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Chapter 11

Consciousness

What are you conscious of right now? You must be seeing this book, and maybe you are also listening to music. Perhaps you have not eaten in a while, so you are feeling hungry. I hope that you are interested rather than bored, and that your emotional state is pleasant. Consciousness includes these kinds of sensory and emotional experiences, as well as basic awareness that you are reading a book.

No question in cognitive science is more challenging, or more fascinating, than the nature of consciousness. Until recently, the study of consciousness was usually considered a matter for philosophy rather than science, but there has been an explosion in the past decade of experiments and theorizing concerning how consciousness works. No consensus has emerged, but some of the neurological and computational elements of a theory of consciousness are starting to appear.

CONSCIOUSNESS AND THE MIND-BODY PROBLEM

Understanding consciousness is crucial for a solution to the mind-body problem described in chapter 8. For each philosophical answer to this problem, there is a corresponding view of consciousness. Dualists, who see mind as separate from body, claim that consciousness is a property of spiritual minds and is not open to scientific explanation. Idealists, who think that everything is mental, can see consciousness as a property of everything in the universe. Materialists argue that consciousness is a physical process, but they differ in what kind of process they think it is. Functionalists claim that consciousness is a property of the functioning of a sufficiently complex computational system, so that consciousness may turn out to be a property of advanced robots as well as human minds. Another version of materialism that I find more plausible views consciousness as emerging from the biological complexity of the human brain, not just from its computational functions. A third version of materialism contends that consciousness is a physical process that is just too complicated to be figured out by limited human minds. This "mysterian" position may turn out to be true, but it would be defeatist to adopt it without a long and serious attempt to understand consciousness scientifically.

What would be the grounds for adopting dualism? Most people acquire dualism as part of their religious education when they are told that people have souls that survive death. This is a very appealing idea, but unfortunately there is no reliable evidence that anyone has ever managed to exist without a body. Philosophers such as Nagel (1979) and Chalmers (1996) use thought experiments to raise doubts about the prospects for a scientific explanation of consciousness. You know what it's like to be you, to have the kinds of sensory and emotional experiences that you have. Imagine what it would be like to be a bat, with a very different set of experiences. How could a computational or neurological explanation possibly account for the qualitative experiences that you have by virtue of being a human being? We can also imagine a population of zombies who function just like us biologically but who lack conscious experience. Some dualists think that this possibility shows that consciousness is not identical to any physical process.

Thought experiments can be useful in science and philosophy when they are used to suggest and elaborate new hypotheses, for example when Einstein imagined himself riding on a beam of light when he was developing the theory of relativity. But they are never a reliable guide to the adopting of hypotheses, because our imaginations are limited by what we already believe. The *Star Trek* movies and TV shows portray "transporters" which dissolve people on a spaceship and then reassemble them on a planet. However, this process is incompatible with what we know of physics and computational complexity: taking apart the trillions of cells in a human body, transmitting them across space, and reassembling them into the original body would require unrealizable physical processes and computing power. According to the calculations of physicist Lawrence Krauss (1996, p. 83), "building a transporter would requires us to heat matter up to a temperature a million times the temperature at the center of the Sun, expend more energy in a single machine than all of humanity presently uses, build telescopes larger than the size of the earth, improve present computers by a factor of 1000 billion billion, and avoid the laws of quantum mechanics." We can imagine transporters, but imagination is misleading because it does not reveal a real physical possibility. On the other hand, imagination is often limited by lack of knowledge: 100 years ago, no one contemplated the Internet or cell phones or the human genome project. It is likely that 100 years from now educated people will be amused that some philosophers in the 20th century denied that consciousness could be explained scientifically.

But is there really a problem of consciousness? The philosopher Daniel Dennett (1991) argues that current puzzles about consciousness are largely the result of confusions deriving from an outmoded dualist theory of mind. The artificial intelligence researcher Drew McDermott (2001) thinks that robots will eventually have consciousness in the same way that people do, namely they will have the *illusion* that they are conscious! However, I doubt that peoples' experiences of sights, sounds, touches, pains, and emotions are illusions. Cognitive science needs to explain these experiences, not deny them. As in the rest of science, explanation consists of identifying mechanisms that produce the observations we want to explain. This chapter will outline some of the key components and processes that currently appear to be plausible ingredients of a neurocomputational theory of consciousness.

Explanations in cognitive science, like scientific explanations in general, consist of identifying mechanisms that produce observable phenomena. To take a simple example, consider how a bicycle works. You observe the wheels turning, but explanation of why they turn requires attention to the bike's mechanisms. The bicycle consists of components such as the pedals, chain, and wheels that interact with each other: when you press down on the pedals, gears attached to it move the chain, which turns the gears on the rear wheel, propelling the bicycle forward. A mechanism consists of a group of components that have properties and relations to each other that produce regular changes in those properties and relations, as well as to the properties and relations of the whole system of which the mechanism is a part. Thus you and the bicycle move forward because its mechanism consists of components that have properties (such as the rigidity of the pedals) and relations (such as the meshing of the chain and the gears) that produce regular changes in the components (such as the wheels moving).

The bicycle's mechanism is relatively easy to understand because we can observe all the components and see them in action. Scientific explanations usually need to go beyond observation by theorizing about hidden components and processes. You cannot see, touch or smell electrons, but your lamp and your computer work by virtue of the electrons flowing through their wires and chips. All physical objects consist of atoms, which are tiny mechanisms involving sub-atomic particles and their interactions. Similarly, cognitive science explains thinking by virtue of non-observable mechanisms. Chapters 1-7 described mechanisms whose parts are representations such as rules and concepts and whose regular changes involve computed changes to systems of representations. In chapters 9 and 10, the emphasis was on neurobiological mechanisms whose components are neurons organized into brain areas and whose regular changes result from their electrical and chemical properties and interactions. What we need is a description of the components and processes of the brain that interact to produce conscious experience. We can learn a lot about a mechanism from the ways in which it breaks down, so it is useful to start with a review of ways that people sometimes cease to be conscious.

HOW TO LOSE CONSCIOUSNESS

What causes consciousness? Current scientific approaches to the study of consciousness approach this question by looking for neural correlates, that is brain processes that occur when people are conscious (e.g. Metzinger, 2000). Here I take a different approach, examining the neural correlates of loss of consciousness. Loss of consciousness can arise from many kinds of events, including death, coma, seizures, concussions, sleep, anesthesia, hypnosis, and fainting. All of these involve cases where a previously conscious person ceases to be conscious. I begin with the most obvious negative circumstance of consciousness: death. Live people are often conscious, as we can infer from their verbal and other behaviors. But after death there is no evidence of such behaviors, so it is reasonable to infer that corpses are not conscious. In the absence of life, consciousness ceases, so it is plausible that life is at least part of the cause of consciousness.

Someone might reply that we can imagine ghosts and other souls who are conscious after death, so that life does not have to be a cause of consciousness. But science is not concerned with causality in all possible worlds, only with causality in this one. The thought experiment that we can imagine B without A is irrelevant to determining whether A in fact causes B. I can imagine a world in which thunder is caused by gods playing baseball rather than by lightning, but that is irrelevant to the inference that in our world lightning causes thunder. We have no evidence that there are ghosts or other post-death souls who are conscious, so the absence of consciousness following the onset of death strongly suggests that life is among the causes of consciousness.

But what is life? Humans are alive because they consists of organs, tissues, and individual cells that are alive. Life is not a mysterious property of cells, but rather consists in them performing functions such as energy acquisition (metabolism), division (mitosis), motion, adhesion, signaling, and self-destruction (apoptosis). The molecular bases of each of these functions is well understood (Lodish et al. 2000). When people die, their cells stop functioning. For example, death by heart attack typically occurs when a clot blocks the blood supply to part of a heart muscle, which dies if it is deprived of oxygen for more than 30 minutes. If much of the heart muscle is destroyed, it loses the ability to pump blood to the rest of the body, so cells throughout the body die from lack of energy. Brain cells are particularly dependent on supplies of glucose provided by blood pumped by the heart, and neurons deprived of energy start to die within a few minutes. Brain death can also occur without damage to the heart, for example by a gunshot wound.

Because consciousness stops when the cellular processes of energy metabolism cease, it is plausible to conclude that the causes of consciousness are biological. This is consistent with our knowledge that at least one kind of living thing is conscious, namely humans, and that non-biological entities such as rocks exhibit none of the behaviors that display consciousness in humans. I leave open the question of whether non-human animals such as dogs and dolphins are conscious; for the current argument, it suffices that even if they are conscious when alive, they display no evidence of it when they are dead. The circumstance of death allows us to narrow down the causes of consciousness to biological ones, but it would be desirable to narrow them down further. Plants live and die too, but exhibit no behaviors indicative of consciousness and its loss. We can, however, get a more specific understanding of the causes of consciousness by looking at circumstances found in humans but not in plants, such as comas and concussions.

Medically, a coma is a state of unarousable unresponsiveness in which even strong stimuli fail to elicit psychological reactions (Wyngaarden, Smith, and Bennett, 1992, p. 2049). Coma is distinguished from stupor, in which people are unconscious but can be aroused by vigorous stimulation, and syncope (fainting), in which people are unconscious only briefly. The common causes of coma include: cerebral or cerebellar hemorrhage, cerebral or cerebellar infarction, subdural or epidural hematoma, brain tumor, infections such as meningitis and encephalitis, anoxia, hypoglycemia, and poisons such as alcohol and opiates. All of these conditions affect the brain, and all can occur while the heart continues beating fairly normally. So consciousness requires proper brain functioning, indicating that the biological causes of consciousness are specifically neurological.

Comas can last for many years, but the briefer loss of consciousness associated with concussions and fainting also point to neurological causes of consciousness. A concussion is a change in mental status resulting from an external force. Typical causes of concussions are direct blows to the head or face and whiplash effects on the neck. Symptoms of mild concussions include confusion, dizziness, and memory loss, while more severe concussions produce total loss of consciousness. Loss of consciousness from concussion results from the rotational movements of the brain inside the cranium, with shearing forces that cause the brain to move in a swirling fashion and bump into the interior of the skull, both at the point of impact and after rebound on the opposite side of the skull. Since blows to the body other than the head are unlikely to cause loss of consciousness, the phenomena of severe concussions supports the coma-based conclusion that the causes of consciousness are neurological.

Syncope is defined medically as brief unconsciousness due to a temporary, critical reduction of cerebral blood flow. It is relatively common, and is colloquially known as fainting. Unlike coma and concussion, heart activity is directly involved in syncope, because the 60% reduction in cerebral blood flow usually results from a large drop in cardiac output. This drop can be caused by abnormal neural reflexes, abnormal cardiovascular function, impaired right heart filling, acute loss of blood volume, and severe hypotension. Hence loss of consciousness in syncope does not serve to eliminate the heart as a major cause of consciousness, but its association with blood flow specifically to the brain does support the general conclusion that the causes of consciousness are at least in part neurological. Together, coma, concussions, and syncope all suggest that brain processes are causally involved in consciousness. Of course, it is desirable to have a much more specific account of what neurological processes produce consciousness, and for this we need to look at additional ways of losing consciousness.

Epilepsy is a group of disorders that involve alteration or loss of consciousness. Epilepsy is now recognized as the result of abnormal brain activity involving spontaneous and transient paroxysms. Epileptic seizures, which can involve either partial or total loss of consciousness, occur when abnormality in the cerebral cortex lead to brief, high-amplitude electrical discharges that can be recorded from the scalp by electroencephalography (EEG). Such discharges, which involve synchronized activity of many neurons, can have many causes, including brain lesions, head trauma, infections, brain tumors, physiological stress, sleep deprivation, fever, and drugs. It is clear, however, that total or partial loss of consciousness in epileptic seizures is accompanied by abnormal electrical activity in the brain. We can thus conclude that the neurological causes of consciousness are at least in part electrical.

People die only once in their lives, and most people never lose consciousness because of comas, concussions, or seizures. But we all lose consciousness every day when we fall asleep. Attention to the neurophysiology of sleep shows that it is associated with chemical changes that point to the role of chemical processes in maintaining consciousness. Falling asleep is marked by electrical changes in the brain. Active wakefulness is accompanied by low-amplitude, high frequency beta waves in the EEG (Sharpley, 2002). In contrast, slow-wave sleep (stages 3 and 4 following a gradual slowing of activity) is characterized by high amplitude, low frequency delta waves. Hence sleep is like seizures in that loss of consciousness is marked by alterations in the electrical activities of the brain.

But recent evidence suggest that the causes of sleep are chemical as well as electrical. According to Benington and Heller (1995), the primary function of sleep is to replenish stores of glycogen, the major source of energy to neurons. As cerebral glycogen stores drop, levels of the neuromodulator adenosine increase, eventually inhibiting neuronal activity sufficiently to induce slow wave activity that is necessary for the replenishment of glycogen. Injections of adenosine promote sleep and decrease wakefulness, whereas caffeine, which is an antagonist for adenosine receptors, promotes wakefulness (Sharpley, 2002). During sleep deprivation, adenosine levels increase significantly, but the levels decrease during sleep. Other neurotransmitters whose levels are altered during sleep include dopamine, histamine, noradrenaline, acetylcholine, serotonin, and GABA (Gottesman, 1999). Hence a full explanation of the loss of consciousness involved in sleep will have to take into account chemical causes such as the accumulation of adenosine.

A similar conclusion follows from recent discoveries about how anesthesia works. General anesthetics such as ether and nitrous oxide have been used in surgery since the 1840s, but understanding of the molecular mechanisms of anesthesia has arisen only recently (see Moody and Skolnick, 2001). Recent research suggests that the neural targets of general anesthetics are the ligand-gated ion channels that control synaptic transmission between neurons. For example, GABA is the main inhibitory neurotransmitter in the brain, and many general anesthetics bind to GABA receptors in presynaptic neurons, leading them to fire and transmit GABA to postsynaptic neurons. Because GABA tends to inhibit firing of postsynaptic neurons, binding of GABA receptors tends to decrease neuronal activity overall, producing anesthetic effects such as loss of consciousness, sensitivity, and mobility. However, increase in inhibitory synaptic transmission is only one of the various mechanisms used by different anesthetics, which can include stimulation of glycine-based neuronal inhibition as well as suppression of NMDA-based neuronal excitation. When patients receive injected or gaseous anesthetics, they become unconscious when concentration of the anesthetic in the blood reaches a critical level, and regain consciousness when the concentration drops.

Hameroff (1998) argues that anesthesia shows that quantum mechanical effects are responsible for consciousness. He contends that anesthesia ablates consciousness because gas molecules act by quantum effects of van der Waals forces in hydrophobic pockets of select brain proteins. Ultimately, chemical explanations depend on quantum effects, since the bonds that conjoin atoms into molecules are currently understood in terms of quantum mechanics. But the explanation of the chemical effects of anesthetics in terms of their effects on receptors for neurotransmitters such as GABA does not draw on quantum-level phenomena. Hence the rapidly accumulating evidence for the chemical nature of the causes of loss of consciousness does not support the hypothesis that the causes of consciousness are quantum mechanical. It may turn out, as Hameroff and his collaborator Roger Penrose contend, that explanation of consciousness will need to descend to the quantum level, but current experimental research suggests that descent to the chemical level may suffice.

So far, consideration of the most important ways of losing consciousness – death, coma, concussion, fainting, sleep, and anesthesia – suggests that the causes of consciousness are biological, neural, electrical, and chemical. To pin down the causes of consciousness further, we need to go into much more detail concerning the neurological processes that underlie conscious experience.

TOWARD A NEUROLOGICAL THEORY OF CONSCIOUSNESS

Crick (1994) has speculated concerning the neural underpinning of visual consciousness (see also Crick and Koch, 1998). We saw in chapter 6 that understanding of visual imagery has been greatly aided by recent work on the brain's visual systems, and Crick tries to put the same kind of neurological discoveries to work to provide an explanation of visual awareness. From experimental psychology, he takes the hint that awareness is likely to involve some form of attention. He conjectures that the mechanism by which the visual brain attends to one object rather than another involves the correlated firing of neurons. Neurons associated with the properties of a particular object tend to fire at the same moment and in the same sort of pattern. Unlike the artificial neurons described in chapter 7, but like the spiking neurons described in chapter 10, real neurons pass activation to each other in bursts, making possible a kind of coordination among neurons that fire in temporally similar bursts. Crick conjectures that neural networks may have the competitive aspect we saw in chapter 7: when some neurons fire, they tend to suppress the firing of others. A shift in visual attention from one object to another could then be the result of a group of neurons firing in coordination with each other and together suppressing another group of neurons that fire in coordination with each other.

The second hint that Crick takes from experimental psychology is that consciousness involves short-term memory. In terms of CRUM, long-term memory consists of whatever representations - rules, concepts, analogs, images, etc. - are permanently stored in memory. Psychological experiments have shown that short-term memory is much more limited: unless people chunk information into more complex structures, they can only hold remember about seven items at once (Miller, 1956). You can remember your phone number by repeating it, but longer strings of digits require complex strategies to encode. Short-term memory and consciousness are associated in that we tend to be conscious of the contents of short-term memory. Crick conjectures that short-term memory might work by means of neurons that have a tendency to fire for a certain time and then fade away, or by "reverbatory circuits" in which neurons in a ring tend to keep each other firing. He describes experiments in which visual neurons in monkeys fire in response to a visual target, and continue to fire for seconds after the target is removed. If they do not continue to fire, the monkeys are more likely to make mistakes in dealing with the target, suggesting that the neurons are important for their short-term memory required to perform the assigned task.

The possible neuronal correlates of attention and short-term memory Crick discusses do not furnish us yet with a neurological explanation of visual consciousness. Much more remains to be learned about the neurological processes of attention and memory, as well as about their relevance to conscious experience. But this kind of research shows the possibility of neuroscience narrowing in on kinds of brain activity that are relevant to consciousness. Crick speculates concerning parts of the brain, such as the thalamus, that seem to be involved in the attentional mechanisms that underlie visual awareness. Dualists will complain that, no matter how much is known about the neural correlates of consciousness, they could still not imagine how the material brain could produce consciousness. This is sometimes called the Argument from Lack of Imagination. It is comparable to saying that no matter how much is known about the motion of molecules, it is difficult to imagine that heat is just that motion rather than some special substance like caloric. Neuroscience is still far from having as much evidence that consciousness is caused by the firing of neurons as physics has that heat is caused by the motions of molecules, but the rapid rate of progress in cognitive neuroscience should lead us to keep a watch for further biological explanations of consciousness.

Crick and Koch'a account only applies to consciousness of visual experience, and different mechanisms are needed to apply to other kinds of consciousness. Morris (2002) has formed an interesting hypothesis about the origins of emotional feelings based on neurological experiments concerning the neural basis of fear. Brain scanning experiments suggest that peoples' conscious awareness of fear depends upon part of the cortex called the *insula,* which integrates information from many bodily senses. Morris conjectures that emotional feelings such as fear arise as the result of a complex interaction of the sort shown in figure 11.1. Suppose you suddenly see a scary face. This is an emotional stimulus that is processed by the visual regions of your brain and the result is transmitted to the thalamus and then on to the amygdala. Physical reactions such as increased heart beat result, but there are also complex interactions with the insula and prefrontal cortex. Emotional feeling then emerges as the result of the overall interactions of all of these brain areas. Similarly, Edelman and Tononi (2000) propose that consciousness arises from integrated activity across numerous brain areas such as the thalamus and different regions of the cortex. See Zeman (2002, ch. 8) for a comparative survey of current scientific theories of consciousness.

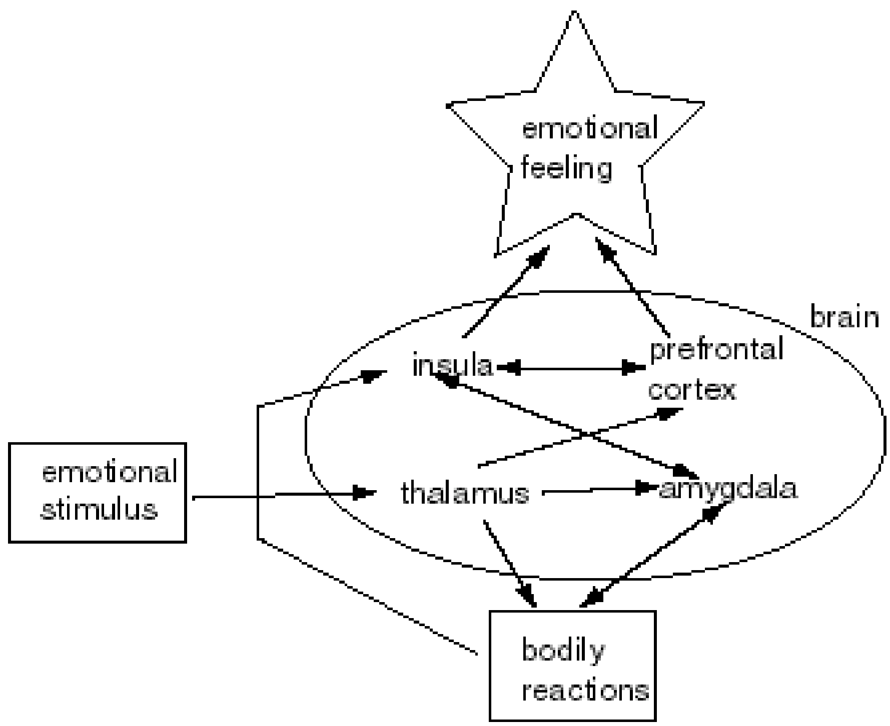

Figure 11.1. Origins of emotional consciousness. Modified from Morris (2002), p. 318.

REPRESENTATION AND COMPUTATION

This chapter has so far concentrated on emerging ideas about the neurobiology of consciousness, and may seem to have left behind the representational-computational understanding of mind reviewed in earlier chapters. But a full account of consciousness will require both representation and computation.

Damasio (1999) develops a neurologically sophisticated account of two kinds of consciousness, core and extended, both of which have a representational component. Core consciousness is a simple kind that involves basic wakefulness and attention. It depends on evolutionarily old parts of the brain such as brain stem nuclei that regulate body states and map body signals, but not on newer parts such as the prefrontal cortex. According to Damasio (p. 169): "Core consciousness occurs when the brain's representation devices generate an imaged nonverbal account of how the organism's own state is affected by the organism's processing of an object." Thus even core consciousness is a representational process.

Extended consciousness is even more obviously representational, since it involves a sense of self based on autobiographical memory. Whereas core consciousness requires only representation of current body signals, extended consciousness requires stored representations of previous experiences as well as higher level structures that represent these representations. Damasio thinks that these second-order structures are produced by neural activity in the cingulate cortex and other parts of the brain found only in animals that evolved relatively recently, like people and other primates. He describes how disorders of extended consciousness, such as amnesia found in Alzheimer's patients, are very different from disorders of core consciousness, such as comas caused by damage to the brain stem.

Representation has also been important in philosophical theories of consciousness developed by Lycan (1996) and Carruthers (2000). According to these theories, consciousness of your mental state such as a pain consists in a representing of that state. Lycan maintains that this representing is like perception by means of a set of internal attention mechanisms. But according to Carruthers, this representing requires only having a thought about the mental state. As in Damasio's extended consciousness, the theory that consciousness is a kind of higher order thought involves the postulation of representations of representations. If these accounts are true, then consciousness is clearly part of the representational understanding of mind.

But what about computation? Could it be that consciousness is a representational process that depends only on physical processes that are not best described as computational? Neither Damasio nor Carruthers describe representations of representations as functioning computationally. However, when more detailed models of conscious experience are presented, such as in the model in figure 11.1, it becomes natural to describe the relevant physical processes as neurocomputational. When input from a stimulus triggers activity in brain areas such as the thalamus, amygdala, insula, and prefrontal cortex, there are complex transformations of representations constituted by populations of neurons firing systematically. These transformations cannot only be modeled computationally, they are plausibly described as *being* computations, because the relevant transitions between brain states are operations on representations. Of course, some of the inputs to brain processing come from physical sources such as the sense organs and the body's sensing of its own internal states, but these get integrated computationally into composite representations found in the insula and amygdala. Hence consciousness can plausibly be understood as a computational-representational process.

Does this mean that sufficiently complex computers will be conscious? I do not know. We do not yet understand enough about how the brain's interactive processes generate consciousness to be able to say whether causally comparable processes can be built into computers. At the very least consciousness will require robots that acquire sensory information from the world and their own physical states. Because future robots will not duplicate the full biological complexity of humans, it may be that consciousness may never emerge from their sensory and representational activities. Even if robots do acquire consciousness, there is no reason to expect that their qualitative experiences will be at all like ours, since their bodies and sense organs will be very different. Even if we use a robot to simulate in great detail human information processing, there will be many aspects of human biology that contribute to human consciousness but which will be lacking in the robot, for example hormones and specific brain areas such as the insula. Given current limitations of knowledge, we just do not know what it might be like to be a robot.

SUMMARY

Explaining consciousness is one of the most difficult problems in cognitive science, but philosophical thought experiments fail to show that no scientific explanation is possible. There is growing reason to believe that consciousness is caused by biological, neurological, electrical, and chemical mechanisms. Neurological theories of various kinds of consciousness, such as visual and emotional experience, are being developed. Core consciousness depends on the brain's ability to represent basic physical experiences, but extended consciousness requires higher level representations of the self and its history. Consciousness appears to be a representational and computational process, but it is not yet possible to say whether computers and robots can be conscious.

DISCUSSION QUESTIONS

1. What would it take to give a robot consciousness?
2. Can consciousness be thought of as representational?
3. Is consciousness an essential aspect of emotions?
4. How big a role does consciousness play in intelligent thought? What is its function?
5. Could consciousness be understood in terms of neurons and brain structures?

FURTHER READING

For a general survey on consciousness, see Zeman (2002). On the neuroscience of consciousness, see Damasio (1999), Edelman and Tononi (2000), and Metzinger (2000). For philosophical discussion, see Block, Flanagan and Güzeldere (1997), Carruthers (2000), and Churchland (2002). Merikle and Daneman (2000) review the experimental psychology of conscious versus unconscious perception. On the neurochemistry of consciousness, see Perry, Ashton, and Young (2002).

WEB SITES

Association for the Scientific Study of Consciousness:
http://assc.caltech.edu/
Christof Koch on the neuronal basis of consciousness:
http://www.klab.caltech.edu/cns120/
David Chalmers page, with extensive bibliographies:
http://www.u.arizona.edu/~chalmers/
Representational theories of consciousness:
http://plato.stanford.edu/entries/consciousness-representational/
University of Arizona Center for Consciousness Studies
http://www.consciousness.arizona.edu/

NOTES

The argument in the section on how to lose consciousness uses J. S. Mill's method of difference, which says that if you want to determine the causes of a phenomenon, it helps to look for what is missing when the phenomenon is absent.

Penrose (1994) argues that consciousness and other mental phenomena arise from the brain being a quantum computer, but there is no evidence that thought depends directly on quantum effects, and only the beginning of the physical construction of quantum computers.