among newcomers; infants are even smaller at birth, and more of them have defects in their blood circulation that prevent full oxygenation of the blood. For lowlanders disembarking at the 4000-metre-high airport at La Paz, Bolivia, the effects of altitude are soon apparent. Most develop rapid heartbeats, shortness of breath, a headache.

The relative importance of acclimatisation and genetics in the responses of different populations to finger cooling is not yet known. An increase in vasoconstriction occurs after a month or two of exposure of the hands to cold, and studies of North Atlantic fishermen suggest that cold exposure over many years may enhance this response. Even so, the fishermen’s response is not as great as that of the Inuit and North Americans of European and West African heritage have different responses even though they have spent their lives in similar microclimates.

Whatever the genetic basis of population differences in the response of limbs to cold, they are climatically adaptive. Vasoconstriction in central Australian Aborigines (and perhaps in other tropical savanna groups) allows them to exploit a savanna with cold nights without the need for clothing, housing or extra food. For the Inuit in a bitterly cold environment, clothing and housing give an adequate body core temperature, but even mittens and boots cannot prevent frostbite unless the vasoconstrictive response is relaxed to allow the central body heat to rearm fingers and toes.

**Attitude tolerance**

Several changes in the physical environment occur with increasing altitude. Average air temperature and water

![Graph showing the oxygen dissociation curve of haemoglobin](image)
and possibly faintness. A hearty meal usually produces severe nausea. Vigorous exercise may have more serious consequences, because the combination of such a low atmospheric pressure and heavy exercise can cause an accumulation of fluid in the lungs or increase fluid pressure inside the skull.

The non-linear effects of altitude arise from the non-linear oxygen-binding ability of the haemoglobin in our blood. At an altitude of 2000 metres, haemoglobin can carry 96 per cent of the oxygen that it can at sea level. However, at 4000 metres it can carry only about 88 per cent of sea-level values; an additional 2000-metre gain in height hence reduces the oxygen level in the blood by twice as much as the initial 2000 metres. At very high altitudes, there is a greatly increased breathing rate. This certainly helps to raise the oxygen level in the lungs, but also reduces blood carbon dioxide and leads to headaches, faintness and irregular breathing.

For the high-altitude visitor, the acute symptoms usually disappear within a few days, because of an acclimatisation that produces better regulation of breathing. The newcomer to 4000 metres may then feel perfectly adjusted to altitude but physiological tests show that he or she has lost some 20 to 30 per cent of the maximal work capacity at sea level because of a reduced ability to deliver oxygen to the muscles. This loss of aerobic capacity persists for at least a year or two at high altitudes but is immediately reversed upon return to sea level.

With continuing residence at high altitude, the number of red blood cells rises for several months. This was once thought to be an adaptation because it increases the oxygen-carrying capacity of the blood, even though it slows blood circulation. However, research now suggests that the red-cell count may be primarily an indication of the amount of altitude stress an individual experiences; there is no evidence that this rise in the red-cell count increases aerobic capacity.

Adaptations to high altitude

High-altitude American Indians in the Andean mountains show many of the same altitude effects as lowlanders. Mothers produce smaller infants at high than at low altitudes, and, even with comparable nutrition and care, children grow more slowly during infancy and adolescence. Despite these similarities, adults show a much higher aerobic capacity than do even long-term migrants from the lowlands. This difference arises mainly from the greater efficiency in extracting oxygen from the air by the highlanders. Maximal aerobic capacity of the highlanders does not increase when they descend to low altitude.

It is not known what produces this high oxygen-extractive ability. Perhaps the unusually large chest and lungs of these highland American Indians help, but comparable efficiencies are found in the Sherpas of Nepal, who do not have unusually large chests. There may be a genetic element in the highlander's ability, as such individuals who grow up at sea level lose only half as much oxygen-extracting ability at high altitude compared with native lowlanders. However, physiological flexibility is also involved; adults brought to high altitudes during early childhood (but not those who moved during adolescence) have an oxygen-extractive capability close to that of the native highlanders. There is hence a long-term or developmental acclimatisation to low oxygen tensions.

Microenvironments – the clue to human adaptability

Without doubt, the major adaptations enabling human populations to live in such a variety of physical environments is the creation of microenvironments that approximate to the conditions in which we evolved. This replication is, however, imperfect. Furthermore, although human populations have great potential for acclimatisation, natural selection has also produced variations in skin colour, body size, nose shape and other traits that improve our ability to function in particular environments. Selection has also resulted in differences in physiology, such as peripheral vasoconstriction and oxygen extraction, which improve survival in harsh environments such as the Arctic and the Andes. In short, natural selection, physiological plasticity and the evolution of culture have combined to render the human species uniquely able to adapt to a great diversity of physical environments.

See also ‘Natural selection in humans’ (p. 284)

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