9.3 Thermoregulation

The chemical reactions that give rise to life require a narrow range of temperatures. The habitats that harbour life, however, experience drastic changes in temperature, and organisms must cope with these changes to survive. From deserts in Australia, Africa, and the United States (where the temperature can rise to over 50 °C) to the Arctic tundra (where the temperature can drop to –40 °C), organisms survive and even thrive by using unique systems of internal temperature regulation. If an organism fails to regulate its temperature, however, it can succumb to the extreme temperatures that cause proteins to unfold and lose their functional form or freeze intracellular fluid and cell organelles. In this section, you will learn about the mechanisms, structures, and behavioural adaptations that enable animals to regulate their internal temperature.

Temperature Regulation: A Built-in Thermostat

thermoregulation the regulation of internal temperature by negative feedback mechanisms

As you learned in Section 9.2, temperature regulation, or **thermoregulation**, is a process that is based on negative feedback mechanisms. Temperature receptors, called thermoreceptors, detect any deviations in the external and internal temperatures from an internal set point and then trigger behavioural and physiological responses that act to maintain the internal temperature at the set point. These responses include adjustments in the rate of exothermic reactions within the body (such as metabolism) and adjustments in the rate of thermal energy exchange through the surface of the body. Individual species have adapted to their unique environments through many different methods of thermoregulation, but the mechanisms of thermal energy exchange are universal.

Mechanisms of Thermal Energy Exchange

Regardless of the organism, almost all thermal energy exchange occurs at the surface where the body comes in contact with the external environment. Like any physical body, animals absorb thermal energy if they are cooler than their environment, and release thermal energy if they are warmer than their environment. This exchange occurs through one of four mechanisms: conduction, convection, radiation, and evaporation.

Conduction is the flow of thermal energy between molecules that are in direct contact. Animals lose thermal energy when they come in contact with a colder body. They gain thermal energy when they come in contact with a warmer body. Convection is the transfer of thermal energy within a fluid (liquid or gas). Radiation is the transfer of thermal energy in the form of electromagnetic radiation. All objects, regardless of temperature, radiate thermal energy, and this radiation increases with the temperature of the object. Animals are constantly losing thermal energy to the environment through radiation. However, they also gain thermal energy through radiation, usually by absorbing it from the Sun. The transfer of thermal energy can be aided by evaporation. The most familiar example of this is sweat. Water on the surface of the skin evaporates, absorbing thermal energy from the skin and causing it to cool.

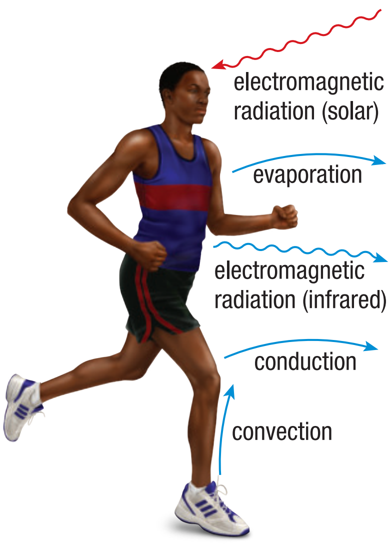

Figure 1 The flow of thermal energy into (red) and out of (blue) a runner on a warm, sunny day when the air temperature is 32 °C.

All animals exchange thermal energy with their environment through these four mechanisms, which usually act simultaneously. **Figure 1** illustrates the interaction of these mechanisms in a runner. Assuming that the air in contact with the runner's skin is cooler than the runner's body temperature, the air gains thermal energy by conduction. This is aided by convection and evaporation. As warm air next to the runner's skin surface rises and is replaced by cooler air, convection increases the rate at which thermal energy is lost through conduction. Similarly, as the runner sweats, evaporation occurs and aids in the conduction of thermal energy. The runner's body is also losing energy through outward infrared radiation. At the same time, the runner is gaining thermal energy from solar radiation. A smaller amount is gained by conduction between the runner's feet and the ground. As well, a large amount of thermal energy is generated from the biochemical reactions in the runner's body, which are fuelling the runner. To maintain a stable body temperature, the amount of thermal energy leaving the body must equal the total of the amount produced within the body and the amount absorbed from the environment.

Homeotherms and Poikilotherms, Ectotherms and Endotherms

All animals can be categorized into two groups based on the stability of their body temperature. Animals that maintain a stable internal temperature, regardless of external conditions, are referred to as **homeotherms**. Birds and mammals are homeotherms because they can maintain a body temperature that is often above the ambient environmental temperature. Animals with a body temperature that varies considerably in response to external conditions are referred to as **poikilotherms**. Fish, amphibians, reptiles, and most invertebrates are poikilotherms because their body temperature varies with, and sometimes matches, the temperature of their external environment. Although the body temperature of poikilotherms can vary considerably, these organisms have some degree of control over their body temperature.

homeotherm an animal that maintains a stable body temperature regardless of the temperature of the external environment

poikilotherm an animal whose body temperature varies with, and often matches, the temperature of the external environment

Homeotherms and poikilotherms have different strategies aimed at regulating their body temperature, and they have different responses to changes in external temperature. There are two general types of mechanisms that animals use to regulate their body temperature. Internal physiological mechanisms that generate thermal energy to regulate body temperature are referred to as endothermy. Animals that use these mechanisms are called **endotherms**. Behavioural mechanisms that involve using external sources of energy are considered ectothermy. Animals that use these mechanisms are called **ectotherms**. They regulate their body temperature by absorbing thermal energy from their environment.

endotherm an animal that maintains its body temperature by internal mechanisms

ectotherm an animal that maintains its body temperature by absorbing thermal energy from the environment

Endotherms are more successful than ectotherms at maintaining a stable body temperature, but they are not necessarily more successful animals. The two types of animals have different responses to changes in external temperature. Endotherms can obtain thermal energy from the environment under some conditions, but all ectotherms generate at least some thermal energy from internal reactions. Some ectotherms (for example, those that live in a habitat with a stable temperature) maintain a fairly constant body temperature and are considered homeotherms. Some endotherms allow their body temperature to vary considerably during certain times of day or in different seasons and are considered poikilotherms.

The strategies that are used by ectotherms and endotherms are very different, and each strategy of thermoregulation has its advantages and disadvantages. The difference between endotherms and ectotherms is determined by their metabolic responses to the environmental temperature (**Figure 2**). The metabolic rate of a resting mouse increases steadily as the environmental temperature falls from 25 °C to 10 °C. By contrast, the metabolic rate of a resting lizard typically decreases over the same temperature range. Because of this dependence on thermal energy generated by metabolic processes, endotherms use about 80 % of the energy from their food to maintain their body temperature. Ectotherms, on the other hand, do not use their metabolism to heat or cool themselves, and their energy requirements are much lower than those of endotherms. Ectotherms require much less energy for the same body mass as endotherms.

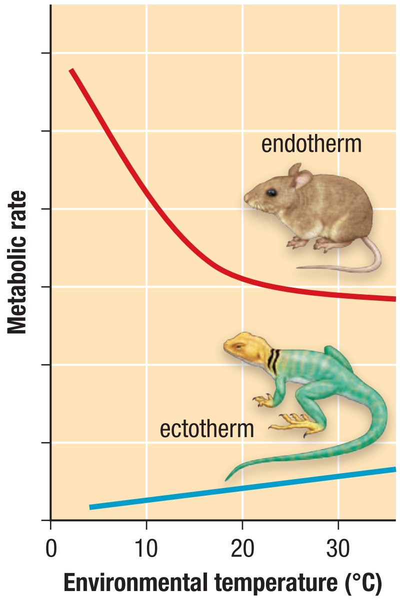

Figure 2 The metabolic rate of an endotherm rises at low environmental temperatures, generating more thermal energy in the body. The metabolic rate of an ectotherm falls at low environmental temperatures, conserving energy.

Endotherms keep their bodies at an optimal temperature by regulating the amount of thermal energy that is generated by internal reactions and the amount of thermal energy that is exchanged with the environment. Endotherms can therefore remain fully active over a wider range of temperatures than ectotherms, but they require a nearly constant supply of energy. Cold weather does not prevent them from foraging, mating, or escaping from predators, but it does increase their energy and food needs. The body temperature of ectotherms tends to fluctuate with the environmental temperature, so ectotherms are usually less active in cold weather. When the environmental temperature drops too low, they become inactive. They move slowly and are unable to capture food or escape from predators. However, their food needs are lower under these circumstances because their metabolic rates are reduced, so they do not have to look actively for food and expose themselves to predators.

Ectotherms

Ectotherms include many diverse groups of animals, with different abilities to maintain a stable internal temperature. Invertebrates, fish, amphibians, and reptiles are ectotherms, and each has its own method of thermoregulation. Aquatic invertebrates have poor thermoregulation abilities, and their body temperature rarely varies from the external temperature of the water. They live in, or seek, warm or temperate environments where the temperature allows them to have optimal physiological performance. Most fish also have a body temperature that is similar to their surroundings, but they are able to use behavioural adaptations to regulate their internal temperature. For example, the thermal layers of deeper lakes and ponds provide thermoregulatory opportunities for freshwater fish. They remain in deep, cooler water during hot summer days, and they move to shallower areas to feed during early morning and late evening when the air and water temperatures are lower.

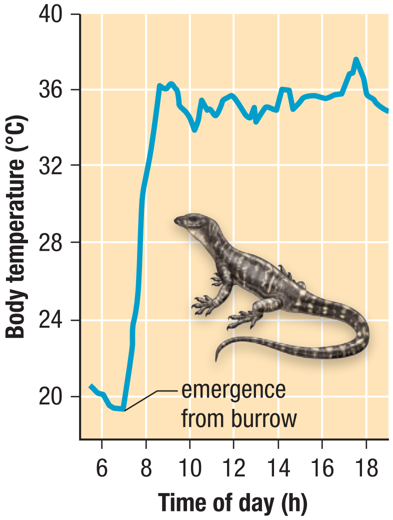

Figure 3 This graph shows the rapid change in a lizard's body temperature when it moves from its cool burrow into the sunlight.

Amphibians and lizards rely heavily on conduction and radiation to regulate their body temperature. The most common thermoregulatory behaviour for many lizards is moving between sunny and shady areas. The classic example is a lizard sunning itself on a hot rock. This makes use of both mechanisms of thermal energy transfer and allows the lizard to reach its temperature set point quickly (**Figure 3**). If the lizard becomes too hot, it will retreat to a cooler area to lower its temperature. This continuous and frequent raising and lowering of body temperature allows lizards and some amphibians to keep an almost constant temperature comparable to endotherms.

In addition to thermoregulatory behaviours, some lizards use physiological responses similar to those of endotherms. For example, Galapagos marine iguanas can increase the blood flow to areas of the skin exposed to infrared radiation. The blood warms quickly, and thermal energy is carried to the organs in the core of the body. When the skin is cooled, the blood flow to the skin is restricted, thereby preventing the loss of thermal energy to the external environment.

thermal acclimatization the process by which an animal gradually adjusts to temperature changes in its environment

Many ectotherms undergo seasonal physiological changes. This adaptation, called **thermal acclimatization**, allows them to adjust gradually to changes in external temperature and usually accounts for seasonal variations. For example, in the summer, the bullhead catfish (*Ameiurus* species) can survive in water temperatures as high as 36 °C but not below 8 °C. In the winter, however, the bullhead cannot survive water temperatures above 28 °C but can tolerate temperatures near 0 °C. In some cases, the mechanisms involved can be rather unusual. The wood frog (*Rana sylvatica*), for example, lives in temperate forests where winter temperatures typically drop below freezing. It spends the winter in a frozen state, with no heartbeat, breathing, or brain activity. This state is facilitated by the release of glucose from glycogen stores in the liver and a suspension of the function of insulin, resulting in an accumulation of glucose in the frog's cells. The extremely high concentration of glucose within the cells lowers the freezing point of water. This creates a "slurry" of ice crystals and sugar that prevents the cells from being damaged. When the ice melts, the wood frog thaws and shows little sign of cellular damage.

Endotherms

As you learned in Unit 2, the mitochondria in the cells produce the energy for all of the biochemical processes. However, all of the energy that is available in the glucose molecules does not go into the production of ATP. Some of it is converted into thermal energy. Scientists have estimated that up to 25 % of the basal metabolic rate of most endotherms can be attributed to the energy that is consumed to offset this loss of thermal energy. The body cells of endotherms contain far more mitochondria, and they are proportionately larger than the body cells of ectotherms.

Birds and mammals make up the majority of endotherms, and they have the most elaborate thermoregulatory mechanisms of all animals. Their temperature set points lie within a narrow range: 39 to 42 °C for birds and 36 to 39 °C for mammals. A given species may experience seasonal environmental variations of 70 °C or more, depending on its habitat, but can survive these variations and thrive in almost any environment.

Thermoreceptors on the skin and within the body alert the nervous system to any changes in external or internal temperature. If the core temperature drops below the set point, the body responds by constricting the arteries that supply blood to the skin. This reduces the amount of thermal energy that is lost to the environment by radiation. Shivering and "goose bumps" also regulate the internal temperature. Muscle contractions during shivering generate thermal energy, and the raised hairs in the skin trap air, helping to maintain warmth.

If the core temperature rises above the set point, the body relaxes arteries to allow excess thermal energy to exit via the skin. In a small number of mammals, including humans, the skin contains large numbers of sweat glands. These secrete sweat onto the skin, which removes thermal energy as it evaporates. **Figure 4** summarizes the thermoregulatory responses in humans.

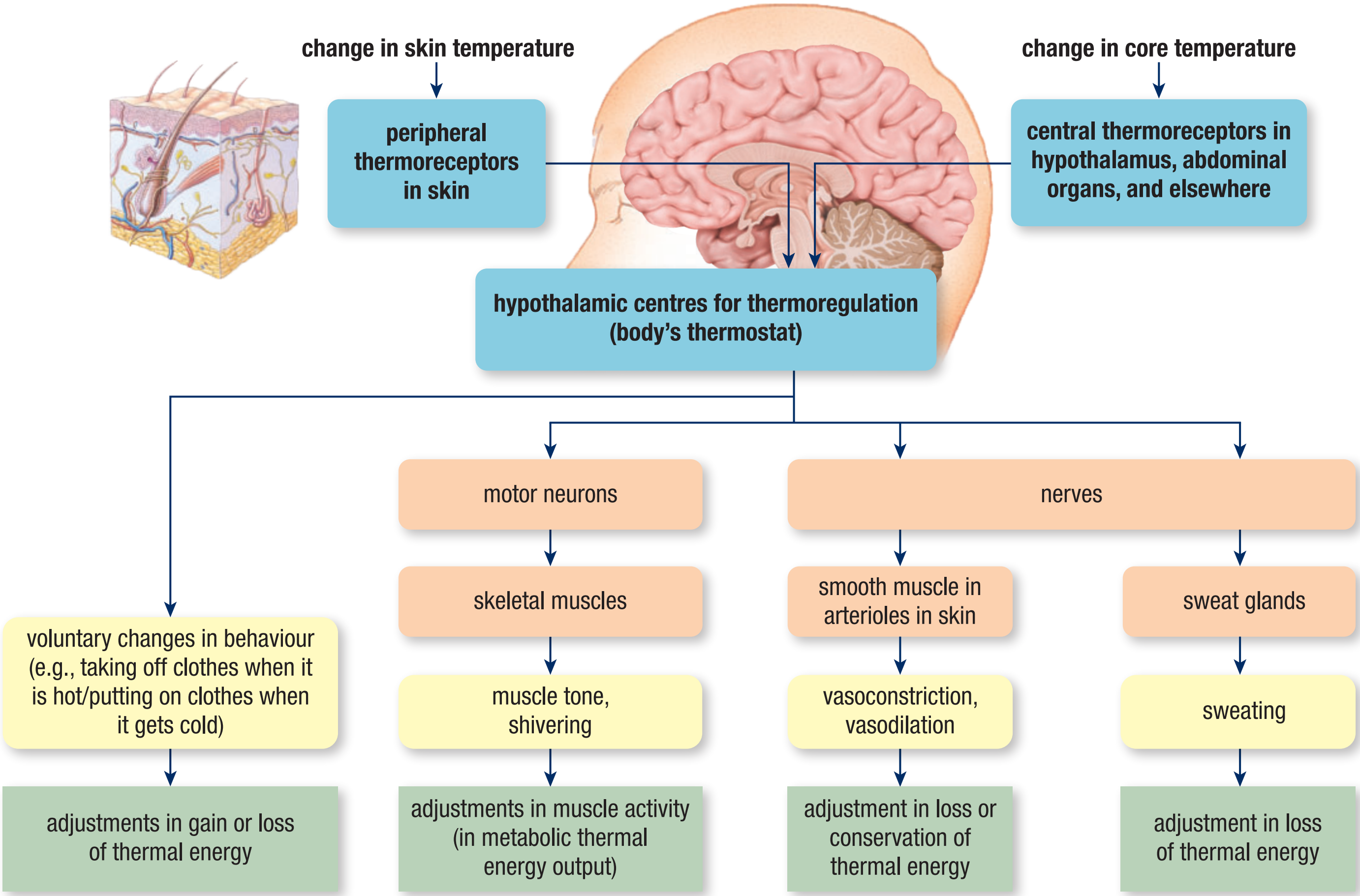

Figure 4 Behavioural and physiological responses of mammals to changes in skin and core temperature

TORPOR, HIBERNATION, AND ESTIVATION

Some endotherms have special behavioural and physiological adaptations that help them thrive in even the harshest climates. These endotherms could be considered poikilotherms because their body temperature varies considerably. One of these adaptations is **torpor**, a sleeplike state in which the metabolic rate and body temperature drop in response to variations in daily temperature. An animal may enter into torpor nightly or even daily, as in the case of some bats and other nocturnal animals. The hummingbird uses daily torpor. During the day, the hummingbird is actively feeding, but it cannot feed at night, and so it becomes inactive and allows its body temperature to drop in order to conserve energy. During the night, the hummingbird can use one-fiftieth the energy that it uses during the day and its heart rate can drop from 1260 bpm to 50 bpm. This conserves enough energy for it to survive overnight without feeding.

torpor a short-term state of reduced metabolic rate and body temperature that reduces the demand for energy during the night or day

hibernation a state of greatly reduced metabolic rate and activity that enables an animal to survive the winter by reducing the demand for energy when food is unavailable

estivation a state of torpor that enables an animal to survive the summer by reducing the demand for energy

In cold climates, many endotherms enter a prolonged state of torpor tied to the seasons. This change is usually triggered by a change in the length of the day, which signals the transition between summer and winter. Extended torpor of small mammals during the winter is called **hibernation**, a state of inactivity and significantly decreased metabolic rate. Hedgehogs, groundhogs, and squirrels can experience a 20 °C or greater drop in body temperature during hibernation. The Arctic ground squirrel, for example, hibernates for eight to ten months of the year. It is the only known mammal whose body temperature falls below freezing. During hibernation, its body temperature can dip to as low as –3 °C. At two- to three-week intervals, without rousing from its sleep, the ground squirrel will shiver and shake to bring its body temperature up to a near-normal 36.5 °C. It then stops shivering and its body temperature quickly falls again.

In large mammals, the depth of the torpor is less pronounced and is not considered to be true hibernation by some scientists. The core temperature of a bear drops only a few degrees to around 30 to 32 °C. Although sluggish, bears will frequently awaken—every day almost, and even more often after the young are born—but they do not eat or drink.

Some animals enter seasonal torpor during the summer, when the environmental temperature is high and water is scarce. This is called **estivation**. Animals such as the ground squirrel remain inactive in the cooler temperatures of their burrows during extreme summer heat. Other ectotherms, such as lungfish, many toads and frogs, and some desert-dwelling lizards, survive hot climates by digging into the soil and entering a state of estivation that lasts throughout the hot, dry season.

Figure 5 Curling into a ball helps dogs conserve thermal energy.

OTHER THERMOREGULATORY STRUCTURES AND BEHAVIOURS

In addition to the mechanisms already examined, there are many other thermoregulatory behavioural and physiological adaptations used by different species. For example, many insects can use exercise to maintain a core body temperature above the environmental temperature. Such species are known as exercise endotherms. The honey bee can contract antagonistic flight muscles without moving its wings. This method of generating thermal energy is only efficient above 9 to 14 °C. Below this temperature, the bee relies on ectothermic behaviours.

Dogs have an uneven distribution of fur that aids thermoregulation. The fur is thickest over the back and sides of the body and the tail, and thinnest over the belly and the legs. In cold weather, a dog curls up, pulls in its limbs, wraps its tail around its body, and buries its nose in its tail so that only the best-insulated surfaces are exposed to the air (**Figure 5**). Other mammals, such as the muskox and the Arctic fox, adapt to seasonal temperature fluctuations by developing a thick fur coat in the winter and shedding it in the summer.

Certain animals have developed specialized adaptations to lower their body temperature. Some birds fly on a hot day with their legs extended. Dogs and other mammals pant to expel thermal energy from the mouth. Elephants and jackrabbits dissipate thermal energy from the large surface area of their ears (**Figure 6**).

Figure 6 A large surface area of skin with blood vessels close to the surface helps jackrabbits dissipate thermal energy.

Research This

Professor Popsicle

Skills: Researching, Communicating — SKILLS HANDBOOK A4.1

Dr. Gordon Giesbrecht of the University of Manitoba investigates the effects of long-term exposure to cold on the human body. Also known as "Professor Popsicle," Dr. Giesbrecht has dropped his body temperature to below 35 °C over 33 times to monitor the effects of hypothermia. Further research shows that children are better able to survive the effects of hypothermia than adults are.

1. Using the Internet and other sources, investigate the work of Dr. Giesbrecht and his research on hypothermia.

A. Describe the different levels of hypothermia, as well as the risks and symptoms of each level. T/I

B. Identify the treatments for each level of hypothermia. T/I

C. Which is more dangerous: hypothermia from air exposure or hypothermia from water exposure? Explain. T/I C

D. Define frostbite, and describe the difference between frostbite and hypothermia. T/I C

E. Summarize your findings in a report. You are free to choose the format for your report. For example, you could choose to do a written report, an oral presentation, or a slide show. C

WEB LINK

9.3 Review

Summary

- Thermal energy is transferred between animals and their environment by conduction, convection, radiation, and evaporation.
- Homeotherms are animals that maintain a fairly constant internal temperature regardless of the external temperature. The internal body temperature of poikilotherms varies in response to the temperature of the external environment.
- Ectotherms are animals that regulate their body temperature by absorbing thermal energy from the environment. Invertebrates, fish, amphibians, and reptiles are ectotherms.
- Endotherms are animals that regulate their body temperature with the internal mechanisms of thermal energy generation, conservation, and dissipation. Endotherms include birds and mammals.
- Both ectotherms and endotherms have behavioural mechanisms that they use to regulate their body temperature.
- Thermal acclimatization is the gradual adjustment to seasonal variations in temperature.

Questions

1. Describe thermoregulation in humans. What occurs when the body temperature is too low? What occurs when it is too high? K/U
2. When an animal wakes in the morning, its core temperature is below the set point. How might an ectotherm and an endotherm respond to this situation differently? T/I
3. Describe the last time that you experienced a notable change in your body temperature. How did your body react? A
4. Using reputable sources, research the use of therapeutic hypothermia for certain medical conditions, such as cardiac arrest, stroke, and brain injury. Briefly summarize your findings. T/I C
5. In the Unit 4 opener, you learned about endurance runner Ray Zahab's expedition across the Sahara Desert. Ray has also run across the frozen Siberian tundra. Describe the physiological dangers of this expedition compared with the Saharan expedition. T/I
6. Extremities such as the hands and feet are usually cooler than 37 °C, which is the body's core temperature. Suggest a reason why they would be cooler. Why would it be important for the body to have a core temperature that is warmer? T/I
7. After learning about thermoregulation habits of ectotherms, suggest a reason why the largest species of ectotherms are found in tropical areas. K/U A
8. Suggest two advantages and one disadvantage of endothermy. K/U T/I
9. In this section, you learned about the wood frog. Using the Internet and other resources, research other frogs that "freeze" during the harsh winter months. Describe their habitat and geography. T/I
10. List several ways, other than torpor, hibernation, and estivation, that animals survive seasons with cold weather. K/U
11. What is the danger of performing heavy physical activity in extremely cold weather? K/U A
12. Compare and contrast estivation and torpor. K/U
13. Bats engage in diurnal torpor (**Figure 7**). Based on what you know about bats and what you have learned about torpor in this section, what do you think diurnal torpor is? Give an example of another organism that engages in diurnal torpor. K/U T/I

Figure 7

WEB LINK