principle of differentiation by localization may seem insignificant as an attempt at classifying brain activity. Nevertheless it serves as the backbone on which the rest of our body of knowledge hinges. Another matter is then how to proceed to the next step in classification and decide to what class of phenomena a living nervous system belongs. It is a unique phenomenon in this world—unique also in ultimately trying to understand itself.

5
Some Approaches to Conscious Awareness

Any science that deals with living organisms must needs cover the phenomenon of consciousness, because consciousness, too, is part of reality. (Niels Bohr in a discussion recorded by Heisenberg in *Physics and Beyond,* London: Allen and Unwin, 1971, p. 114.)

The introductory quotation illustrates the agreement of two physicists of the first rank (Bohr and Heisenberg) on what many of those with some experience of neurophysiology regard as self-evident. Others think of consciousness as an epiphenomenon or as something that merely has semantic existence. I do not intend to spend any arguments on them. From the evolutionary standpoint of modern biology, consciousness is an emergent novelty, probably still existing in an increasingly rudimentary form as one descends in the phylum. Sherrington, speaking of mind and often meaning consciousness, regarded it as a product of evolution, developing from unrecognizable to recognizable with no lower limit accessible to definition.[62] He held mind to have arisen in connection with the motor act whose improvement gave it survival value. A similar attitude based on evolution is that of Teilhard de Chardin (1955) who cut the Gordian knot by simply maintaining that "toute énergie est de nature psychique."[71] However, a more tangible approach than this is needed.

A better differentiated version of the evolutionary attitude is that of Polanyi who, in agreement with Hughlings Jackson,[4] Paul Weiss,[3] the present author, and many others, emphasizes creation of hierarchies as a component of evolutionary progress: "the principles governing the isolated particulars of a lower level leave indeterminate conditions to be controlled by a higher principle. Voice production leaves largely open the combination of sounds into words, which is controlled by a vocabulary. Next, a vocabulary leaves largely open the combination of words to form sentences, which is controlled by grammar, and so on. Consequently, the operations of a higher level cannot be accounted for by the laws governing its particulars on

the next lower level. You cannot derive a vocabulary from phonetics; you cannot derive grammar from a vocabulary; a correct use of grammar does not account for good style; and a good style does not supply the content of a piece of prose" (p. 1311).[72] This analogy shows how conscious man makes use of neurophysiological mechanisms without being governed by them.[73] In an analogous way a computer makes use of the laws governing electrical circuits, so-called hardware, but the purpose embodied in its design cannot be reduced to terms of hardware without losing its relevance.

Nevertheless we have to know the principles utilized by Nature in the choice of hardware, as well as the hardware itself down to the last limit of reductionism, because all these facts and rules of operation impose constraints on the phenomenon of conscious awareness without directly being awareness as such. When, for instance, we observe that consciousness is lost in deep sleep, the conclusion that it is tied to cellular processes subject to inhibition can be justified, but this does not define its nature; it merely fixes one particular constraint. In the same way Sherrington's statement that consciousness seems to develop in parallel with the expansion of the cerebral cortex—a likely hypothesis—defines another boundary condition. Such facts are often interesting and important in themselves as contributions to physiology and its application in medicine, but they do not explain the phenomenon of conscious awareness. And how could they? To deliver a conscious explanation of the essence of consciousness involves a feat such as Baron von Münchausen's lifting himself and his horse out of a morass by his own queue. "We cannot reach further than to understand what can be understood and realize what we cannot

understand" (Berzelius, introductory quotation to Chapter 1).

Often the unavoidability of a concept or attitude is more important even than full understanding of all its implications. When I consciously demand from myself the performance of a complex motor act, "demand" is a useful concept embodying certain constraints; but in spite of this I may not understand what "demanding" is. To this general category belongs "conscious awareness," whereas "mind" epitomizes a general desire to deal with experience from one particular point of view. It means that we intend to classify our material in psychological terms. We then keep to the hierarchic top level of organization, the evolutionary summit that serves as a carrier of the whole of our civilization taken in the widest possible sense of that word.

Evolutionary Assets of Consciousness

As held already by William James, conscious awareness is a process engaged in evaluating the resources of a brain that has grown too complex to do itself justice without it.[74] In this respect, what other advantages could it tender a neural machinery that does so well without it?*

1. Consciousness makes possible long-range anticipation of events. Anticipation is tied to purposive acts in which, as we shall see, it also may become automatic. However, my emphasis here is on the great expansion in two dimensions, time and complexity of association, that consciousness alone can engender. Because no anticipation is possible

*"The *distribution* of consciousness shows it to be exactly such as we might expect in an organ added for the sake of steering a nervous system grown too complex to regulate itself." (James, p. 144.)

without predictability, perhaps one of the most remarkable properties of consciousness is that it has supplied a high degree of predictability to an organism that in ontogeny has undergone the hardships of genetic chance, environmental challenges, and developmental interactions between its parts.

2. Time runs through the whole world of biology, but consciousness has added an element of awareness to it. A dog can be trained to use a time interval as a stimulus in conditioned reflexes but, over and above that, man has introduced the notion of the past and the future to characterize experience.

3. Consciousness can raise to the level of awareness most sensory experiences and an incredible number of engrams (memories). It therefore serves as an activator capable of selecting cells and circuits and keeping them in focus to the exclusion of others. This again means that it makes use of both excitation and inhibition.

4. Given time, consciousness can deal with vast amounts of information. No animal can compete with man though higher mammals may be equal to man in pure associative learning.

5. However, learning complex matters presupposes conscious awareness which therefore plays a definite role in stamping in engrams.

6. Consciousness is necessary for the development of communication at the level of man.

7. Consciousness facilitates correction of misinterpretations or errors including those of automatized acts.

8. As pointed out in discussing adaptability, consciousness reigns supreme in this regard. In adaptability conscious man exceeds all other species.

Conscious awareness has been an enormous asset in the

evolution of higher organisms. Its raison d'être is perfection of control over the environment—and indeed, some today believe that in man it has become too successful.

Timing Consciousness

Patients in whom the sensorimotor area of the cortex has been partially laid bare for surgical purposes have allowed the surgeon to stimulate it electrically. The electrodes have been applied to the bared surface or pushed slightly into the white matter of nerve fibers below it. The procedure is painless. In such experiments by Libet and his colleagues it turned out that although each shock elicited a virtually instantaneous electrical cell response, an evoked potential, it required a whole series of shocks before the patient registered conscious awareness of the stimulus in the form of a percept.[75] In fact, the interval or latent period was as long as half a second. Because the cortical cells were activated instantaneously they could hardly have been the sole neuronal substrate of the much-delayed conscious response. This agrees with the experience of neurosurgeons. Therefore, as Penfield points out, any portion of the cerebral cortex can be removed without causing loss of consciousness. It is, however, inevitably lost when the function of the higher portion of the brain stem is interrupted by injury, pressure, disease, or local epileptic discharge.

The latent period of the conscious response suggests that coengagement of the brain stem by a network of nervous loops is the most elementary assumption one can make to explain the onset and disappearance of awareness of an event that one has good reasons for localizing to the cortical gray matter. It also means that when afferent nerve stimuli elicit fast movements, they are well underway before one becomes aware of them. This is true not only of reflexes but of acquired skillful responses as well. Such movements can now be traced at several sites by electrical recording within the brain, spinal cord, and muscles of monkeys. Formerly the experimenters were restricted to measuring the reaction time of human subjects, which implicitly was regarded as a conscious response indicated by the motor act of pressing a Morse key. Now it seems likely that this act, too, is completed long before it has reached the level of conscious awareness. Reaction times are of the order of 0.1 to 0.2 sec. If Libet and his coworkers are right about awareness requiring about half a second, then conscious recording of the act of pressing a key must succeed the motor response and turn up after the completion of the reaction time. In favor of this conclusion is the observation of psychologists (Craik; Vince)[76] that the least interval between the conscious identification of two visual stimuli as doubles is of the order of half a second, a figure in good agreement with a latent period of the same order, as Libet's group found.

It will be shown with examples in subsequent chapters that whenever motor acts or perceptions have been properly analyzed, they have been found to involve a very large number of neurons in different parts of the brain. For this reason and because of the involvement of the brainstem, it also seems likely that conscious awareness as a process necessarily implicates a vast number of cells from different sites. The long latent period would be largely caused by the mobilization of this elaborate cellular apparatus. Physiologists call the act of mobilizing the brain "arousal." They record its electrical signs and hold arousal to be an important neural component in stirring up attention that is excited by the appearance of some object of interest. The trend of

evolution seems to have favored the capacity of making conscious use of attention. We feel it in our power to direct our attention to anything we choose to consider.[77]

Signs of Conscious Mentation and of Arousal

When speaking of signs in this sense, I mean events that can be measured and even produced in various ways by the objective method of psychophysiology. Generally known is the electroencephalogram (Berger) obtainable by recording with electrodes placed on the scalp.[78] This has the character of synchronized waves of potential changes across membranes of neurons including their dendritic expansions. In the state of rest there is a basic rhythm, 10 per second, on which are superposed irregular wavelets. One of Berger's early observations was that these waves grow smaller and reach higher frequencies when the subject's attention is engaged. The state of deep sleep is characterized by slow waves of large size, the electroencephalogram of the active awake subject by smaller and faster waves. These changes are seen also in animals and are similarly interpreted as signs of sleep and awareness, with the additional requirement that behavioral signs of awareness must also be present to indicate that the animal really has been alerted.

A descriptive science of electrophenomenology has been erected on the basis of electroencephalography. This has become useful in the clinic for localizing tumors and epileptic tendencies and states, but beyond underlining our conviction that conscious awareness is tied to cellular activity it does not tell us anything about its nature. The dead brain is electrically silent. The living brain responds with electrical signs of alertness (arousal) to electrical stimulation of the brainstem within a region whose role seems to be to collect branches from all incoming (afferent) fibers from the various sense organs and to make use of the information obtained through them to activate the cortex of the entire cerebrum (Magoun's reticular activating system.)[77] In the absence of this system, permanent sleep ensues.

The electroencephalographic technique of recording brain waves by electrodes on the skull of man has recently been much improved by using computers for electronic summation of otherwise invisible changes of potential. A sensory stimulus, for instance a visual contrast pattern, would produce a minute change of potential but this alteration would be lost in the noise consisting of the background wavelets of the living brain. However, by repeating the stimulus, say, up to 200 times, the computer would sum the minute changes of each test until its effect has become recordable. Some results of such work will be mentioned in the next two chapters. Its main interest in the present connection is that the method has revealed long-lasting electrical changes during mentation, such as in the state of expectancy or waiting for something to happen (Grey Walter).[79] (See Chapter 9.) In connection with different psychologically defined operations the method is of interest for problems concerning timing, duration, and elementary localization of otherwise inaccessible processes. It can be used also to measure the intensity or degree of a process and is thus a valuable asset for the science of psychophysiology. On the whole it seems likely that this branch of physiology faces a time of expansion.

Engrams, Communication, and Levels of Awareness

Much could be added on the role of consciousness in different connections but I shall restrict myself to some interesting cases. One is Penfield's observation that large strips of awareness of long-since forgotten incidents can be revived in conscious patients by electrical stimulation of the temporal region of the bared cortex, made accessible for surgical purposes.[80] To what place the effect of the stimulus is conducted is not known, but the effect is in the nature of a remembered awareness of an experience that is reincarnated as such, despite the patient's parallel awareness of being on the surgeon's table in a hospital. The remembered incident may be complete, as it evolved in time many years earlier, and it possesses its original emotional tone, as if it had been stored in a sequence and been sealed off as originally experienced. Somehow the electrical stimulus must have facilitated access to it. In daily life we often speak of remembering in the sense of becoming conscious of something deposited in the past, but as such memory is a much wider concept.

A still more interesting case concerns observations by Sperry and his coworkers on the split brain.[81] This operation separates the outwardly symmetrical halves of the brain. It involves sectioning the main bridge between them (corpus callosum) whose 200 million nerve fibers pass information making it possible for the two hemispheres to function as one single brain. This surgical incision was carried out in certain epileptics for whom it has been of great curative value. By taking proper precautions the two hemispheres can in these patients be stimulated independently using separate eyes. What is led to the left half-brain reaches the speech center, which in virtually all people is in

that hemisphere. The right half-brain is mute in the sense that its communication by language with the experimenter is undeveloped. The right hemisphere perceives and comprehends something but cannot express itself verbally. But upon reading simple words, representing objects simultaneously flashed into it, it can pick them out with the hand at its disposal (the left one, because the motor paths cross). With the dominant left hemisphere controlling the right hand, there is full normal communication. Recent methods of temporally silencing either hemisphere, for example, by localized anesthesia, and investigations on people with a removed diseased hemisphere have shown the minor or mute hemisphere to possess important talents of its own.[82] It has, for instance, considerable manual dexterity in visual-spatial manipulation. An isolated right hemisphere has been found by Luria to retain musicality, to the extent of being able to compose music.

What about consciousness in such experiments? The dominant left hemisphere in possession of full powers of communication is obviously normally conscious in the sense we think of consciousness. The question in this connection is whether the mute brain with deficient communication is less conscious than its partner. Sperry and his coworkers assign to the right hemisphere a conscious awareness different from the verbalized type: "For example, while the patient was dressing and trying to pull on his trousers, the left hand (mute hemisphere) might start to work against the right (talking hemisphere) to pull the trousers down on that side. Or, the left hand, after just helping to tie the belt of the patient's robe, might go ahead on its own to untie the completed knot, whereupon the right hand would have to supervene again to retie it. The patient and his wife used to refer to the 'sinister left hand'

that sometimes tried to push the wife away aggressively at the same time that the hemisphere of the right hand was trying to get her to come and help him with something." [75] With some right, Bogen (1969) states that in this problem we have barely scraped the surface of "a vast unknown."[82]

It seems probable that communication with others or internal monologizing represent high degrees of conscious awareness. Thus consciousness is not one particular state only but something that, like other nervous states and acts, runs through a scale of intensities or levels. It would not be surprising if normal levels of consciousness in a population were determined by a Gaussian distribution curve. Some people seem to maintain a much higher level of conscious awareness than others. However, we have not yet the methods for testing my hypothesis. On the other hand, we are familiar with deviations from the assumed normal degree of consciousness other than deep sleep. There is, for instance, the so-called paradoxical sleep (REM sleep, parasleep) in which the brain exhibits electrical activity reminiscent of that in wakefulness (Dement, Jouvet).[83] The experimental evidence suggests that during this state, which is perfectly normal, the subject is dreaming and thus is apparently conscious in some way. Among other things this state involves inhibition of his spinal reflexes (Pompeiano).[83] And all of us know from personal experience states between half-sleep and full awareness.

The pathology of sleep also demonstrates different levels of conscious awareness such as somnambulism (sleepwalking) and somnolism (hypnotic sleep). Henry Head points out that "a sufferer from minor epilepsy may become completely unconscious and yet remain ignorant that he has had an attack; the stream of mental processes seems to him as unbroken as that of the astonished spectators.

But during this period of unconsciousness he can carry out the most elaborate acts, guided by what appear to be reasonable though extraordinary motives."[84]

The boundaries between conscious acts and automatisms are fleeting. We see this best in practicing complex motor acts when our main endeavor is to automatize them as soon as possible. In the end consciousness is used merely as a trigger to deliver a command and, sometimes, also to select the channel for its execution. If anything goes wrong in the accomplishment of the intent, then again consciousness is mobilized to correct for the unwanted deviation.

These are some examples of the ways in which it has been possible to approach conscious awareness from the physiological end. The neuronal changes underlying consciousness are still a secret. Only some boundary conditions such as those described are known. Biochemists may like to imagine that conscious awareness depends on the release of a quite specific substance at or within a large number of neurons; molecular biologists may want to implicate nucleotides; and neurophysiologists hypothesize the existence of special neurons interspersed among the cortical cells and requiring activation from the brain stem. However, all such notions are conjectural. It only seems certain that some kind of circuitry must be postulated, as shown by the inhibitory processes at work in sleep and by the involvement of the brain stem in cortical processes (Moruzzi).[85]

The brain as a whole, and with it conscious awareness, depends on a normal inflow of sensory messages. This seems almost a corollary of the fact, mentioned in Chapter 3, that the brain contains cells whose functions are fabricated or modified by experience. Sensory deprivation, achieved by asking volunteers to dwell for some time in the dark in a soundproof room (Hebb), has a disastrous effect

on normal, balanced control of the environment, implicating also conscious acts and thoughts.[86]

It is likely that the enormous, cumulative transfer of knowledge from generation to generation has had and will continue to have an influence on conscious awareness. Tinbergen has reminded us of the fact that a nongenetic transfer of this kind is without precedent in biology.[87] In this respect we are Nature's guinea pigs.

The Epistemological Point of View

In presenting some physiological approaches to conscious awareness, I have avoided the ageless controversy concerning matter and mind. This does not belong to the realm of science but to that of philosophy. Descartes (1596–1650), at the dawn of modern science, formulated the dualistic version of this relationship by his assumption of two worlds "absolument distinctes," that of "esprit" (soul, spirit) which expresses itself in thought, and that of "corps" (body) characterized by "étendue" (extensiveness).[26] In this manner he lent his great authority to the perpetuation of Jean Fernel's (1497–1558) difficulty of how to account for the entry of the spirit into the body. [88] Fernel, a physician who coined the word "physiology" and advocated a scientific study of disease based on observation, solved the problem by stating that the spirit entered the body on the fortieth day after conception!

In the beginning of this century Ernst Mach, in his important *Analyse der Empfindungen*, removed the problem of matter and mind from the domain of science.[89] He stated that science is "concerned with different basic variables and different relations. This is the main issue. Neither the facts nor the functional relationships will be changed if we treat

everything as conscious experience (*Bewusstseinsinhalt*) or as partly or wholly physical. The biological task of science is to provide the rational human being with as complete an orientation as possible. A different scientific ideal is nonrealistic and is also meaningless" (my translation, pp. 29–30).

In essence Mach's standpoint still seems valid to me, but from the background of evolutionism and the acceptance of hierarchic order in biology in these essays it needs some amendments. Hierarchic organization implies that at each level new functional relationships are created which use lower organizational levels, as in the example given of the tongue ultimately being used in speech (Chapter 1). But the tongue cannot run the speech.

A warp of creative purposiveness is woven into the fabric of biological hierarchies with consciousness at its top level. It is one of our tasks to trace it. The scientific explanations we are pursuing should, indeed, provide what Mach called "as complete an orientation as possible." But there must be a reorientation of purpose from level to level, extreme "reductionist" molecular details at one end, physiology in its mechanistic and integrative aspects in the middle, and rules for behavior and an independent science of psychology at the other end. Many of these explanations do not and never will end in the differential equations that the physicist uses for his world of interpretation. Life creates novelty from one level to the next. We often see the same principles applied over and over again, the way the architect uses the same bricks for new ends. As scientists we are delighted when we recognize such "bricks," of which I have given some examples, but explaining means understanding the use to which they have been put in hierarchic organizations.

Science does not require dualism. "Pluralism" would be a

better word for summarizing the many-faceted aims of biological science, not in the least in its interpretations of the central nervous system. In science we do not reach out for the soul of man that "catches the gleam of sunlight as it falls on the foliage. It nurtures poetry. Men are the children of the Universe, with foolish enterprises and irrational hopes. A tree sticks to its business of mere survival; and so does an oyster with some minor divergencies. In this way, the life-aim at survival is modified into the human aim at survival for diversified worth-while experiences" (Whitehead, pp. 42–43).[90] As human beings, we may need the dualism of body and mind, matter and soul, or we may regard it as a practical way of describing experience. It is not, however, the scientific way.

6
In Search of Building Blocks for Perception

The early unitary analysis, by H. K. Hartline[38] and the present author, of optic nerve discharges drew attention to movement-sensitivity of the retina and suggested that "[S.C. impulse] frequency must be of particular importance for the discrimination of stimulus intensity pattern, not only for this task but for the recognition of spatial phenomena such as the dominance of contour and 'local sign'. . . . The accurate appreciation of contour, in particular, must be due to minute fluctuations of the eyeballs resulting in on- and off-effects as well as sudden inhibitions of the latter. Even if it were possible to keep the eye absolutely still, every sharp intensity gradient must give rise to very complicated excitation inhibition patterns tending to emphasize the gradients and giving the higher centres a cue for discrimination." (Author in *Sensory Mechanisms of the Retina*, Oxford University Press, 1947, pp. 168–169.)