

Some agenda items for a neurobiology of cognition: An introduction*

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Introduction

Professor Frank Schmitt has written "... theories of higher brain function (learning, memory, perception, self-awareness, consciousness) ... in general lack cogency with respect to established anatomical and physiological facts and are without biophysical and biochemical plausibility" (Schmitt, 1978, p. 1). Not surprising in light of this statement, we find that Schmitt has also applauded efforts attempting to construct a "... detailed, self-consistent theory ... that specifies the operational repertoires at the level of molecules, individual neurons, or groups (circuits) of neurons, and that explicitly defines the postulated information processing mechanism" (p. 1). This goal, obviously desirable to most cognitive scientists and neurobiologists, can be achieved only if cognitive scientists and neurobiologists alike make concerted efforts to know those aspects of neurobiology and cognitive science, respectively, that are most relevant to their own research, and to keep abreast of updated accounts. Indeed, we foresee little hope of a theory that is a biologically consistent, realistic description of human cognition in the absence of interdisciplinary knowledge. It is the purpose of this special issue of *Cognition* to bring to its readership a sample of instances in which theory in neurobiology has begun to become explanatory of complex behavioral processes, or in

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which such theory seems possible in a reasonable, not-too-distant future.

There is little doubt in the minds of cognitivists that there is an entity called "the brain", and there is likewise little uncertainty in the brains of most neuroscientists regarding the existence of "the mind". But there is certainly an absence of unanimity among cognitive scientists for the belief that "the brain" will provide the ultimate explanations for things cognitive in complex organisms, or among neuroscientists that current formulations of "the mind" by cognitive scientists represent realistic accounts of what the behaviors of brain actually are. Nevertheless, few cognitivists would hold to the beliefs of substance dualists; virtually all are materialists in the sense of believing that for each and every act of cognition, whether, for example, perceiving an object as a separate, three-dimensional entity among a myriad of entities or understanding passages of poetry, there is to be found a neuroanatomical structure and a neurophysiological correlate, that is, an instantiation in the workings of the brain. Nevertheless, there is sentiment among some that there are limits on materialism, that is, on the extent to which explanations of the cognitive may be found in the physical. Thus, for example, Fodor (1975) argues that the natural kinds of the science of cognition, for instance intentions and the constituents of human language as exemplified by phrases, clauses, and sentences, will not be captured by the natural kinds constituting brain science. The latter include, for example, the anatomical constructs of DNA, neurotransmitters, peptides, ion channels, synapses, axons and dendrites, small neural nets, larger neural maps, larger distributed neural systems, or whole nervous systems. The constructs of neurobiology also include the physiological processes that these structures support, such as transcription, synaptic transmission, enzymatic activity, ionic transport, axonal and dendritic depolarization, neuronal group firing, event-related potentials, or hemispheric glucose consumption.

There is an interesting (and to some maddening) direct counter to the contention that the natural kinds of cognition cannot be reduced to the natural kinds of neuroscience. This is the argument of eliminative materialism, recently presented in an articulate and comprehensive treatise by Patricia Churchland (1986). While philosophers holding to this view recognize, as sentient beings, the activities of mental life, especially those that are so readily available to conscious awareness, for example, the intentional attitudes of believing, knowing, or desiring, they dispute the validity of these and other descriptors of cognition as descriptors of the activity of the brain during acts of cognition. They argue that the state of functional descriptors and explanations of cognition is primitive and, like the primitive structures of other sciences in their earliest stages of development, undoubtedly incorrect. Such structures, as a consequence, should not be driving (constraining) forces in the construction of neurobiological theories of cognition. Rather,

as the argument continues, once there is a completed science of neurobiology, a full understanding and explanation of cognition will be naturally and readily derived consequences. Within this view it is of course possible, although unlikely – argue the eliminative materialists given the history of science – that (some of) the constructs of modern cognitive science, the present descriptions and terms of explanation, will find correspondence with the descriptors of neurobiology. This is all to say that the science of cognition in its present guise will be (to some extent) reduced to the science of neurobiology, rather than replaced by some other cognitive description. Of course, if the eliminative materialists are correct and the descriptive categories of mind are incorrect, then one aspect of the problem is eliminated, namely the translation (reduction) of these cognitive mentalistic constructs into the descriptive terms of brain science. But even if this view is true, there still remains the problem of describing the levels of organization of the brain and determining how they result in, for example, the comprehension of a specific sentence or connected discourse, however they are represented in cognitive theory. The position of the eliminative materialists would seem only to eliminate one set of descriptors that presently inform a considerable part of the effort to understand human cognition, while leaving a physical solution as open (our polite word for uninformative) as it is at present.

These views are, of course, modern philosophical reflections on the mind–body problem, and not part of the working assumptions of modern neuroscience, although we suspect that the basic premises of eliminative materialism are not infrequently received with considerable sympathy by neurobiologists as well as by a substantial number of cognitive scientists. Like those who claim that the science of cognition is in principle an irreducible, autonomous science (e.g., Fodor, 1975), the eliminative materialists offer an extreme view of the mind–body problem – one that does not easily fit with our intuitions. We offer no further comment on either of these extreme views. Rather, we note only that we prefer the stance of most scientists in both fields, or what we believe to be the majority view, namely, that whether there are complex cognitive functions, ranging from intentional attitudes to perception, to understanding language, and to problem solving, that are explicable in neurobiology is simply an open empirical question. And on this view rests this special issue of *Cognition*.

For completeness we should add that there is the strong belief among many that there is a third, algorithmic (i.e., computational) level of analysis in addition to the level of brain and the level of cognition (Marr & Poggio, 1979). This level is presumed to be logically distinct from either the activities of the mind or the hardware that instantiates (i.e., implements) activities and computations, but still constrained by both the possible activities and the hardware of the species. This view of three logically independent levels of

analysis does not, however, find universal acceptance. Changeux and Dehaene (this issue) and Edelman (1987a), among others, argue against a separate level of computation, which they view as a program that requires instruction, if not by a homunculus, then by the environment *or* a detailed genetic code, which in their view are equally improbable. It remains, however, to be empirically determined whether there is really a logically independent computational level and, if so, whether it will find a neurobiological explanation, although we will assume for the present discussion that a computational level exists.

Brain and mind, the objects of study of neurobiology and cognitive science respectively, also represent in the history of science interesting and attractive metaphors to explain the evolution of the behavior of complex systems, most notably that of humankind. For example, natural selection acts most obviously on behavioral capacities. Consequently, these capacities, and the mind they presumably reflect, are the clearest measure of the accomplishments of human evolution, and their study, when comparative in nature, can enlighten the origins of the characteristics that define humanity – an endeavor of immense inherent interest even if the methodology by its very nature leaves the mechanisms of evolution unspecified. By contrast, the phylogenetic path taken by the human brain over its 2.5 million years of evolution (or thereabouts), and its computational characteristics, are most likely slavish to the behavioral consequences of its physical and computational changes. On the other hand, of course, the metaphor of brain takes its strength, its appeal, in the fact that the brain has an undeniable physical presence that permits more directly the study of the evolutionary mechanisms underlying this most complex of biological structures. Indeed, with sufficient knowledge of the relation between neurophysiology and cognition the (partial) reconstruction of our cognitive evolution may be possible from the reconstruction of neural structures from fossil records.

The problem for a neurobiology of cognition, however, lies not in whether each metaphor, brain and mind, represents a valid, if not always mutually interesting, approach to the study of cognition, the behavioral acts and mental events of complex biological organisms, most notably human beings. Instead, the main issue, as we have noted – empirically answerable and hence the focus of this special issue – is the extent to which it will be possible to explain observations made under the guise of one metaphor in terms of observations derived from use of the other metaphor. Of course, adequate theoretical descriptions will enable us to move beyond explanations, for example, to formulate predictions about degree and type of change in one plane from observations of change in the other – an advancement that should have enormous practical consequences.

Structure of mind

For all of us, there is the mind, that seemingly lofty structure that is perceptive, thoughtful, and even reflective, the most mysterious of all its functions. However, as most scientists believe, these and other workings of the mind reflect a set of inherited dispositions to behave according to principles and rules, slowly being discovered, that were established over the long course of our species' evolution (phylogeny) and also the individual's personal history of interactions with the environment (ontogeny). The latter determines the actualization of individualized cognitive structures, just as is true of course for physical structures. In the metaphor of mind, there is a functional architecture that represents the organization of cognitive structures and that determines their manner of interaction with the environment and with each other. It is this functional architecture that presumably provides a theory of the workings of mind, that is, of cognition. It is a neurobiological description of the functional architecture that is sought when we speak of the physical instantiation of cognitive theory.

The functional architecture that represents mind and the processes of cognition can be analyzed at many levels. This is perhaps made most explicit in our descriptions of the processes – the representations, their transformations, and the use of knowledge structures – that are involved in the production and understanding of spoken language. On most views of spoken language understanding, representations of the physical signal are available at auditory, phonetic, lexical, syntactic, and semantic levels. The knowledge structures that are presumed to underlie the transformations include the processes of speech perception and production, the phonological and syntactic rules, the meanings of individual lexical units as well as rules and constraints on their generalization and combination, the pragmatics of language use, and finally world knowledge. But, as is well known, we do not as yet have a comprehensive and coherent theoretical description of the content, organization, or manner in which these levels of representation and knowledge structures operate so as to permit the rapid and effortless execution and interpretation of speech acts. Nevertheless, sufficient knowledge and theory exist to begin a detailed search for neurobiological understanding of language and its manner of function. Similar analyses can be given for other aspects of cognition – the perception of form, for example, which is actually an interesting and relatively rare example, inasmuch as both functional and physical descriptions and explanations are advancing and are even beginning to find correspondence (see, for example, Hubel & Wiesel, 1977; Marr, 1982).

Structure of brain

Brain by the very fact of its being a physical structure has seemed to many inadequate to capture the properties of mind, especially its intentionality and its awareness of itself. But this seeming inadequacy, as we have tried to argue, is not to be taken as an *a priori* truth, but rather an issue to be empirically determined. Like mind, brain reflects phylogenetic and ontogenetic experience. The phylogenetic history delimits the overall physical architecture, the types of elements constituting this architecture, and the rules and principles governing their interaction, all arising from a narrow range of possibilities that involve highly regulated combinations and chronologies of gene expression; for example, Jane's brain and all normal human brains are large, have temporal lobes, Heschl's gyri, callosal connections, Meynert stellates, asymmetrical synapses, testosterone receptors, and cell adhesion molecules. The ontogenetic history, through environmental (epigenetic) interactions capable of modifying the expression of the more modifiable of these genes, determines the particular brain architecture that emerges from within the genetically determined range of possibilities and thus, to continue our example, Jane's brain weighs 1500 g, has asymmetric temporal lobes, two Heschl's gyri on the right, a thick corpus callosum, and increased sensitivity to testosterone possibly as a result of abnormal early exposure to the sex steroid, and a tendency to tomboyish behaviors (Money & Ehrhardt, 1972); thus, this variability has functional correlates. In other instances of epigenetic influences, the receptive fields in the sensory cortex for the hand surface of adult monkeys varies among adult individuals (Merzenich et al., 1987), a developmentally determined decrease in the magnitude of anatomical asymmetry of some language areas correlates with disorders of reading acquisition (Galaburda et al., 1985), and a proportion of humans do not show aphasic symptoms after lesions in the left frontal lobe (Mohr et al., 1978). But, in all cases the variation of normal individuals finds expression within the constancy of the species.

An understanding of the architecture of brain requires delineation and understanding of its many levels of functioning. First, there is the gross anatomical level of hemispheres and lobes, frontal and occipital poles, dorsal and ventral and medial and lateral surfaces, cortical and subcortical grey masses, gyri and sulci which during the phrenological period were thought to correlate with cognitive and emotional traits and which today are found to be moderately useful for predicting functional deficits after injury and some gross developmental abnormalities. At the next level, in terms of decreasing structural complexity, there are widely distributed neuronal systems or more locally restricted networks or maps. These assemblies are composed of

specific numbers and types of neurons and interconnections, with each assembly presumably having separate and distinct functional properties. For example, there is the neuronal assembly that contains huge numbers of parvocellular neurons in the lateral geniculate nucleus and "blob" and thin-stripe neurons in the visual cortices and participates in (motionless) color perception (Livingstone & Hubel, 1988). Conversely, there may be a much smaller neuronal assembly such as that responsible for the vestibulo-ocular response, for instance, which contains only a few thousand input neurons, motor neurons, interneurons, cerebellar neurons, and sensory feedback neurons (Lisberger, 1988). Next we find the level of the individual neuron with specific functional properties, for example, the orientation (Zeki, 1983) or color-sensitive (Hubel & Livingstone, 1983; Zeki, 1983) neuron, useful for determining "receptive field" maps of *neural representation* of the external space, or the Mauthner neuron, which appears to play a role in impulse propagation (Yasargil, Adert, & Sandri, 1986).

At subcellular levels of description, the first is that of synapses. Examples of brain functioning at this level are illustrated by the presynaptic impingement of the mantle neurons onto the tail neuron, which modifies the latter's influence on the motor neuron to the gill of *Aplysia* during that invertebrate animal's habituation or sensitization (Kandel, 1976). The level of membrane is next in order with the activity of the postsynaptic *N*-methyl-*D*-aspartate (NMDA) receptor for excitatory amino acids in the mammalian hippocampal neuron, thought to mediate plasticity associated with long-term (declarative, but not procedural) memory (Morris, Anderson, Lynch, & Baudry, 1986; also see Cotman & Lynch, this volume), as well as with the actions of chemoreceptors, adhesion molecules, and ionic channels. Here local cell-cell interactions are determined, for example, by the closing of a calcium channel and decreasing release of neurotransmitter that is associated with habituation to a sensory stimulus in the behaving *Aplysia* and by the transformation of the cell adhesion molecule seen at the point when the cells forming a feather adopt the desired architecture (Gallin, Chuong, Finkel, & Edelman, 1986). The process of an emerging structure – resulting from the interaction between genetic and epigenetic effects – continues at each of these levels throughout life, albeit less at maturity and senescence (e.g., McKinley, Jenkins, Smith, & Merzenich, 1987; Wall & Eggers, 1971).

As we have claimed and attempted briefly to show, analysis of the architecture of the brain at multiple levels is necessary if the functional architecture and the complexities of human cognition evident in even its most basic forms, including perception, learning, categorization, and memory, are to be understood in terms of neurobiological principles. Moreover, the structural development of the brain, specifically, the change in morphology during

ontogenesis (Edelman, 1987b; Hubel & Wiesel, 1970) that might accommodate a new memory, or percept, or category (Changeux & Dehaene, this issue), has been demonstrated at many levels. For example, it has been shown in the number of cells comprising a neuronal assembly (Cowan, 1973; Graziadei & Monti Graziadei, 1979a, 1979b; Hamburger & Oppenheim, 1982; Oppenheim, 1981; Williams & Rakic, 1988), in the detailed structure of individual neurons (their dendritic and axonal structure) (Altman & Tyrer, 1977; Bastiani, du Lac, & Goodman, 1985; Kramer, Goldman, & Stent, 1985; Purpura, 1974; Ramón y Cajal, 1929), and in the detailed pattern of connections (inputs, outputs, overlaps; local circuits and long-ranging projections) (Easter, 1983; Ebesson, 1984; Hubel & Wiesel, 1977; Innocenti & Clarke, 1983; Ivy, Akers, & Killackey, 1979; Jones, 1981; Wise & Jones, 1976). This variation has, in addition, been shown in the arrangement of neurons in specific laminar and columnar arrays (cytoarchitectonics), with each cell type present in particular positions and at appropriate densities (Rakic, 1988; Woolsey et al., 1981), in the type of chemical transmission available to cells in a group and to cells at different times (Anderson & Cohen, 1977; Bixby & Spitzer, 1982; Goodman & Spitzer, 1981), in the electrical properties of single and distributed neurons (Goodman & Spitzer, 1981; Kano, 1975; Miyake, 1978; Mountcastle, 1978), in the chemical and electrical properties of synapses and membranes, which determine their dynamic responses (Carew, Hawkins, Abrams, & Kandel, 1984; Changeux & Danchin, 1976; Kandel, 1976; Llinás, Steinberg, & Walton, 1976; Lynch, Dunwiddie, & Gribkoff, 1977; Scholz & Byrne, 1987; Goodman & Spitzer, 1981), in the metabolic and transport properties of neurons (Bayon et al., 1979; Giacobini, 1975; Shaw & Meinertzhagen, 1986; Sokoloff, 1981; Swaab & Boer, 1983; Van Orden, Bloom, Barnett, & Giarman, 1966), including the effects of hormones originating in distant endocrine sites (McEwen, De Kloet, & Rostene, 1986; Nottebohm, 1981), and, finally, in the interactions between neurons and other elements such as glia (Fedoroff, 1978; Hatten, Liem, & Mason, 1984).

Mind-brain correspondences

The first problem to be solved in the quest for a neurobiology of cognition is how levels of description of mind correspond to levels of description of brain. On one extreme, some behaviors are associated with change in an ionic channel or a protein constituent (Alkon, 1984; Scholz & Byrne, 1987; also see Cotman & Lynch, this issue); others may require change in the response properties of a whole neuron (Braak & Braak, 1976; Chan-Palay, Palay, & Billings-Gagliardi, 1974; Winfield, 1982; Yasargil et al., 1986); and,

still others, on the other extreme, are associated only with demonstrable changes in a large neuronal network (Fox, Burton, & Raichle, 1987; Ingvar, 1983; Larsen, Skinhoj, & Lassen, 1978; Llinás, 1981). But the problem is even more complex. We know that a particular knowledge structure may be neurally represented in more than a single locus, with some representations in distinct architectonic areas (Fox et al., 1987; Ingvar, 1983; Larsen et al., 1978; Posner, Petersen, Fox, & Raichle, 1988; also see Damasio, this issue). Obviously these multiple representations for a single knowledge structure, as well as for the many structures that are needed to represent the things and events of the world, must be concatenated in terms of time and space if neurological explanations are to capture the complexity and coherence that are characteristic of the world we know. An idea of the enormity of this problem is readily forthcoming when we contemplate the possible neurological requirements for the production or comprehension of even a single sentence, to draw once more on our favorite example, that of language. Thus, we need to know what are the physical counterparts of cognitive representations and their temporal organizations as we move from auditory to phonetic to lexical to syntactic and to semantic structures, and how internalized information in the form of rules and knowledge of varying forms are physically instantiated (See Miller & Juczyk, this issue) so as to yield the multi-leveled, yet unified description that is apparently necessary for any instance of language understanding or production. There is some thinking (see Damasio, this issue), but little empirical evidence, informing the problem of binding, that is, the reconstitution of an entity from parts that appear to be spatially segregated in the nervous system, and the problem of bonding, that is, the unification of sequential experience into whole events.

Empirical challenges and approaches

With our improving capacity to describe behavior and brain at several levels at once, and to measure accurately changes in functional (cognitive) and physical (brain) states, it is becoming increasingly probable that we shall be able to detect how the structures and mechanisms of brain and the processes of cognition map onto one another, if indeed they do. If this is ultimately to occur, however, a fastidiously chronological approach is crucial in both descriptive planes. As is amply demonstrated in the brain, changes occurring at one anatomical level and locus usually propagate to other levels and to other anatomically or humorally related loci, which can potentially obscure the level and locus at which physical change is relevant (causally related) to the originally observed behavior. This potentially confounding phenomenon,

moreover, occurs with both relatively long and quite short time spans and in both immature and mature nervous systems. For example, at relatively longer spans of time, monocular enucleation (and to an extent even less severe environmental deprivation) in developing monkeys leads to cellular, architectonic, and connectional changes in the visual thalamus and visual cortex (see Rakic, 1988; Sretavan & Shatz, 1986a, 1986b); similarly, injury to the developing visual system of the hamster leads to plastic reorganization that further complicates the original visual loss (Schneider, 1981). At lower levels injury might be associated with the release of trophic molecules (Needels et al., 1986), which themselves can alter the behavioral capacities of the brain by their actions on these levels (Aloe, Cozzari, Calissano, & Levi-Montalcini, 1981). Even in the mature state damage to the (possibly) behaviorally relevant architecture of a neuronal circuit will propagate rapidly to the lowest levels of gene regulation and expression, and the physical events that follow may merely reflect attempts at repairing the damage, whereas the physical state that actually explains the behavior may not be as easily observed. In other words, before one can say that a particular protein or messenger is responsible for a particular behavioral state, it is important to determine whether these substances might not be involved in epiphenomena such as maintenance and upkeep of the machinery or even reaction to the behavior. This is a particularly sticky point in contemporary research on neurodegenerative disorders such as Alzheimer's disease, in which it is difficult to tell whether accumulated substances in the brain parenchyma cause the disease and its behavioral accompaniments, or simply reflect a point in a cascade of secondary changes. In some well-documented experimental research involving lesion-induced abnormal behaviors, the observed behaviors appear indeed to be the result of anatomical reactions to the injury more so than a direct consequence of the injury itself (Schneider, 1981).

At quite short periods of time, we need to be able to describe how interactions with environmental forces operate so as to change synaptic resistances, electrical activity, metabolic characteristics, and network organization, as well as their subsequent effects on levels at a far remove. Numerous data (Bartlett et al., 1987; Byrne, 1987; Fischler et al., 1983; Hillyard & Kutas, 1983; Ingvar, 1983; John et al., 1986; Lang et al., 1987; Mazziotta, Phelps, & Carson 1984; Rugg, Kok, Barrett & Fischler, 1986; Posner et al., 1988) are available on local changes in metabolic activity, electrical activation, and blood flow related to language, visual perception, and memory functions, which provide an idea about the structures involved in the processes (actively or passively; excited or inhibited), within the time scales tapped by the procedures, but not about the nature of the processes themselves or their relationship to the observed behaviors. In other words, the "physiological"

codes, which these measures appear to represent, do not approximate the explanatory value that would be afforded by a truly computational code, that is, the brain's algorithm for the observed behavior. And similarly, if the current metaphor of mind is correct, the various representations that are presumed to be formed for brief periods of time in response to environmental signals, whether they be simple visual forms or the complex acoustic signals of connected discourse, require that we be able to independently measure them and the processes of transformation across real time if we are to discover how the presumed stages of processing in the mental plane find instantiation in the physical domain of brain. And longer experiences that result in relatively permanent modifications of functional structures, such as must occur after we have acquired (or fixed) the rules or codes that determine how various objects and events in the environment are to be categorized and sentences are to be defined, must likewise be carefully measured across time. There would seem to be no other course if we are to understand the locus of these modifications and how such relatively permanent modifications exert their influence in both an upward and downward fashion and how they are mapped onto physical descriptions.

The incorporation of developmental phenomena, including descriptions of the initial state(s) (Mehler & Fox, 1985) and their development into stable states (cf. Changeux & Dehaene, this issue, and Edelman, 1987a), into material and functional theories of cognition is but a further example of what we have labeled a chronological approach to the study of mind and brain. It offers a precious opportunity for observing and comparing changes in states of brain and mind. Moreover, it permits examination of the functional or physical plane at, or close to, its beginning, when there has not been sufficient time for the unfolding of every physical and behavioral disposition and their subsequent modifications. Systems of interest are thus caught at relatively simple states of being, which surely must enhance the chances of successful mappings between the cognitive and neurobiological planes of description.

Experiments of nature, whether originating in corrupted genetic blueprints (presenting anomalous initial states), or in deviant environmental interactions during sensitive periods of development or maintenance, or in mature states that have sustained damage, can lead to variability or frank abnormality characterized by extraordinary functional and physical architectures. The study of these architectures can enlighten the understanding of the relationship between mind and brain. For instance, preliminary research has suggested a relation between processing styles in language activities and variants of cerebral lateralization that are distinguishable from one another by virtue of their distinct patterns of neuronal and connectional organization (Bever et al., in press; Galaburda, Aboitiz, Rosen, & Sherman, 1986;

Galaburda, Corsiglia, Rosen, & Sherman, 1987a; Galaburda, Rosen, & Sherman, 1987b). Similarly, individuals with some developmental language disorders differ in the patterns of cerebral laterality and asymmetry, and may exhibit alterations in local and widespread cortical architecture and connections (Galaburda & Kemper, 1979; Galaburda et al., 1987a, 1987b). Analysis of the plasticity and regenerative capacities of physical structures after experimentally induced injury can refine this understanding through carefully timed manipulations and observations in both physical and functional structures. As with developmental studies, experimentally induced loss of physical structures can be examined for the emergence of new functional properties or the alteration of old properties. Furthermore, the degree of change at one level of the physical plane can be evaluated with respect to the degree of change at other physical levels and at multiple levels within the functional plane. Such observations can help to answer questions regarding, for example, the extent of change in the physical state, in terms of source and propagation, that is required before changes in functional capacities will be detected, and whether continuous changes in one level of alterations result in continuous or discontinuous effects in other physical levels and in functional capacities.

The study of biological systems that are simple by virtue of their ontogenetic state may be complemented by studies of animals that are simple by virtue of their phylogenetic history (see Cotman & Lynch, this issue). These (usually invertebrate) animals exhibit extremely simple neuronal arrangements and behavioral repertoires, perhaps only distantly telling of the human brain and mind. Nevertheless, some fundamental aspects of the human brain and mind appear to be highly conserved in evolution and thus found in these relatively easily studied organisms. A particularly striking example of this is the work by Kandel and his associates (Kandel, 1976; also see Cotman & Lynch, this issue). Thus, the retraction of a gill and similar simple motor responses in association with either conditioned or unconditioned stimuli have been shown to relate to specific changes in the ionic channels of the presynaptic neuron, and longer lasting effects have been linked to new protein synthesis. Even these simple paired associate effects, however, do not occur (as some might suggest) in an unbiased "connectionist" arrangement (see below) of input, output, and hidden units, but rather presuppose an already complex innate structure, an initial state, upon which certain stimuli and not others are capable of producing certain responses and not others. Similar statements can be made about research done on cell cultures and tissue slices, which reflect attempts to simplify the biology of complex vertebrate nervous systems.

Beyond empirical knowledge

We note as a final comment on strategies for realizing a neurobiology of cognition that there is need for formalisms that go beyond empirical research. What we have offered in our discussion to this point is in effect a metatheoretical discourse on the neurobiology of cognition. We have related some rather uncontroversial general principles, or so we believe, describing brain and mind that would be necessary in one form or another in any neurobiological or functional account of cognition. Thus, for example, we see no potential counter to the idea that operation of both brain and mind are multi-leveled and that the initial steps in constructing a neurobiological theory of some facet or facets of cognition will be to delineate these levels within each descriptive plane, determine the mappings across planes, and show how change in the levels in one plane of description determines and maps onto change in levels of the other. Recent examples of the use of principles of this nature are found in Kosslyn (1988) and Posner et al. (1988) in their analyses, respectively, of mental imagery and the codes (representations) that are involved in reading. Nor do we foresee objections to the idea that this analysis into levels within each descriptive plane must by necessity have a chronological character. The acts of cognition are not momentary, nor do they consist of single, discrete entities. Quite to the contrary, even relatively simple acts of perception and most certainly acts of problem solving, language comprehension, foresight, and remembering, are best described as being constituted of sets of continuously unfolding events that are coherent because of their chronological order, which by necessity must be functionally and neurally represented. To ignore this chronicity can only result in theoretical descriptions that have no correspondence with environments or organisms.

But even with problems of this nature solved, and this is certainly far from the case at present, and perhaps not for some considerable time despite increasing recognition of the issue (Changeux & Dehaene, this issue; Damasio, this issue; Edelman, 1987a), a comprehensive neurobiology of cognition requires more. First, biological descriptions of cognition cannot, given the current state of technology, rest solely on descriptions of genomic activity, synaptic strengths and connections, neural groupings or networks, and the anatomical interactions and interconnections across levels. This is not to claim that such descriptions are not necessary. Rather our contention is that such descriptions must, in view of present (and quite possibly future) methodologies, remain incomplete, given that they involve 10^{11} neurons and as many as 10^{15} connections. What descriptions there are at present must be augmented by abstract generalizations and formalisms that go well beyond our empirical knowledge. Thus, just as we require an innate predisposition

early in life for deriving rules and meanings from the otherwise chaotic and seemingly disorganized spoken language around us during language acquisition, a theoretical "predisposition" of a formal nature is indispensable for the efficient acquisition of knowledge about the mind and its relationship to brain. Only in this manner, or so we believe, will neurobiologists overcome the obviously inherent limitation on our abilities to determine empirically the architectural and organizational details that are necessary for providing a neurobiological description of the complexities and coherence of cognition that we seek. Alternatives must be sought, and they have been, in the form of mathematical descriptions of neural functioning and neural networks. Of course, this is not a new development. Since the writings of McCulloch and Pitts (1943), formal descriptions of neural mechanisms and organized structures, based to varying degrees on known principles of neurophysiology and neurobiology, have been proffered in the attempt to explain behavior, including often quite complex acts of human cognition. At no time, however, has this endeavor been more prevalent than at present (e.g., Anderson & Hinton, 1981, Anderson & Rosenfeld, 1988; McClelland & Rumelhart, 1986), and equally impressive are the increasing sophistication of the formalisms that are used and the growing adherence to neurological realism.

Nevertheless, there is also a large body of criticism of this theoretical effort (e.g., Pinker & Mehler, 1987). A major concern of some cognitivists is whether formalisms based solely on associatively organized neural networks, without a formal representation of rules, will accommodate what appears to them to be rule-governed domains of cognition. And indeed the accomplishments of these formal models, while impressive in some domains, for example the acquisition and dissolution of associative links among lexical items (Kawamoto, 1985; Rossen, 1988), have done little to dispel the skepticism of those who hold that one of the benchmarks of cognition, especially in such domains as that of human language, is its rule-governed nature. We offer another complaint, namely, the very nearly universal lack of concern for inherited dispositions. It is our contention that it is the initial state(s) of a species – the very early, and, later, maturationally driven, biologically determined dispositions – that provide the origins of many specific cognitive achievements. Indeed, it is possible to argue that without such dispositions, without constraints on cognitive development, the very bases of our mental life, a rich conceptual network and a language, would in principle not be possible (e.g., Chomsky, 1965, 1980a, 1980b; Fodor, 1980). Evidence showing rather remarkable cognitive abilities in very young human infants has done much to strengthen our view that there are strong and pervasive innate dispositions that must find expression in neural models of cognition (e.g., Mehler & Fox,

1985, provide a number of reviews of the cognitive capacities across a wide range of activities). For how else are we to accommodate the findings that infants well within the first half year of life are able to perceive objects as unified entities (Kellman & Spelke, 1983), to form categorical representations for the sounds of speech and a seemingly indefinite number of groupings based on geometrical shapes and various artifacts (see Eimas, Miller, & Jusczyk, 1987; and Quinn & Eimas, 1986, for recent reviews), as well as to imitate motions and facial expressions (Meltzoff & Moore, 1977; and Field, Cohen, Greenberg, & Woodson, 1982)? In our view there is no other way; nor is there any alternative for accommodating the species-specific coherence that all successful organisms find in their environments, despite the indefinite number of alternatives that are available to all. In all fairness, we should note that the problem of innate dispositions has been a concern of neuronal group selection theory (e.g., Changeux & Dehaene, this issue, and Edelman, 1987a) and there is even evidence that the computational formalisms of the connectionists are beginning to change, and growing attention is now being paid to attempts to build "innate" properties into models (Hinton, 1988); these, so-called, innate properties will of course only make sense if they are constrained by knowledge of the behaviors (cognitive science) and of the brain (neuroscience).

The contributions

Having presented a general overview of what we believe is necessary for neurobiologically based theories of cognition and a brief review of recent accomplishments that makes us reasonably confident that successes will be forthcoming, we note in closing the plan of this issue.

There are six contributions, selected in part to provide a view of the range of activities that we believe constitute the growing endeavor to provide a neurobiology of cognition. Our selections range from what might be considered approaches in the style of the "grand scheme", that is, an attempt to provide the means of encompassing and explaining the full range of human cognition, to an examination of the functional structures for echolocation in the bat and their possible means of neuronal instantiation, and finally to the cellular and molecular structures of memory and learning.

The first contribution is by Antonio Damasio. He describes a global view of brain functioning. His treatise is a true example of a "grand scheme" – an overarching view showing how brain operates as an organized and organizing entity in contacting the world, in placing the organism in the world, and in directing cognition and the actions that result from cognition. Damasio

presents the brain as a complex system with multiple levels and assemblies that represent aspects – features – of the world and the manner in which those aspects are bound together spatially to form entities and how entities are bound temporally to form coherent events. He introduces us to the interesting concept of convergence zones that perform the operation of binding. Working from these basic ideas, he attempts to describe a coherent view of brain: one that can ultimately accommodate human cognition from its simplest functions to its most complex accomplishments in the realm of perception and memory, and even provide an account of consciousness. This approach puts us in mind of Hebb's *Organization of behavior*.

The second contribution is by Jean-Pierre Changeux and Stanislas Dehaene. Their discussion provides us with a sophisticated and we believe realistic framework for the construction of abstract, formal models, the purpose of which is to capture and explain human cognition at both its simplest and most complex levels of functioning. In their overview they describe how their position is by necessity developmental (and chronological) in nature, both in a phylogenetic and ontogenetic sense, and tied deeply (not nominally) to the facts of neuroscience. Changeux and Dehaene also describe the principles and mechanisms for the acquisition and memory of knowledge at cellular and subcellular levels, briefly here and in greater detail in their other publications. They bring to their readers a picture of how synaptic organizations occur and assemblies of ever-changing neuronal arrangements form and reform and are “selected” by environment events for a role in cognition. Their Darwinistic approach is rare among theoretical neuroscientists, but in our view correct – there is little reason to believe that the growth of neuronal structures and the acquisition of knowledge follows principles other than those that have applied to the organism as an evolving entity or to other systems within the organism – the immune system, for example. Their contributions can be viewed as providing a means for the acquisition and retention of knowledge as well as a framework for constructing another form of “grand scheme”, one that like Damasio's is potentially capable of accommodating even the most complex forms of cognition, for example, the recognition and execution of organized sequences of activity.

Next is a discussion of speech perception by Joanne Miller and Peter Jusczyk. Here, we contact that unique functional structure in humans – language. The authors are concerned solely with perception at the level of phonetics, which in being in closest contact with the acoustic representations of speech offers us the greatest hope of beginning the enterprise of building a neurobiological description of language that goes beyond descriptions of linguistic functions in anatomical terms. Although, as Miller and Jusczyk note, we have a good understanding of the physical signal and of a large

number of perceptual phenomena as well as considerable knowledge of mammalian auditory systems, neurophysiological models of speech perception that can accommodate the basic, but complex, functions of segmentation and perceptual invariance remain as yet a matter for the future. What we have at present consists of a number of reasonably well-grounded speculations of a neurophysiological nature that are beginning to accommodate a number of interesting perceptual phenomena. The reasons for this state of affairs, as described by Miller and Jusczyk, include ethical limitations on investigations into the human auditory system as well as the fact that we are dealing with a highly complex system that may well be species specific and uniquely dedicated to the perception of speech. If the latter is true, our neurobiological theorizing must proceed to a large extent in the absence of directly comparable animal models, even from those primates that number among our closest relations. Nevertheless, this does not mean that principles of animal communication including those of a neurobiological nature may not inform our physical descriptions of how human language is acquired and used at least at the level of speech, as Miller and Jusczyk extensively argue.

In the fourth contribution, Held provides a discussion of how the modern view of the nervous system can provide a basis for conscious perceptions – one that is less mysterious, less magical than the classical view that assumes a very special transformation in a specific anatomical locus is the means by which we become aware of the world about us. He uses his findings on infant visual development to illustrate his view of perception and how we are to understand the necessary and sufficient neuronal mechanisms, as well as the processing characteristics that underlie perception. More specifically, he shows how the (functional) processes of grating, vernier and stereo acuity, when examined at or near the time of their initial state, enable neurobiologically based explanations that include processes of development. What is particularly interesting for those who have followed Held's work is that his approach and findings provide not only a means for considering the difficult problem of how perception arises, but also insights into development itself and a rationale for remedial procedures to help children who have been afflicted with ocular and visual perceptual disorders early in life.

The fifth contribution is a detailed description of the most recent research of James Simmons and his colleagues on the manner in which echolocating bats represent the distance and physical characteristics of targets in three-dimensional space. Simmons gives us a remarkably detailed picture of how one form of biologically significant information is perceived and what information in what form must ultimately be represented in the neural structures. He also provides us with some ideas as to how this complex representation is instantiated in neuronal structures of the bat. This work provides a clear example

that a detailed neurobiology of an extraordinary processing systems appears to be possible. This is true undoubtedly because of the fine-grained description of what the bat represents that is now available, and quite possibly also because Simmons is concerned with what certainly appears to be a modular system (cf. Fodor, 1983) that serves a unique function in the bat. Moreover, a neurophysiological theory of echolocation should, we believe, provide principles of functioning that are applicable to other systems that process information of biological significance, for example, the mechanisms for speech perception.

In the final contribution, Cotman and Lynch offer a comprehensive discussion of recent developments concerning the acquisition and remembrance of information at systemic, cellular, and subcellular levels of neuronal organization. Thus, the authors review recent work, a substantial portion of which is their own, reinforcing the distinction, in neuroanatomical terms, between declarative or factual memory and procedural or rule memory. They also underline synaptic turnover and other processes that evidence the neuronal plasticity that is under environmental influence. Their examples illustrate that some of the basic mechanisms of classical conditioning, sensitization, habituation, short-term and long-term memory are beginning to be understood in terms of changes in synaptic properties at molecular levels. Their work, and that of their many colleagues, has been one of the major accomplishments of the neurosciences over the past decade or two. They show that we are approaching a solution to Lashley's search for the engram, and we are doing so at multiple levels of description, from the biochemical to the gross anatomical. The latter, as Cotman and Lynch interestingly inform us, has benefited considerably from studies of neurologically impaired humans. This reinforces our view that progress toward a neurobiology of cognition must by the nearly overwhelming complexity of the task take many forms ranging from the study of very simple organisms to complex organisms who have suffered neurological injuries of varying types.

A final comment on our selection of contributors is perhaps in order if only to begin to explain what must seem to some a rather eccentric view of a neurobiology of cognition. Our selections resulted from our own interests and opinions (biases, perhaps) as to what constitutes progress in the neurobiology of cognition and what is exciting, as well as an attempt to bring together a wide range of the approaches to a neurobiology of cognition. We were eager to show examples of work at very global levels as well as examples at quite molecular levels of analysis. Of course, our selections also reflect constraints imposed by space – handbooks can take a more comprehensive approach to their domains than can a single issue of a journal. In addition, the willingness of researchers to contribute to this endeavor, especially some

who are less optimistic about the ultimate success of a neurobiology of cognition, was a source of limitation. But the latter is another story, one more in keeping perhaps with a special issue on the ever-shifting battle lines in the philosophy of mind and brain.

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