

or repeated patchiness (Purves, Riddle, and LaMantia 1992) and to a wide range of functional or anatomical collectives. The best candidate for a true module was the “hypercolumn” (Hubel and Wiesel 1977): two adjacent ocular dominance columns, each containing a full set of orientation columns, suggested similar internal wiring, whatever the patch of visual field being represented. However, newer mapping techniques have shown that ocular dominance repeats are somewhat independent of orientation column repeats (Blasdel 1992), making adjacent hypercolumns internally nonidentical, that is, not iterated circuitry. Module remains a fuzzy term for anything larger than a macrocolumn but smaller than a map—though one increasingly sees it used as a trendy word denoting any cortical specialization, for example, modules as the foundation for “multiple intelligences.”

See also CONSCIOUSNESS, NEUROBIOLOGY OF; NEURON; SELF-ORGANIZING SYSTEMS; VISUAL CORTEX, CELL TYPES AND CONNECTIONS IN; VISUAL PROCESSING STREAMS

—William H. Calvin

References

- Bartfeld, E., and A. Grinvald. (1992). Relationships between orientation-preference pinwheels, cytochrome oxidase blobs, and ocular-dominance columns in primate striate cortex. *Proc. Natl. Acad. Sci. USA* 89: 11905–11909.
- Blasdel, G. G. (1992). Orientation selectivity, preference, and continuity in monkey striate cortex. *J. Neurosci.* 12: 3139–3161.
- Bullock, T. H. (1980). Reassessment of neural connectivity and its specification. In H. M. Pinsker and W. D. Willis, Jr., Eds., *Information Processing in the Nervous System*. New York: Raven Press, pp. 199–220.
- Calvin, W. H. (1995). Cortical columns, modules, and Hebbian cell assemblies. In Michael A. Arbib, Ed., *The Handbook of Brain Theory and Neural Networks*. Cambridge, MA: Bradford Books/MIT Press, pp. 269–272.
- Calvin, W. H. (1996). *The Cerebral Code: Thinking a Thought in the Mosaics of the Mind*. Cambridge, MA: MIT Press.
- Calvin, W. H., and G. A. Ojemann. (1994). *Conversations with Neil's Brain: The Neural Nature of Thought and Language*. Reading, MA: Addison-Wesley.
- Diamond, I. (1979). The subdivisions of neocortex: A proposal to revise the traditional view of sensory, motor, and association areas. In J. M. Sprague and A. N. Epstein, Eds., *Progress in Psychobiology and Physiological Psychology* 8. New York: Academic Press, pp. 1–43.
- Favorov, O. V., and D. G. Kelly. (1994). Minicolumnar organization within somatosensory cortical segregates: I. Development of afferent connections. *Cerebral Cortex* 4: 408–427.
- Gilbert, C. D. (1993). Circuitry, architecture, and functional dynamics of visual cortex. *Cerebral Cortex* 3: 373–386.
- Goldman-Rakic, P. (1990). Parallel systems in the cerebral cortex: The topography of cognition. In M. A. Arbib and J. A. Robinson, Eds., *Natural and Artificial Parallel Computation*. Cambridge, MA: MIT Press, pp. 155–176.
- Horton, J. C., and D. R. Hocking. (1996). Intrinsic variability of ocular dominance column periodicity in normal macaque monkeys. *J. Neurosci.* 16 (22): 7228–7239.
- Hubel, D. H., and T. N. Wiesel. (1977). Functional architecture of macaque visual cortex. *Proc. Roy. Soc. (London)* 198B: 1–59.
- Katz, L. C., and E. M. Callaway. (1992). Development of local circuits in mammalian visual cortex. *Ann. Rev. Neurosci.* 15: 31–56.
- Livingstone, M. S. (1996). Oscillatory firing and interneuronal correlations in squirrel monkey striate cortex. *J. Neurophysiol.* 75: 2467–2485.
- Livingstone, M. S., and D. H. Hubel. (1988). Segregation of form, color, movement, and depth: Anatomy, physiology, and perception. *Science* 240: 740–749.
- Lund, J. S., T. Yoshioka, and J. B. Levitt. (1993). Comparison of intrinsic connectivity in different areas of macaque monkey cerebral cortex. *Cerebral Cortex* 3: 148–162.
- Mountcastle, V. B. (1979). An organizing principle for cerebral function: The unit module and the distributed system. In F. O. Schmitt and F. G. Worden, Eds., *The Neurosciences Fourth Study Program*. Cambridge, MA: MIT Press, pp. 21–42.
- Peters, A., and E. Yilmaz. (1993). Neuronal organization in area 17 of cat visual cortex. *Cerebral Cortex* 3: 49–68.
- Purves, D., D. R. Riddle, and A-S. LaMantia. (1992). Iterated patterns of brain circuitry (or how the cortex gets its spots). *Trends in the Neurosciences* 15: 362–368 (see letters in 16: 178–181).
- Shaw, G. L., E. Harth, and A. B. Scheibel. (1982). Cooperativity in brain function: Assemblies of approximately 30 neurons. *Exp. Neurol.* 77: 324–358.
- White, E. L. (1989). *Cortical Circuits*. Boston: Birkhauser.
- Yuste, R., and D. Simons. (1996). Barrels in the desert: the Sde Boker workshop on neocortical circuits. *Neuron* 19: 231–237.

Communication

See ANIMAL COMMUNICATION; GRICE, H. PAUL; LANGUAGE AND COMMUNICATION

Comparative Psychology

The comparative study of animal and human cognition should be an important part of cognitive science. The field of comparative psychology, however, emerged from the paradigm of BEHAVIORISM and so has not contributed greatly toward this end. The reasons for this are telling and help to explicate the main directions of modern evolutionary thinking about behavior and cognition.

The general program of comparative psychology began with Charles DARWIN's *Origin of Species* (1859). Darwin believed that the comparative study of animal behavior and cognition was crucial both for reconstructing the phylogenies of extant species (behavioral comparisons thus supplementing morphological comparisons) and for situating the behavior and cognition of particular species, including humans, in their appropriate evolutionary contexts. Toward these ends, Darwin (1871, 1872) reported some informal comparisons between the behavior of humans and nonhuman animals, as did his disciples Spencer (1894), Hobhouse (1901), and Romanes (1882, 1883). The goal was thus clear: to shed light on human cognition through a study of its evolutionary roots as embodied in extant animal species.

Arising as a reaction to some of the anthropomorphic excesses of this tradition was behaviorism. During the early and middle parts of the century, researchers such as Watson, Thorndike, and Tolman espoused the view that the psychology of nonhuman animals was best studied not informally or

anecdotally, but experimentally in the laboratory. Within this tradition, some psychologists became interested in comparing the learning skills of different animal species in a quantitative manner, and this procedure came to be known as comparative psychology. One especially well-known series of studies was summarized by Bitterman (1965), who compared several species of insect, fish, and mammal on such things as speed to learn a simple perceptual discrimination, speed to learn a reversal of contingencies, and other discrimination learning skills. An implicit assumption of much of this work was that just as morphology became ever more complex from insect to fish to mammals to humans, so behavior should show this same "progression" (see Rumbaugh 1970 and Roitblatt 1987 for more modern versions of this approach).

Comparative psychology came under attack from its inception by researchers who felt that studying animals outside of their natural ecologies, on experimental tasks for which they were not naturally adapted, was a futile, indeed a misguided, enterprise (e.g., Beach 1950; Hodos and Campbell 1969). They charged that studies such as Bitterman's smacked of a *scalae natura* in which some animals were "higher" or "more intelligent" than others, with, of course, humans atop the heap. That is, many of the comparative studies of learning implicitly assumed that nonhuman animals represented primitive steps on the way to humans as evolutionary *telos*. This contradicted the established Darwinian fact of treelike branching evolution in which no living species was a primitive version of any other living species, but rather each species was its own *telos*.

Another blow to comparative psychology came from experiments such as those of Garcia and Koelling (1966), which demonstrated that different species were evolutionarily prepared to learn qualitatively different things from their species-typical environments. More generally, many studies emanating from the traditions of ETHOLOGY and behavioral ecology at this same time demonstrated that different animal species were adapted to very different aspects of the environment and therefore that comparisons along any single behavioral dimension, such as learning or intelligence, were hopelessly simplistic and missed the essential richness of the behavioral ecology of organism-environment interactions (see Eibl-Eibesfeldt 1970 for a review). Ethologists and behavioral ecologists were much less interested in finding general processes or principles that spanned all animal species than were comparative psychologists, and they were much less inclined to treat human beings as any kind of special species in the evolutionary scheme of things.

Today, most scientists who study animal behavior have incorporated the insights of the ethologists and behavioral ecologists into their thinking so that it would currently be difficult to locate any individuals who call themselves comparative psychologists in the classic meaning of the term (see Dewsbury 1984a, 1984b for a slightly different perspective). However, there does exist a journal called the *Journal of Comparative Psychology*, and many important studies of animal behavior are published there—mostly experimental studies of captive animals (as opposed to ethological studies, which are more often naturalistic). In contrast to the classic, behavioristic form of comparative psychology, modern comparative studies pay much more

attention to the particular cognitive skills of particular species and how these are adapted to particular aspects of specific ecological niches. This enterprise is sometimes called COGNITIVE ETHOLOGY.

For these same reasons, modern comparative studies typically compare only species that are fairly closely related to one another phylogenetically—thus assuring at least some commonalities of ecology and adaptation based on their relatively short times as distinct species. As one example, in the modern study of primate cognition there are currently debates over possible differences between Old World monkeys and apes, whose common ancestor lived about 20 to 30 million years ago. Some researchers claim that monkeys live in an exclusively sensori-motor world of the here-and-now and that only apes have cognitive representations of a humanlike nature (Byrne 1995). Other researchers claim that all nonhuman primates cognitively represent their worlds for purposes of foraging and social interaction, but that only humans employ the forms of symbolic representation that depend on culture, intersubjectivity, and language (Tomasello and Call 1997). These kinds of theoretical debates and the research they generate employ the comparative method, but they do so in much more ecologically and evolutionarily sensitive ways than most of the debates and research in classical comparative psychology.

Comparative studies, in the broad sense of the term, are important for cognitive science in general because: (1) they document something of the range of cognitive skills that have evolved in the natural world and how these work; (2) they help to identify the functions for which particular cognitive skills have evolved, thus specifying an important dimension of their nature; and (3) they situate the cognition of particular species, including humans, in their appropriate evolutionary contexts, which speaks directly to such crucial questions as the ontogenetic mechanisms by which cognitive skills develop in individuals.

See also ADAPTATION AND ADAPTATIONISM; ECOLOGICAL VALIDITY; EVOLUTIONARY PSYCHOLOGY; PRIMATE COGNITION

—Michael Tomasello

References

- Beach, F. (1950). The snark was a boojum. *American Psychologist* 5: 115–124.
- Bitterman, M. (1965). Phyletic differences in learning. *American Psychologist* 20: 396–410.
- Byrne, R. W. (1995). *The Thinking Ape*. Oxford: Oxford University Press.
- Darwin, C. (1859). *On the Origin of Species by Means of Natural Selection*. London: John Murray.
- Darwin, C. (1871). *The Descent of Man and Selection in Relation to Sex*. London: John Murray.
- Darwin, C. (1872). *The Expression of Emotions in Man and Animals*. London: John Murray.
- Dewsbury, D., Ed. (1984a). *Foundations of Comparative Psychology*. New York: Van Nostrand.
- Dewsbury, D. (1984b). *Comparative Psychology in the Twentieth Century*. Stroudsburg, PA: Hutchinson Ross.
- Eibl-Eibesfeldt, I. (1970). *Ethology: The Biology of Behavior*. New York: Holt, Rinehart, Winston.

- Garcia, J., and R. Koelling. (1966). The relation of cue to consequent in avoidance learning. *Psychonomic Science* 4: 123–124.
- Hobhouse, L. T. (1901). *Mind in Evolution*. London: Macmillan.
- Hodos, W., and C. B. G. Campbell. (1969). Scala naturae: Why there is no theory in comparative psychology. *Psychological Review* 76: 337–350.
- Roitblat, H. L. (1987). *Introduction to Comparative Cognition*. New York: W. H. Freeman and Company.
- Romanes, G. J. (1882). *Animal Intelligence*. London: Kegan, Paul Trench and Co.
- Romanes, G. J. (1883). *Mental Evolution in Animals*. London: Kegan, Paul Trench and Co.
- Rumbaugh, D. M. (1970). Learning skills of anthropoids. In L. A. Rosenblum, Ed., *Primate Behavior: Developments in Field and Laboratory Research*. New York: Academic Press, pp. 1–70.
- Spencer, H. (1894). *Principles of Psychology*. London: Macmillan.
- Tomasello, M., and J. Call. (1997). *Primate Cognition*. Oxford University Press.

Competence/Performance Distinction

See INTRODUCTION: LINGUISTICS AND LANGUAGE; LINGUISTICS, PHILOSOPHICAL ISSUES; PARAMETER-SETTING APPROACHES TO ACQUISITION, CREOLIZATION, AND DIACHRONY

Competition

See COOPERATION AND COMPETITION; GAME THEORY

Competitive Learning

See UNSUPERVISED LEARNING

Compliant Control

See CONTROL THEORY; MANIPULATION AND GRASPING

Compositionality

Compositionality, a guiding principle in research on the SYNTAX-SEMANTICS INTERFACE of natural languages, is typically stated as follows: “The meaning of a complex expression is a function of the meanings of its immediate syntactic parts and the way in which they are combined.” It says, for example, that the meaning of the sentence

$$S \text{ [}_{NP} \text{ Zuzana [}_{VP} \text{ [}_{VP} \text{ owns [}_{NP} \text{ a schnauzer]]]],}$$

where the commonly assumed syntactic structure is indicated by brackets, can be derived from the meanings of the NP *Zuzana* and the VP *owns a schnauzer*; and the fact that this NP and VP are combined to form a sentence. In turn, the meaning of *owns a schnauzer* can be derived from the meanings of *owns* and *a schnauzer* and the fact that they form a VP; hence, the principle of compositionality applies recursively. The principle is implicit in the work of Gottlob FREGE (1848–1920), and was explicitly assumed by Katz and Fodor (1963) and in the work of Richard Montague and his followers (cf. Dowty, Wall, and Peters 1981).

In some form, compositionality is a virtually necessary principle, given the fact that natural languages can express an infinity of meanings and can be learned by humans with finite resources. Essentially, humans have to learn the meanings of basic expressions, the words in the LEXICON (in the magnitude of 10^5), and the meaning effects of syntactic combinations (in the magnitude of 10^7 ; see SYNTAX). With that they are ready to understand an infinite number of syntactically well-formed expressions. Thus, compositionality is necessary if we see the language faculty, with Wilhelm von Humboldt, as making infinite use of finite means. But compositionality also embodies the claim that semantic interpretation is local, or modular. In order to find out what a (possibly complex) expression *A* means, we just have to look at *A*, and not at the context in which *A* occurs. In its strict version, this claim is clearly wrong, and defenders of compositionality have to account for the context sensitivity of interpretation in one way or other.

There are certain exceptions to compositionality in the form stated above. Idioms and compounds are syntactically complex but come with a meaning that cannot be derived from their parts, like *kick the bucket* or *blackbird*. They have to be learned just like basic words. But compositionality does allow for cases in which the resulting meaning is due to a syntactic construction, as in the comparative construction *The higher they rise, the deeper they fall*. Also, it allows for constructionally ambiguous expressions like *French teacher*: *French* can be combined with *teacher* as a modifier (“teacher from France”), or as an argument (“teacher of French”). Even though the constituents are arguably the same, the syntactic rules by which they are combined differ, a difference that incidentally shows up in stress (see STRESS, LINGUISTIC).

A hidden assumption in the formulation of the principle of compositionality is that the ways in which meanings are combined are, in some difficult-to-define sense, “natural.” Even an idiom like *red herring* would be compositional if we allowed for unnatural interpretation rules like “The meaning of a complex noun consisting of an adjective and a noun is the set of objects that fall both under the meaning of the adjective and the meaning of the noun, except if the adjective is *red* and the noun is *herring*, in which case it may also denote something that distracts from the real issue.” But often we need quite similar rules for apparently compositional expressions. For example, *red hair* seems to be compositional, but if we just work with the usual meaning of *red* (say, “of the color of blood”), then it would mean something like “hair of the color of blood.” *Red hair* can mean that (think of a punk's hair dyed red), but typically is understood differently. Some researchers have questioned compositionality because of such context-dependent interpretations (cf. Langacker 1987). But a certain amount of context sensitivity can be built into the meaning of lexical items. For example, the context-sensitive interpretation of *red* can be given as: “When combined with a noun meaning *N*, it singles out those objects in *N* that appear closest to the color of blood for the human eye.” This would identify ordinary red hair when combined with *hair*. Of course, prototypical red hair is not prototypically red; see Kamp and Partee (1995) for a discussion of compositionality and prototype theory.