What is Cognitive Science?[+]

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Rich scientific disciplines defy simple definition, and Cognitive Science is no exception. For present purposes Cognitive Science can be defined broadly as the scientific study of minds and brains, be they real, artificial, human or animal. In practice Cognitive Science has been more limited, largely restricting itself to domains in which there is reasonable hope of attaining real understanding. The richness and diversity of the contributions to these volumes show that there are now many such domains.

By "understanding" we mean going beyond common-sense intuitions, often to the point of radically subverting them. It is no longer surprising when a cognitive system is shown to work in highly unexpected ways. One of the insights of modern cognitive science is that the mind often works in counter-intuitive ways.

Mature sciences owe much of their initial progress to the pursuit of phenomena and hypotheses within a few "windows of opportunity", often opened by chance. Many of these seem, at their inception, to be quite far from the daily concerns of ordinary people, but they come to have great impact. The cognitive sciences have also thrived on the deep exploration of such windows. The analysis of language impairments following stroke or war injuries by a group of outstanding neurologists in the 19th century (Broca, 1878; Wernicke, 1874) is an example, leading to important insights both about the organization of language and its instantiation in the brain. The use of rapid-succession photography by the French physiologist Marey (1830-1904) (Braun, 1992) and by the expatriate Englishman Eadweard Muybridge (also, by a curious coincidence, born in 1830 and deceased in 1904) in the US (Haas, 1976) made possible the

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analysis of the natural motion of people and horses and opened the way to present understanding of the uniqueness of such motion in perception and planning.

The development of highly selective neuron staining methods, which led to the emergence of the "neuron doctrine" is yet another example. The ability to visualize fine details of the central nervous system (CNS) settled the debate between the Italian Camillo Golgi and the Spaniard Santiago Ramon y Cajal over the nature of connection and communication within the brain. Golgi had argued that the nervous system was a meshwork of connected elements. Cajal, on the other hand, argued that there were discrete elements within the CNS, subsequently called neurons, that were not actually in contact, but instead communicated across a gap – the synapse. Stained sections supported Cajal, and the era of neurons and synapses began [2] [3]. The subsequent study of neuronal transmission in the squid giant axon, and the development of single neuron recording methods in vertebrates built upon this early work. Parallel developments in the study of logic and computation generated early attempts to apply mathematical principles to nervous system function (McCulloch & Pitts, 1943), and these in turn eventually led to modern approaches in computational neuroscience.

Attempts to ameliorate diseases of the nervous system have played a significant role in the history of cognitive science. The treatment of recurrent epileptic seizures resistant to all drugs led to experimental surgical treatments that have produced fundamental knowledge about brain function. The use of radical resection of the temporal lobe had the unfortunate consequence of causing a massive amnesic syndrome, but the study of H.M. (Scoville and Milner, 1957) and other such patients has contributed greatly to our understanding of memory. Similarly, the use of surgical section of the corpus callosum led to the discovery of the "split brain", which has ever since fascinated philosophers and the public at large (Gazzaniga, 1970; Sperry, 1968).

In this general introduction we will briefly explore these and some other "windows of opportunity" that helped create cognitive science as we know it today. We cannot be exhaustive (in the online version of this Encyclopedia we will offer a more analytic "view" into some selected windows) but we hope in this short introduction to provide a broad road map to the

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[2] A century later, matters are not quite as settled as they appeared to be. There is now considerable evidence of direct contacts between at least some neurons in the CNS – so-called electrical synapses.

[3] Golgi and Cajal were jointly awarded in 1906 the Nobel Prize "in physiology or medicine".

field, where it has come from, and where it might be headed. We are aware that the names of protagonists are often introduced without proper biographical presentation, and that many concepts and terms are briefly characterized or sometimes just mentioned. It is our goal, in this brief introduction, to offer a general synopsis, partly historical, partly analytic, but hopefully sufficient to situate people and ideas in a vast web, trusting that the reader will be stimulated to locate related articles in these volumes, and anticipate those yet to be written for the online version. Our task is made somewhat easier by the existence of some excellent histories of cognitive science (Baars, 1986; Bechtel, Abrahamsen & Graham, 1999; Dupuy, 2000; Gardner, 1985), as well as numerous reflections on history by key participants (to which we shall refer below). Inevitably, our road map will reflect the journeys we ourselves have taken; we apologize in advance to those of our colleagues whose contributions to cognitive science have been overlooked in what follows.

Some Prehistory

Interest in mind and brain is as old as recorded history, and any complete rendering of the prehistory of Cognitive Science would treat early philosophers at some length. That, however, is not our purpose. Rather, we will take it for granted that interest in fundamental questions about cognition and its physical bases has long existed, well before the term "cognitive science" was coined, and pick up our story when genuinely scientific analyses became possible in the 19th century. An interesting perspective on this gestational era is offered in Albertazzi (Albertazzi, 2001) .

We can identify several strands of 19th century thought as clearly antecedent to modern cognitive science: the work of the neuropsychologists who studied the impact of brain damage on language and other cognitive abilities; the development by Darwin and others of the theory of evolution (later to be extended into theories of the evolution of the brain and mind); the creation of modern experimental psychology and psychophysics (Ebbinghaus, Helmholtz and Wundt deserve special mention here); and, the initial efforts of neurologists and psychiatrists to relate complex human conditions to underlying neuroanatomy and neuropathology [4].

[4] There were important "schools" of neuropsychologists and neuropsychiatrists throughout Europe at this time. In Germany, Brodmann, Pick, Alzheimer, and Korsakoff are noteworthy. In France there were Janet and Charcot, among others. In England Hughlings-Jackson, Head, and Ferrier deserve note. In Russia, Sechenov was extremely influential, and had a major impact on Pavlov.

Several landmarks at the very end of the 19th century stand out: (1) the publication in 1890 by William James of The Principles of Psychology; (James, 1890) (2) the aforementioned emergence of the neuron doctrine in the work of Cajal; (3) and the development of Freud's psychodynamic approach. All three had profound and lasting effects, although many might argue that the influence of Freud's thinking has waned. Time will tell. A fourth strand of intellectual development that has had a profound influence on cognitive science can also be traced back to the 19th century – the emergence of computational devices. Fascinating histories have been written about the role of key individuals such as Augusta Ada Byron (Stein, 1985) and Charles Babbage in this development, but real progress in this domain was not seen until the 20th century. Finally, within philosophy and linguistics, there had been the development of powerful systems of logic (Frege, 1879; Russell, 1900, 1919; Tarski, 1935, 1996; Whitehead and Russell, 1910)

These various advances began to provide the basis for formal treatments of many aspects of cognitive function, and it is these treatments that, in the fullness of time, combined with germane developments in experimental psychology, neuroscience, linguistics and anthropology. The convergence of these strands produced modern cognitive science.

The Behaviorist Interregnum

Notwithstanding the explosion of possibilities offered by the developments noted above, the beginning of the 20th century saw a turning away from many of the issues central to cognitive science, especially in North America. The behaviorist revolution, exemplified by John B. Watson (Watson, 1924), can be viewed in retrospect as a reaction against the overly ambitious reach of early cognitive scientists [5]. Behaviorists rightly pointed out that not enough was known

[5] An interesting example is offered by Freud's Project for a Scientific Psychology (1895). This remarkable piece of work started out in a blaze of glory, defining in a very clear way what the issues were, and what kinds of answers would be necessary. Indeed, Karl Pribram (Pribram and Gill, 1976) resurrected this remarkable essay from near oblivion and justified the subsequent characterization of Freud, by Frank Sulloway, as a "biologist of the mind" (Sulloway, 1979). However Freud's approach went gloriously off the rails, and was ultimately abandoned by Freud altogether. This failure can now be seen as inevitable, given the tools that Freud had to work with at the time.

about what goes on inside the organism to ground any sort of meaningful theory. This judgment combined with an infectious enthusiasm for spreading "rigorous" scientific methodology to all fields of inquiry, effectively banishing all appeals to internal states and representations (concepts, ideas, meanings, percepts, computations etc) [6]. Better to focus on what could be observed and measured if one wanted to create a science.

A strict behaviorist view, and its emphasis on general learning mechanisms persisted for about 50 years in North America, during which time the center was occupied by narrowly conceived research programs, some of which bore considerable fruit. Clark Hull's (1943) early efforts at producing mathematical models of behavior (Hull, 1943) were largely unsuccessful but they provided the foundation upon which a more modern and influential mathematical psychology was subsequently built [7].

Three major exceptions to the narrow behaviorist perspective of this era were Karl Lashley, Edward Chace Tolman and Egon Brunswik. Lashley's (1929) work on neural mechanisms underlying intelligence (Lashley, 1929), and his thoughts about the localization of

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[6] Somewhat later, spelling out in full a judgment that had been implicit all along, the probehaviorist analytic philosopher Quine referred to these mind-internal entities as "creatures of darkness" (Quine, 1956). It was inevitable that the chief architects of an unrepentantly mentalistic, internalist, computational and representational theory of mind (usually referred to as RTM – Representational Theory of Mind), most notably Noam Chomsky and Jerry Fodor, found themselves fighting a long and sustained battle against behaviorism and its avatar in contemporary analytic philosophy (methodological behaviorism). Chomsky's destructive review of Skinner (Chomsky, 1959/1980) and Fodor's anti-behaviorist book-long essay "The Language of Thought" (Fodor, 1975) helped shaped the turn away from behaviorism and much of modern mentalistic cognitive science for many years. Chomsky argued in favor of the specificity and universality of grammar. He defended an internalist, individualistic, intensional (as opposed to extensional) characterization of grammars (Chomsky, 1955, 1956, 1957, 1986), against a Wittgensteinian conception of language as a collective conventional public entity, individually mastered through the tuning up of a "skill", eternally subject to the cumulative action of infinitesimally small variations, from one dialect to the next, from one generation to the next. (Cf. Chomsky's and Fodor's writings in reaction to theses by Quine, Putnam, Davidson, Dummett, Kripke) (Chomsky, 1980; Chomsky, 1988; Chomsky, N., 1995; Chomsky, 1998) (Fodor, 1981; Fodor, 1990; Fodor and Lepore, 1992). We will expand in the text and in subsequent notes Chomsky's critical role in the early days of cognitive science, his debate with Piaget, and the present revival of Piagetian and neo-behaviorist theses in the domain of connectionist cognitive science.

[7] Hull's attempt to generate mathematical treatments of learning, especially animal learning, was brought into the modern era by (Rescorla and Wagner, 1972), and (Mackintosh, 1975). Reacting to critical new findings such as the phenomenon of "blocking" (Kamin, 1969), they produced learning rule equations that anticipated some of the more powerful algorithms to be developed within the connectionist framework 20 years later.

function in the nervous system, provided a foundation for the subsequent efforts of many influential neuropsychologists of the 1940s and 1950s, including Donald Olding Hebb (Hebb, 1949). Tolman and Brunswik were strongly influenced by the Gestalt movement in Germany and in turn set the stage for a return of cognitive approaches in North America. Tolman's early book, Purposive Behavior in Animals and Men (1932) (Tolman, 1932) provided a roadmap for the pursuit of aspects of behavior that went beyond the observable. Brunswik, an expatriate Viennese, joined the psychology faculty of Berkeley in 1937 thanks to Tolman, but remained a maverick his entire life (committing suicide in 1955) (Bower, 2002). He introduced the term and the notion of "ecological validity" (usually associated with the much better known work of James Gibson and Ulric Neisser) defying the relevance of the narrow laboratory settings so dear to the behaviorists. Brunswik studied the role of sensory cues and subjective estimates in shaping perception and judgment. He advocated the view that knowledge is a probability-based process, developed a 'probabilistic functionalism' and was among the first to reveal subjective probability biases. His better known "lens model" pictures systematic distortions at the interface between the external scene and the observer, whereby the structure of the environment is filtered by the structure of subjective perception and knowledge. This results in "perceptual compromises", fit to serve the relevant purposes of the observer [8].

Behaviorism was not as dominant in Europe as it was in North America, and elements of what was to become cognitive science proceeded in a variety of domains. The Gestalt psychologists, including Wertheimer, Kohler and Koffka, steadfastly retained a focus on the role of organization in perception and problem solving, with Kohler's work on "insight" being a particularly important contribution. Bartlett's (1932) book "Remembering" (Bartlett, 1932) explored the role of schemata in the formation of memory, and remains influential to the present.

[8] Brunswik influenced Rosenblatt, who developed the perceptron model in the 1950s. He also had a significant influence on Julian Hochberg, who two decades after his student days at Berkeley talked about perception in terms of piecemeal perception, mental structures and the intentions of the viewer. Hochberg (Hochberg, 1956, 1978) emphasized integration over inputs obtained from successive glances, hence the critical role of memory and other cognitive factors in perception, a line that has been continued by Hochberg's students to the present day (Peterson, 1999). An explicit revival of Brunswikian models in decision-making is presently advocated by Gerd Gigerenzer and his colleagues at the Max Planck Institute for Human Development in Berlin (Gigerenzer, Hoffrage & Kleinbölting, 1991), by A.J. Figueredo at the University of Arizona (Figueredo, 1992), and by Kenneth R. Hammond, now emeritus professor at the University of Colorado in Boulder, who has recently edited an extensive collection of reprints of Brunswick's original papers (Hammond and Stewart, 2001).

Piaget's (Piaget, 1930, 1954) comprehensive studies on development that emphasized the internal models children formed in comprehending the world had an enormous impact in Europe, and subsequently in North America when they were made widely known after the second world war [9]. Finally, there were the convergent contributions by Kurt Gödel, Alan Mathison Turing, Alonzo Church and Stephen C. Kleene on fundamental issues in computation, recursion and the theory of automata (Church, 1936; Kleene, 1936; Turing, 1936a, 1936b) [10].

The Modern Era Begins

We would suggest that the modern era in cognitive science began in the late 1930s and early 1940s. In 1936 Turing published his crucial paper on "computability" in which he spelled out the design for a machine that could carry out any set of well-defined formal operations. Two years later Shannon (1938) demonstrated that on-off electrical circuits could carry out basic mathematical procedures, an idea that ultimately led to the development of "information theory" (Shannon, 1938, 1948; Shannon and Weaver, 1949/1998). A critical early contribution was published by Kenneth Craik, entitled "The Nature of Explanation" (Craik, 1943). Craik sought ways to link mental and mechanical operations, and settled on the notion of <u>internal models</u> that would become central to cognitive science in the future. He claimed that:

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[9] Piaget's work covered a variety of crucial domains, from the child's conception of numbers to moral judgment, from the development of the concept of causality to a cognitive approach to the historical development of physics and of science in general. Many schoolteachers and avant-garde research teams in developmental psychology had tried with some success to apply Piaget's central ideas to their teaching in the classroom. The progressive spontaneous unfolding of higher cognitive capacities in the developing child had been modeled by Piaget and his collaborators at the University of Geneva through a series of successive "stages", characterized as "logically necessary" and universal, that the child attains one after the other at characteristic ages. Each stage was described in detail by means of novel characteristic mental operations that were either absent or only embryonic in the preceding stages. The internal mental engines of this stepwise process had been identified by Piaget as consisting of increasing auto-regulation, thematization, grouping, and "reflective abstraction" (in French: abstraction réfléchissante) (Piattelli-Palmarini, 1980). He pictured these processes as present already, at lower levels, in all living beings, making cognitive science continuous with biology. It hardly needs to be stressed how radically opposed to behaviorism this whole conception was, and how refreshing it appeared to many psychologists in the 50s and 60s. (See text and notes 31 and 33)

[10] These classical papers have been reprinted in (van Heijenoort, 1967) and in (Davis, 1965). For a modern systematic treatment see (Lewis and Papadimitriou, 1981; Rogers, 1988 paperback ed., first ed. 1967). For the impact of these theories on early linguistic models see (Bar-Hillel, 1953a, 1953b; Barton, Berwick & Ristad, 1987; Chomsky, 1956)

> "thought is a term for the conscious working of a highly complex machine, built of parts having dimensions where the classical laws of mechanics are still very nearly true, and having dimensions where space is, to all intents and purposes, Euclidean. This mechanism, I have argued, has the power to represent, or parallel, certain phenomena in the external world as a calculating machine can parallel the development of strains in a bridge" (p. 85)

According to Craik, thought involved three critical steps: first, external processes were translated into words, numbers or symbols; second, these "representations" were manipulated by processes such as reasoning to yield transformed symbols; and, third, these transformed symbols were retranslated into external processes to yield a product, such as behavior. The critical assumption here is the idea that minds create internal models, and then use these models to predict the future. Such a thought process allowed an organism the luxury of trying out possible futures before settling on the one that would be most adaptive. For Craik, thoughts could not be separated from feelings, a perspective that early cognitive science ignored to its detriment. He died a few years after the publication of this work in a bicycling accident, and further development depended upon others.

One of the major historical forces propelling this development was the second world war, and a set of military problems that required rapid computational solution. The breaking of military secret codes, the calculation of artillery fire trajectories, and several problems faced by the real-time reactions of airplane pilots, soon occupied the best minds of the time, and enormous progress in understanding complex systems resulted. "Cybernetics", arguably the most crucial of the disciplines that paved the way to cognitive science (cf. Dupuy, 2000), was defined by one of its inventors (the MIT mathematician Norbert Wiener) as the science of communication between complex systems (natural or artificial) and of the control of such systems by intelligent agents. It derives its name from the Greek "kybernetis" (the skipper of a boat and, by extension, the pilot of an airplane), betraying its origin in concrete problems posed by the war effort (Wiener, 1948).

Many of the participants in this fascinating era have provided at least some historical record, as noted already, and the interested reader is directed to these sources for a fascinating tour (McCulloch, 1988) (Heims, 1991) Almost all agree that a few critical concerns fueled the enterprise: first, there was a strong desire to bring the insights of mathematical modeling (the solution of complex differential equations) and of mathematical logic into contact with both biology and engineering. Two of the key players were trained by giants in logic: Norbert Wiener under the guidance of Bertrand Russell, and Walter Pitts under Rudolph Carnap. Second, there was a strong commitment to the notion, outlined by Craik, that thought could be viewed as a computational process utilizing internal models, and hence cognition would ultimately be accounted for in terms of finite and specifiable procedures that could be performed by the "computers" that were then being developed. In this context we must mention John von Neumann, who played a central role in the early days of cognitive science. His work on game theory (Von Neumann and Morgenstern, 1944), and his contributions to the development of computers (von Neumann, 1951) were critical at the outset, and he was a major participant in the emergence of cybernetics until his early death in 1957. His posthumously published essay on "The computer and the brain" discusses the fundamental properties of computation in machine and brain, laying out "an approach toward the understanding of the nervous system from the mathematician's point of view" ((von Neumann, 1957) p.1).

A powerful additional incentive, though initially mostly indirect, came from plans to put the new programmable computers and proto-robots (Ashby, 1960; Walter, 1953) to good use in navigation and learnable self-steering, text translation between languages, selective and addressable archiving, automatic abstracting of documents, visual detection and discrimination, problem-solving and automated induction. The impact of a practically oriented engineering perspective and of generous financial resources for what had previously been abstract and elusive domains of academic research generated some rather naïve approaches and exaggerated expectations. But there were also fresh starts, original redefinitions of many problems and new models that were unencumbered by ancient paralyzing paradoxes and a stifling received wisdom.

Arguably the best example is to be found in linguistics, which had been mostly a literary, comparative and philological discipline. It suddenly received a new impulse to rethink its very foundations and to explore computer-assisted applications. These new approaches to the structure of language (Bar-Hillel, 1954; Chomsky, 1955, 1957, 1975; Harris, 1951, 1952a, 1952b, 1957, 1986/1951) were in some measure a reaction to shotgun engineering attempts to build automatic translators. It is emblematic, for instance, that starting in the mid-Fifties, and for decades to come, the team of linguists that gave rise to generative grammar was assembled and then sustained in a school of electrical engineering [11].

All in all, that early seminal period proved crucial in engendering the conviction that long-standing hard problems in the study of the mind and brain were open to radically new insights, and that an intense collaboration between different scientific fields (from logic to neurology, from text analysis to the mathematical theory of recursive functions) was not only possible, but mandatory. An era of "visiting" scientists, mobile young PhDs and ardent interdisciplinary exchanges opened, right at the end of World War II. Not unlike the immense impact that high-level scientific meetings had previously had on physics in the Twenties and Thirties, and were then still having, the role that some meetings in the Forties and the Fifties had in shaping what later became cognitive science deserves special attention.

The 1940s: Meetings, Meetings, and more Meetings

In reconstructing the history of the early years one cannot escape the crucial role played by a number of critical meetings at which key participants from several fields were profitably brought together. The first such meeting, held in 1942 in New York City, focused on the topic of central inhibition in the nervous system. It was sponsored by the Josiah Macy, Jr. Foundation, which would play an absolutely essential role in the birth of cognitive science over the next decade. At this meeting Warren McCulloch and Arturo Rosenblueth presented material related to the papers they were about to publish. (McCulloch and Pitts, 1943; Rosenblueth, Wiener & Bigelow, 1943) These papers, in rather different ways, suggested that aspects of mental activity could be modeled in a formal way using idealized nervous system elements (an idea that was to be revamped many years later by the connectionists, with radically different mathematical models, as we shall see). McCulloch & Pitts showed that networks of on-off neurons could compute

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[11] The intellectual climate at the Research Laboratory of Electronics (RLE) of MIT in the early Fifties was one of excitement and imminent accomplishment. The injection of ideas and models from cybernetics and information theory into the study of language appeared capable of leading towards a full understanding of complex communication in humans, animals and machines. The modern scientific theory of language, and its momentous impact on cognitive science as a whole, largely originated in those laboratories, in the mid- and late Fifties, thanks to a disillusionment both with traditional classificatory linguistics and the statistical approaches to language that modeled it as a largely repetitive "signal" interspersed with "noise", in conformity with the then influential theory of information.

logical functions, while Rosenblueth et al., concerned with purpose, showed that goal-directed behavior could emerge in systems with feedback.

In the winter of 1943-44 another meeting was held at Princeton, attended by McCulloch and Pitts, by a prominent neuroanatomist, Lorente de Nó, and two leading figures in the emerging computer paradigm, John von Neumann and Herman Goldstine. This line-up suggests the coming together of formal logic, neural nets, real neuroanatomy, and computation. Lorente de No (1938) had previously demonstrated, in elegant anatomical work, that conditions existed within the cerebral cortex for reverberatory circuits that could instantiate re-entrant loops (Lorente de Nó, 1938). These loops were seen as critical to maintaining memory within the brain, a requirement that had been hinted at earlier by Kubie (Kubie, 1930) and was adopted in Hebb's (1949) neuropsychological theory of cell assemblies and phase sequences. Hebb's book *The Organization of Behavior* stands out as a crucial contribution, merging psychology and physiology in pursuit of explanations of cognitive function. [12]

Ten Macy Foundation conferences on "cybernetics" were held between 1946 and 1953. The major moving force behind these meetings was Warren McCulloch, as portrayed in considerable detail by Heims (1991) and Dupuy (2000). No written record exists of the first five meetings, but proceedings of the final five were published. Over the course of these meetings ideas central to cybernetics, such as control, feedback, and communication, were imparted to a wide range of scientists. What distinguished these meetings was their interdisciplinarity. The anthropologists Gregory Bateson and Margaret Mead were as central to the proceedings as the neurophysiologist McCulloch, the mathematicians Wiener and von Neumann, the information theorist Shannon and the psychologists Kluver and Lewin. Another distinguishing feature of these early meetings on cybernetics was the lack of concern with computation as a "symbolic" activity. This perspective, which came to dominate cognitive science in the 1950s, was largely absent from these early formative discussions.

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[12] According to Hebb, perception could be accounted for in terms of organized sets of neurons (cell assemblies); thought would then follow from the concatenation of many of these assemblies into phase sequences. Memory involved changes in the efficacy of connections between neurons composing these ensembles. This deceptively simple approach had a dramatic impact on that subset of investigators willing to pay attention to the brain at the time, and over the past few decades has had an even wider effect. In Hebb's time his theory led to a variety of important research findings, including work on the effects of sensory deprivation, the stabilization of visual inputs to the retina, the impact of enriched or deprived rearing conditions, and a good deal more.

Some of the same individuals participated in the famous Hixon symposium, held at Caltech in 1948, and published a few years later (Jeffress, 1951) [13]. It was at the Hixon meeting that von Neumann gave a paper on "The general and logical theory of automata", and Lashley wowed the audience with his famous paper on "serial order" (Lashley, 1951), in which he took a strong stand against the reigning behaviorist stance, pointing out that the requirements of speech and language rendered stimulus-response theory implausible.

Another critical meeting was held September 10-12, 1956 at MIT – the second Symposium on Information Theory. George Miller has referred to the session held on September 11 as the actual birth day of cognitive science (but see (Wildgen, 2001) for a different perspective). Speaking that day were Newell and Simon, who presented material on their logic theory machine; Rochester, who had been using a large digital computer in a failed effort to test Hebb's theory of cell assemblies (Rochester et al. 1956); Chomsky, who showed how linguistics could produce results with considerable mathematical rigor; Miller, who talked about the limits of short-term memory; and Swets, who presented on signal detection theory and perceptual recognition. George Miller later claimed that he went away from this meeting with the feeling that a new science was emerging.

Some months before this germinal meeting a research seminar on artificial intelligence was held at Dartmouth, attended by most of the individuals active in the area at the time [14]. Newell and Simon (1972) point out in the Historical Addendum to "Human Problem Solving" (Newell and Simon, 1972) that Minsky's (1961) essay, "Steps Toward Artificial Intelligence", first circulated in draft form at this summer meeting, captures the consensus views that existed at that time (Minsky, 1961) (now available on Minsky's website at http://web.media.mit.edu/~minsky/).

In meetings such as these one can see the mix of disciplines that would come to define much of modern cognitive science. One can also see the groping for methodologies that would

[13] This meeting was presided over by Henry Brosin,a psychiatrist from Pittsburgh who played a significant facilitatory role throughout this early era. Brosin later retired to Tucson, Arizona and a fair number of his books from these formative days, copiously annotated, have found their way into the hands of one of us (LN).

[14] John McCarthy, Marvin Minsky, Nat Rochester, Claude Shannon, Oliver Selfridge, Herbert Gelernter, Alan Newell and Herb Simon, among others.

permit scientists to ask meaningful questions about mental activity. The single-minded emphasis on behavior at the expense of cognition was clearly at an end. Within a few years the first of many centers of Cognitive Studies was started, at Harvard, by Jerome Bruner (focusing on spontaneous reasoning) (Bruner, Goodnow & Austin, 1956) and George Miller (focusing on language and memory) (Chomsky and Miller, 1963; Miller and Chomsky, 1963). Roger Brown soon transferred there from MIT, enriching the research domain with his pioneering studies of first-language acquisition (Brown, 1958, 1973) The impact of this Center was enormous: its interdisciplinary mix included faculty, research fellows, visitors, and local-area researchers who over the years made substantial contributions to cognitive science [15]. Now, slightly more than 40 years later, many such programs exist.

In the 1950s, as clearly seen in the 1956 MIT meeting, the close connection between biology and cognitive science fell apart. Simon was perhaps the leading, but by no means the only, exponent of the view that to understand cognition one needn't pay much if any attention to the underlying biology. Newell and Simon (1972), for example, characterized Hebb's position as "confused" insofar as Hebb thought he was proposing a physiological account of behavior. In their view it was essential to interpose "a specific layer of explanation lying between behavior, on the one side, and neurology on the other" (p. 876). This perspective foreshadowed a similar position, presently mainstream, adopted by Marr (1982) a decade later, in his classic treatise on "Vision" (Marr, 1982). The net result of this shift in emphasis was that the integrative perspective of the cyberneticists was sacrificed, and an era of symbolic modeling, of direct study of mental computations and representations, and of artificial intelligence research without much reference to real brains, blossomed.

It is of historical interest to consider why this happened. We would suggest a few possible reasons: (1) The early biologically-driven approach to neural nets, as exemplified by the perceptron model (Rosenblatt, 1962) apparently failed, the limitations of these early models being subsequently made clear in Minsky & Papert (1969/1990). Hanson (1999) provides an interesting perspective on the competition between Rosenblatt and Minsky, and how the latter's

[15] The list includes, in alphabetical order: Ursula Bellugi, Tom Bever, Roger Brown, Jerome Bruner, Susan Carey, Noam Chomsky, Jerry Fodor, Merrill Garrett, Janellen Huttenlocher, Roman Jakobson, Dan Kahneman, Jerrold Katz, Paul Kolers, Pim Levelt, David McNeill, Jacques Mehler, George Miller, Don Norman, Eleanor Rosch, Dan Slobin, Amos Tversky, Peter Wason, Nancy Waugh.

views, tilted towards artificial intelligence and away from biology, carried the day. And, initial attempts by Rochester and his colleagues (Rochester, Holland, Haibt & Duda, 1956) to simulate the neurobiology of Hebb and Peter Milner were largely unsuccessful, as noted already; (2) writers such as Chomsky argued persuasively that it was the formal properties of the mind-brain that mattered, not the underlying biology that allowed it to compute [16]; (3) one of the main representatives from neuroscience, Karl Lashley, was himself rather skeptical about the enterprise. At a symposium on "The Brain and the Mind" at the American Neurological Association meeting in 1951 Lashley served as a discussant on several papers and had this to say about the enterprise of linking brains and computers: "I suggest that we are more likely to find out how the brain works by studying the brain itself and the phenomena of behavior than by indulging in far-fetched physical analogies. The similarities in such comparisons are the product of an oversimplification of the problems of behavior" (quoted in (Beach, Hebb, Morgan & Nissen, 1960) p. xix). What is more, Lashley's probabilistic views of nervous system function were very much at odds with the connectionist requirements of the cyberneticists. Lashley participated in many of the early critical meetings, and his views had a major impact. The rather

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[16] Chomsky's position vis-à-vis the neurobiological foundations of language and mind deserves a word of clarification. Over many years he has insisted that all kinds of relevant data (the qualification relevant is essential here) from any domain of science or even from everyday observation are of interest. Having constantly used the hyphenated expression brain-mind, and having always insisted that linguistics is part of the natural sciences (verbatim: part of biology "at a suitably abstract level"), he is clearly aware of the potential power of the neurosciences to corroborate or refute abstract linguistic hypotheses. While encouraging a serious search for neuronal correlates, Chomsky maintains, however, that the neurosciences must cooperate with other relevant disciplines (eg., linguistics, developmental psychology, the study of first and second language acquisition, genetics) and also must not forget the power of logic, of abstract arguments and even of physics and mathematics. His early participation in meetings with neurologists (especially on aphasia and other language deficits, as we have stated here), his close interaction with Eric Lenneberg, and his co-organization of a group focused on bio-linguistics at MIT with the molecular biologist Salvador E. Luria and the neuropsychologist Hans Lukas Teuber, testify to his active interests in biology (for an insightful reconstruction of that initiative, see (Jenkins, 2000)). Some may interpret his attitude towards the brain sciences as tepid (at best) because of the quintessentially internalist-mentalist character of his theories in linguistics, and a consistent refusal to give a privileged scientific status to data on brain structures and mechanisms, as compared to data on linguistic intuitions. Chomsky concurs with Fodor in cautioning against "the intimidation by white blouses" (an expression used by Fodor in public discussions to refer to brain scientists) who present as truly scientific only "wet" data, as opposed to cogent and rationally supported theories.

more positive approach of Hebb, who disagreed with Lashley about the role of specific neural pathways, could not overcome Lashley's influence at that time.

Because of this schism, cognitive science and neuroscience developed separately after the 1950s. For the better part of 25 years much of neuroscience was reductionist in scope and purpose, rarely speaking to questions of interest to cognitive scientists. On the other side, much if not all of cognitive science proceeded within a symbolic framework that required little or no contact with the brain. Neurons were relegated to the role of 'mere implementation'.

The then prevailing philosophy of mind, called "functionalism" (Dennett, 1987; Fodor, 1975; Fodor, 1981; Putnam, 1960, 1973) offered principled arguments as to why any physico-biological implementation of cognitive functions was secondary to a thorough abstract characterization of the logical structure of the mental representations and transformations involved in those functions (Block, 1980, 1981). [17]

Empirical Results

The 1950s and beyond witnessed an impressive growth in empirical results, in all the domains of cognitive science. Chomsky revolutionized the study of language, Broadbent (1958) and others focused on attention (Broadbent, 1958), Bruner and his colleagues (1956) looked at thinking, Newell, Shaw and Simon (Newell, Shaw & Simon, 1958) produced the General Problem Solver,

[17] In recent times, Putnam (the acknowledged father of philosophical functionalism) has retreated from his earlier position, advocating a pivotal role for our intuitions about the material nature of cognitive systems (Putnam, 1987; Putnam, 1988). Ned Block, a former student of Putnam, has pointed out some serious "troubles with functionalism", requiring a considerable expansion of this conception (Block, 1978). John Searle, over many years, has challenged the very consistency of functionalism, pleading for the centrality of a specific causal role attributed to the unique biological structure of the brain (Searle, 1980a, 1980b; Searle, 1992; Searle, 1996). At the other extreme, John Haugeland has challenged the legitimacy of functionalism on more abstract grounds, espousing the holist doctrines of human cognition proposed by the German phenomenologists (Haugeland, 1981, 1997). As we write, nonetheless, some variant of functionalism still appears to constitute the spontaneous (and often implicit) philosophy of the mind/brain for most cognitive scientists. However, the recent development of refined brain imagery techniques (see text) and the growing number of publications dealing with specific brain correlates of higher cognitive functions (from language to numerical cognition, from decision-making to categorization), might eventually modify somewhat the functional conceptual scheme of cognitive science. A direct match between abstract cognitive characterizations and real brain structures is now increasingly possible. Except for a minority of unrepentant symbolists, and, at the other extreme, of irreducible reductionists, the complex expression brain/mind is taking on a more insightful and richer unified meaning. It's interesting to realize that the core of this problem had already been identified, and vibrantly debated, in the early conferences on cybernetics.

Hochberg (1956) studied the role of memory and other internal factors on perception, Sperling's (1960) work on brief visual presentations and partial report methods led to the notion of an iconic memory store (Sperling, 1960), and there were various thrusts in artificial intelligence (eg., Samuel's checkers program (Samuel, 1959)), including interesting work on mathematical neural networks (Rosenblatt, 1958; Selfridge, 1958 (November)) . But, there were problems. In many cases the successes were garnered in severely restricted systems, with no certainty that they would scale up or generalize. Some domains were simply not part of the mix – the study of emotion, or consciousness, was ruled off limits. In these days only those phenomena of which humans were somehow at least partially conscious qualified as "cognitive" – implicit capacities did not make the grade, nor did any animals.

Although cognitive science at this time paid little heed to the brain, neuroscience pushed ahead, making great strides in a number of areas. In the late 1940s the discovery of the "reticular activating system" (Moruzzi and Magoun, 1949) had a major impact. This landmark event shifted thinking about the brain in a fundamental way. It showed that, contrary to prior notions, the brain was not a passive organ waiting to respond to external stimulation. Instead, it was constantly active, and the critical question was no longer what brought it into activity but rather what kind of activity it engaged in. The selectivity of brain function was shown to reflect not just exogenous factors, but endogenous ones as well. The implications of this were enormous, as Hebb noted [18].

Another critical research program centered around Penfield and the group of scientists at the Montreal Neurological Institute (MNI), largely focused on patients about to undergo surgery to control for epilepsy. Penfield and Rasmussen (Penfield and Rasmussen, 1949) pioneered the method of stimulating the exposed brain in areas adjacent to the presumed site of the focus, as a means of determining which tissue should be excised and which spared. This method yielded several remarkable and widely reported results. First, this method generated the famous pictures of sensory and motor maps in the cortex, within which various body parts were represented in often unusual proportions. Second, punctate stimulation in the temporal lobe apparently could yield the retrieval of a highly specific and detailed memory. This finding strongly countered Lashley's non-localizationist perspective, and dramatically affected views about the organization

[18] More recently, the special epistemological importance of the spontaneous oscillatory activities of the brain has been stressed by Rodolfo Llinas and Jean-Pierre Changeux (2002).

of information in the brain. It seemed to promise that an approach depending upon specific neural connections might indeed have merit, much as Hebb (Penfield's colleague at McGill, and Lashley's former student) had proposed. At the same time, the study of HM, another patient at the MNI, who had lost the capacity to memorize recent events, though he maintained some capacity to remember events that preceded the surgical bilateral section of part of the medial temporal lobe, generated enormously important information about the critical role of the hippocampal formation in memory. The capacity of such patients to learn new procedural tasks and to find their way in new environments, without any explicit memory of what they were doing or why, also raised considerable interest (Milner, 1965; Scoville and Milner, 1957).

A final critical discovery dependent on the study of epileptic patients followed upon the use of callosal section to prevent the spread of the epileptic focus from one brain hemisphere to the other. These "split-brain" patients were quickly shown (by Roger Sperry [19] and his colleagues) to have remarkable psychological characteristics that have informed us for nearly 50 years about how cognitive functions are carried out in the brain.

Two very important meetings that were held in the 1950s involved many of the neuroscientists involved in the work just described. Both were sponsored by the Council for International Organizations of Medical Sciences (CIOMS). The first was held in August 1953 in the Laurentian Mountains near Montreal, and brought together researchers in various fields to discuss the implications of the reticular activating system – it was titled "Brain Mechanisms and Consciousness" (Delafresnaye, 1954) [20]. The second, held in August 1959 in Montevideo, brought together an even wider array of neuroscientists under the title "Brain Mechanisms of Learning" (Delafresnaye, 1961) [21].

The inclusion of scientists from the USSR and Eastern Europe at the second meeting was particularly noteworthy, as the cold war had precluded such interactions for much of the period

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[19] Awarded the Nobel Prize in "physiology or medicine" in 1981, with David Hubel and Torsten Wiesel.

[20] Papers were presented by Magoun, Moruzzi, Penfield, Hebb, Lashley and Kubie, among others.

[21] Papers at this meeting were presented by Hebb, Olds, Magoun, Morrell, Hernandez-Peon, and a number of others. An important aspect of this meeting was the inclusion of a number of key researchers from Russia and both West and East Europe. Anokhin, Asratyan, Eibl-Eibesfeldt, Fessard, Grastyan, Jouvet, Konorski, Lissak, Naquet and Thorpe participated.

from 1946-1957. Once again, the Macy Foundation had an important role to play, sponsoring (with the National Science Foundation) three yearly conferences beginning in 1958 on "The Central Nervous System and Behavior" (Brazier, 1958, 1959, 1960). The first meeting had as a central goal bringing Russian neurophysiology to the west; although no scientists from the USSR were present, the work of Sechenov, Pavlov, Bechterev and others was the focus of the discussion [22] . The second conference broadened this base by including several prominent researchers from Eastern Europe – Bures (Prague, Czechoslovakia [23]), Grastyan (Pecs, Hungary) and Rusinov (Moscow, USSR). The third meeting included Luria and Sokolov, both from Moscow. Yet another critical meeting held at this time (October, 1958) was the "Moscow Colloquium on Electroencephalography of Higher Nervous Activity" (Jasper and Smirmov, 1960). This meeting ranged widely over many topics, and brought together the most prominent neuroscientists from both east and west.

The impact of these 6 meetings, focused on the brain, was immense. It is not an exaggeration to say that an entire generation of cognitive neuroscientists (although not yet called by that name) was weaned on the books from these meetings. While these meetings focused largely on arousal, memory, perception and the like, similar undercurrents were at play in the study of language.

By the mid-1950s the view had emerged that the careful study of aphasia from a variety of perspectives could yield real gains in understanding language. This feeling led to a six week long seminar, held in 1958 at the Boston VA Hospital [24]. The discussions at this lengthy seminar were captured in a book published some years later (Osgood and Miron, 1963). A few years after the Boston VA meeting another meeting focused on aphasia was held in London, sponsored

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[22] Participants included Magoun, Brazier, Doty, Olds, Pribram, Purpura, Galambos, John, Morrell, Sperry, and Teuber.

[23] With whom LN subsequently was a postdoctoral fellow (1967-70). The Prague laboratory of Jan Bures and his wife and scientific partner Olga Buresova became a mecca for neuroscientists from around the world, and remains so today. Their work on memory and more recently the spatial functions of the hippocampus has been influential for more than four decades.

[24] Participants included Roger Brown, Noam Chomsky, Norman Geschwind, Kurt Goldstein, Harold Goodglass, Eric Lenneberg, Brenda Milner, Charles Osgood, Karl Pribram, and Hans-Lukas Teuber.

by the Ciba Foundation (De Reuck and O'Connor, 1964)[25]. The spirit of both meetings was interdisciplinary, and though these efforts were not in the mainstream of cognitive science at the time they were important in setting the agenda in cognitive neuropsychology [26]

At a more neurophysiological level, tremendous discoveries were being made, largely in the wake of technical advances that made possible the recording of activity from individual neurons in response to carefully controlled inputs. Here, the work of Mountcastle (Mountcastle, 1957) in the somatosensory system and Hubel & Wesel (Hubel and Wiesel, 1962a, 1962b; Hubel and Wiesel, 1977) in the visual system stand out as seminal, to be followed by a literal explosion of studies that continues to the present day. In this vein it is also important to mention the classic study by (Lettvin, Maturana, McCulloch & Pitts, 1959) in the visual system of the frog. These authors claimed to have found the neuronal correlates of Kant's a priori synthesis, and McCulloch later (1988) referred to this study as a first step towards experimental epistemology. All of these studies showed that the activity of neurons could be related in

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[25] Participants at this meeting included Macdonald Critchley, Lord Brain, Roman Jakobson, Donald Broadbent, Alexander Romanovich Luria, Brenda Milner, Henri Hecaen, Oliver Zangwill, Hans-Lukas Teuber and Colin Cherry. There were a number of other important meetings held in the United Kingdom in the 1950s and 1960s, including a series of meetings held in London in the 1950s, under the title "London Symposium on Information Theory". At the Fourth Symposium (Cherry, 1961), held in 1960, Averbach & Sperling reported on their methodology involving brief visual exposures to asked to report only a subset of the presented material. Using this partial report method, the authors were able to show that immediate visual memory has available to it a good deal more information than subjects can retrieve when asked for a full report. The "Mechanisation of Thought Processes" symposium held at the National Physical Laboratory in 1958 included presentations by Minsky, Mackay, McCarthy, Ashby, Uttley, Rosenblatt, Selfridge, McCulloch, Sutherland, Gregory, and Bar-Hillel. Other noteworthy atttendees included Bartlett, Buerle, Cherry, Gabor, Wason, and J.Z. Young.

[26] At about this time a small group of neuropsychologists, the International Neuropsychological Symposium, started to meet every year in Europe. According to Boller (Boller, 1998), the group was launched in 1949 at a party Henry Hécaen held at his home on the occasion of the International Congress of Psychiatry. After dinner, he outlined a proposal to found an international group to promote knowledge and understanding of brain functions and cognate issues on the borderland of neurology, psychology and psychiatry. This group, which continues to meet yearly, strongly promoted the integrative, multi-disciplinary perspective that became characteristic of cognitive science. Later on, in Italy, cognitive neuropsychology was to flourish beyond any other domain of cognitive science, gaining considerable international recognition. Individuals and groups were scattered in many different universities (Eduardo Bisiach in Turin, Anna Basso in Milan, Carlo Umiltà, Remo Job and Renzo de Renzi in Padua, Elisabetta Ladavas in Bologna, Gabriele Miceli in Rome, to name a few). Ever since the early 1980s, the annual international conferences held in Bressanone in January, under the auspices of the University of Padua, have regularly assembled the Italian "contingent" of cognitive neuroscientists with colleagues from many other countries.

meaningful ways to certain properties of external stimulation, without being a passive copy of the surrounding scene, and in so doing began the process of explaining how internal models of the world could be instantiated in the brain.

Another key finding was the discovery by Olds & Milner in 1954 (Olds and Milner, 1954) of systems in the rat brain that subserve reward. Although it has taken nearly half a century for the study of affect to be re-integrated with the study of thought, reasoning and "pure" cognition, the basis for this synthesis was laid in these early studies. This finding was important at that time for another reason: it contributed to the demise of Hull's drive reduction theory. Along with contemporary studies demonstrating the power of curiosity and stimulation seeking in the perceptual domain, self-stimulation of the brain presented a form of behavior that simply could not be accounted for in terms of drives and their reduction. As the 1960s dawned, one could get the feeling of great progress, but in a compartmentalized way. The decade itself ended with the publication of a landmark book by Miller, Galanter & Pribram (Miller, Galanter & Pribram, 1960) that proposed a model for cognitive function applying the insights of Craik (internal representations) and cybernetics (feedback) to the problems identified by Lashley (serial order) and Chomsky (generative linguistics).

Consolidating the Gains

The 1960s were a period of consolidation of the gains made in the previous decade, but fraught with danger. Little progress was being made in connecting minds with brains, and the grand promises issued by proponents of the symbolic approach to artificial intelligence were beginning to look unattainable. It seemed that there were quite a few things that human brains could do much better, and even faster, than computers – especially digital computers. The realization that visual recognition was actually a very complex phenomenon followed from repeated failures to get computers to solve even simple recognition problems. Language translation by machines, as we have said, also seemed a lot harder than was once imagined. But, a signal event in the 1960s was the publication of Ulric Neisser's book, *Cognitive Psychology* (Neisser, 1967) . This was the first textbook in the field, and it had a powerful didactic and organizational influence for many years. Sternberg's work on memory stages using reaction time studies (Sternberg, 1966), and Posner's approach to abstraction and recognition made important contributions to this new domain (Posner, 1969).

While many areas of cognitive science were in a consolidation phase in the 1960s, psycholinguistics blossomed into a highly influential discipline. The groundwork was laid in part by an ongoing seminar at MIT on language acquisition lead by Roger Brown, attended regularly by Chomsky and others, which formulated the basic approach to the study of language acquisition that exists today. At the same time Miller inspired a group of young psychologists to take as an object of experimental investigation Chomsky's theory of grammar as presented in "Syntactic Structures" (Chomsky, 1957). That model had rocked the linguistic world by proposing a "deep" structure which represented the essential thematic relations between verbs and arguments, regardless of their surface order (harking back to the "inner form" of sentences proposed by Wilhelm Wundt and others). Miller and his students created a set of experiments that seemed to demonstrate the "psychological reality" of deep structure in memory for sentences. Thus was born an exciting period in which it seemed that results from the highly speculative and theoretical discipline of Linguistics could be immediately tested in the laboratory: the rallying cry was "one linguistic rule - one mental operation". Extended and careful research as well as logical argument later disproved this idea. Fodor and Garrett noted that the relationship between the grammar and behavior must be "abstract" to some degree (Fodor and Garrett, 1966): Bever (1970) proposed a direct "strategies" model of comprehension that short-cuts linguistic rules. Their joint book (Fodor, Bever & Garrett, 1974) laid out systematically the implications of these ideas for the major areas of psycholinguistics: acquisition, perception and production [27].

The fierce debate about the linguistic (or proto-linguistic) capacities of higher primates started in earnest in these years (Fouts, 1989; Gardner and Gardner, 1971; Gardner, 1989), opposing the unshakable believers in the evolutionary continuity of all cognitive functions [28] to the bona fide linguists, led by Chomsky, who stressed that the unique central components of human languages (discrete infinity, boundless recursivity, constituency, generative power, compositionality) have no counterpart in the communicative systems found in animals, higher

[27] For a recent revisitation of the origins of psycholinguistics, and for a development of the "strategic" approach to language comprehension, see (Townsend and Bever, 2001).

[28] Eg. Allen and Beatrice Gardner, Duane and Sue Savage-Rumbaugh, Roger and Diane Fouts and, from a distant shore, Jean Piaget. (For a recent reappraisal, see (Savage-Rumbaugh, Murphy, Sevcik, Rumbaugh, Brakke & Williams, in press).

primates included. The negative conclusions on the linguistic capabilities of chimpanzees by the prominent cognitive primatologist David Premack (Premack, 1972; Premack, 1986), and the thorough longitudinal study of the male chimp Nim Chimpsky at Columbia University (Seidenberg and Petitto, 1979, 1987; Terrace, Petitto, Sanders & Bever, 1979) reset the debate for quite some time. Though remarkably intelligent and capable of sophisticated cognitive operations, chimpanzees are provably devoid of the most central components of human linguistic competence. While productive comparative studies between animals and humans in the domains of vision, motor control, brain development, acoustic perception and categorization were destined to blossom from the early Sixties to this date, the comparative study of language dwindled as a result [29] [30].

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[29] Except for a few unrepentant "continuists", mainstream cognitive science in the domain of language followed different paths, unearthing deep and hard-to-detect similarities among distant languages, broaching the gap between syntax and semantics, exploring subtle lexical structures, modeling the "logical" problem of language acquisition with formalized mathematical tools, developing computational models of linguistic competence and performance. The very issue of the biological evolution of language was to be tackled afresh at its roots by generative linguists, steering a course away from simplistic adaptationism and continuism, examining the possibility conditions of the evolution of the very roots of linguistic competence (recursiveness, constituency, compositionality, infinite discreteness, generativity) (Jenkins, 2000; Lightfoot, 1982; Nowak, Komarova & Niyogi, 2002; Piattelli-Palmarini, 1989; Uriagereka, 1998). For a recent reappraisal by Chomsky himself, see (Hauser, Chomsky & Fitch, in press).

[30] A special position in this debate between continuists and modularist-innatists was occupied by the influential biosemiotician Thomas Sebeok. He rejected wholesale all the experiments on the alleged linguistic abilities of apes, claiming a much deeper, more universal and more meaningful underlying substrate: the "semiotic function". He described incremental steps of complexification in this universal underlying substratum and insisted that a unified theory could range from the "syntactic" (sic) nature of Mendeleeff's table of the chemical elements (Sebeok, 1995/2000), up to all systems of human communication, be they vocal, gestural, graphic or pictorial, passing through the genetic code, the immune code, the systems of communication between cells, between unicellular organisms (microsemiotics), plants (phytosemiotics) and the circuits of neurotransmitters in the nervous system (neurosemiotics). These incremental steps in the quality and complexity of signaling were analyzed as accruing to a common semiotic substrate, displaying a universal "perfusion of signs" which, according to Sebeok, authorizes a unified conceptualization, a semiotic "ecumenicalism" (Sebeok, 1977). Sebeok's conceptualization and his alleged semiotic "theorems" and "lemmas" have found attentive ears in some literary quarters, and in some schools of communication (notably in Italy), but have remained, in the main, alien to cognitive science. The semantics of natural language has developed a radically different approach (for a textbook synthesis, see (Larson and Segal, 1995).

In the period beginning in the late 1960s, neuroscience had pushed forward as well, but now the contributions were of a sort that clearly could connect with cognitive science. Work in the visual system began to make contact with perception as studied in cognitive laboratories 1971; (Blakemore and Campbell, 1969; Gross, Rocha-Miranda & Bender, 1972; Zeki, 1978), and a line of research on vision began that has yielded tremendous insights into how we see the world, and why we see it the way we do. Much of this research depended on neurophysiology carried out in primates, who in the early studies were anesthetized, then only stabilized, and in recent years even capable of moving about in the world. Studies carried out in ever more natural environments are producing increasingly sophisticated understandings of how the brain subserves vision.

Equally dramatic was a series of discoveries about the hippocampus, a brain structure implicated in memory since the pioneering work on HM in the 1950s. O'Keefe & Dostrovsky using new methods to record the activity of single neurons in freely-moving animals, discovered "place cells" in the hippocampus, neurons whose activity reflected the animal's location in the environment (O'Keefe and Dostrovsky, 1971). This discovery provided the basis for O'Keefe & Nadel's theory that the hippocampus instantiated "cognitive maps" of the sort postulated by Tolman (1948) (O'Keefe and Nadel, 1978; O'Keefe and Nadel, 1979). This was one of the first neurophysiological research programs that made direct connection between the activity of individual neurons, and complex cognitive activities. Bliss & Lømo (1973) discovered a form of synaptic plasticity in the hippocampus (long-term potentiation, or LTP) that seemed to verify Hebb's early speculations about how learning might occur in the nervous system (Bliss and Lømo, 1973). Research on the hippocampus has continued at a furious pace ever since.

Another research program worth noting involved the efforts of a displaced psychiatrist, Eric Kandel, to uncover the neural mechanisms of learning and memory. Taking the bold step of shifting his research attention to an invertebrate (the sea slug, *Aplysia californica*), Kandel began the process of painstakingly working out the synaptic mechanisms underlying various forms of plasticity, laying the basis for an understanding of the cellular and molecular mechanisms of memory [31].

[31] See Kandel (Kandel, 1980) for a review of some of this research program, begun in the 1960s, presented at a symposium held in Texas in 1978 to commemorate the 30th anniversary of the Hixon Symposium, and to honor Lloyd Jeffress, who edited the volume from that earlier historic meeting. Kandel was awarded the Nobel Prize in 2000, with Arvid Carlsson and Paul Greengard. His

The Royaumont Meeting: A debate between (and around) Jean Piaget and Noam Chomsky, 1975

This meeting was motivated largely by an attempt to "reconcile" Chomsky's approach to language with Piaget's approach to cognition in general [32]. Both Chomsky and Piaget professed a deep link with biology, so a reconciliation seemed possible. Piaget opened the conference with a summary of basic assumptions that he believed would be received as innocent, obvious and hardly worth discussion. Much to his amazement, the whole meeting (3 days) was dedicated to a multi-faceted discussion of these very assumptions. The biologists questioned Piaget's reliance on auto-regulation without specific pre-existing regulators [33], and his attempts to reintroduce in subtle ways the inheritance of acquired traits. Chomsky offered basic facts about language (mostly syntax) that, he claimed, could not be even remotely explained in terms of abstractions from motor schemas, nor by any general conceptual grasp of the world. Fodor argued that

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monumental textbook "Principles of Neural Science", updated and translated into many languages, has been adopted in many countries.

[32] The published volume (Piattelli-Palmarini, 1980), and the afterthoughts by its principal organizer (Piattelli-Palmarini, 1994) spare us from having to summarize this rich multi-disciplinary conference (organized by Monod, Piattelli-Palmarini, Atran and Changeux). Besides Piaget and Chomsky, the main participants from cognitive science were Jerry Fodor, Barbel Inhelder, Guy Cellerier , David Premack, Seymour Papert, Gregory Bateson, Dan Sperber, Scott Atran and Jacques Mehler. Other disciplines were also represented: in attendance were the molecular biologists Jacques Monod and François Jacob, the neurobiologist Jean-Pierre Changeux, the philosopher of science Stephen Toulmin, the anthropologist Claude Lévy-Strauss, the ethologist Norbert Bischoff, and the mathematician Jean Petitot. Important additional contributions to the volume by invited participants who had been unable to attend, came from the logician and philosopher Hilary Putnam and the mathematician René Thom. The post-conference exchange between Putnam, Chomsky and Fodor was included by Ned Block in his anthology of writings on "The Philosophy of Psychology" (Block, 1980). In the preface to this book, Howard Gardner suggested that the meeting was one of the seminal events at the very origins of cognitive science.

[33] François Jacob (the co-discoverer, with Jacques Monod, of the "operon", a complex genetic unit of regulatory genes) stated that regulation can only take place as a result of pre-existing regulatory genes that actually and selectively kick-in (or remain shut off) to regulate metabolic pathways. Piaget's conception of progressive cascades of higher and higher auto-regulations was at odds with this very concrete finding. It quickly appeared to some participants that Piaget's concept was a metaphor, not a model. Piaget immediately retorted that Jacob's idea was exceedingly "narrow", and that he knew other biologists who concurred with him in presenting a more general and more flexible picture of auto-regulation.

genuine conceptual novelty and any genuine potentiation of a pre-existing language could not be the result of learning. Other participants added their bit of specialized knowledge, some defending Piaget (notably his collaborators Cellerier and Inhelder, but also Papert, Bateson, Wilden, Toulmin), others siding with Chomsky and Fodor (Premack, Sperber, Mehler, Piattelli-Palmarini and in indirect ways, Monod, Jacob and Changeux). The core issues, as now appear more clear in hindsight, were: (a) the modularity of mind and the autonomy of syntax; (b) the specificity of innate cognitive structures and the poverty of the stimulus; (c) reasons to keep rejecting (a) and (b) in spite of what Chomsky and Fodor presented as overwhelming evidence that one should accept them. Sequels of these issues, and codas to point (c) are still very much alive as we write. While the arguments put forth by Chomsky and Fodor remain to many as strong as they were then, unshakable resistance to modularity, specificity and innateness survives in many quarters of cognitive science in various incarnations (Bates and Dick, 2000; Bates and Elman, 1996; Cowie, 1999; Elman, Bates, Johnson, Karmiloff-Smith, Parisi & Plunkett, 1996; Karmiloff and Karmiloff-Smith, 2001; Karmiloff-Smith, 1993, 1994) [34]. In particular, debate rages over just how "impoverished" the environment of the growing infant really is, and whether or not powerful abilities to extract statistical regularities from the environment might not make possible the ontogenetic, rather than phylogenetic, acquisition of various aspects of language including syntax.

As of the mid-Fifties, Chomsky had argued for the "autonomy of syntax", offering sort of incidentally the now famous example of the sentence "Colorless green ideas sleep furiously", that every speaker of English identifies as syntactically well-formed, though it is utterly

[34] Over the years, readers of different scientific orientations have drawn strikingly different conclusions from the proceedings of this debate. One of us (MPP, the editor of the book), a few months after its publication, during a visit at MIT, was told that it was "obvious" (sic, a qualification whose importance will be clear in a moment) that Chomsky and Fodor had won the debate. A few weeks later, in Geneva, he was told that it was "obvious" (again, sic) that Piaget, Inhelder, Céllérier and Papert had won the debate. The self-imposed neutrality of MPP while editing the proceedings was, thus, powerfully, albeit indirectly, acknowledged. Many years later, this neutrality was abandoned in an afterthoughts piece in "Cognition" (1994), decidedly in favor of Chomsky and Fodor. But opposite conclusions and afterthoughts have been reached in other quarters. Those who have sided with Piaget typically accuse Chomsky and Fodor of having been quite ungracious in rejecting Piaget's many overtures and concessions to their positions, and of having countered his simple, untendentious and unassailable theses with a flurry of possibly (just possibly) relevant paradoxes and conundra, for which (so the story goes) they had no solutions to offer. Present and future readers will have to decide for themselves which conclusion is more correct.

meaningless. Subsequent studies by Chomsky and his early collaborators (Chomsky, 1965) revealed basic syntactic principles of a very specific nature, common to many, and arguably to all, languages and dialects, as an integral part of the speaker-hearer's tacit "knowledge of language". These did not resemble in the least the then known basic principles of visual perception, motor control and generic reasoning, forming an integrated cluster of autonomous cognitive rules and representations. "Knowledge of language" had to be kept separate from generic knowledge of the world. The metaphor of a "language organ" defied all traditional conceptions of a small set of "horizontal" multi-purpose mental faculties. These two separate strands of a modular conception of the mind/brain, one focusing on language and "input systems" (Fodor, 1981, 1983) at the level of mental contents, representations and symbols, the other on central systems (memory, perception and planning) at the level of neuronal substrates in the animal and in humans, were to converge eventually, though emanating from different starting points.

On the neurobiological front, in the early 1970s Tulving (Tulving and Thompson, 1973) suggested that there might be two rather different kinds of human memory – episodic and semantic. In 1974 three papers were published suggesting the same thing, but based instead on animal research (Gaffan, 1974; Hirsch, 1974; Nadel and O'Keefe, 1974) This notion applied to the brain an idea first promulgated by Tolman in a classic paper (1949; "There is more than one kind of learning"). It was discussed by O'Keefe & Nadel (1978) for both animals and humans as part of their "cognitive map" theory, and was also applied within the human amnesia literature by Kinsbourne & Wood (Kinsbourne and Wood, 1975) and then Cohen & Squire (Cohen and Squire, 1980). The general notion that there are multiple neural modules concerned with different kinds of memory is now widely accepted (Schachter and Tulving, 1994). A somewhat similar history unfolded in the study of visual cognition, beginning with the seminal work of Ungerleider & Mishkin on "two visual systems" (Ungerleider and Mishkin, 1982). When a few years later Jerry Fodor published his landmark philosophical treatise "The modularity of mind" (1983) the strands were ready to be intertwined. It is safe to say that the idea that the brain is comprised of a large number of specialized modules is now the accepted wisdom – the challenges we face lie in figuring out how these semi-autonomous systems interact to generate cognition and behavior.

In the 1970s and early 80s cognitive scientists made considerable strides, in particular in the study of spontaneous mental imagery (later assembled and expanded in (Kosslyn, 1980), mental rotation (Shepard and Metzler, 1971), concept and category formation (Rosch, 1973; Rosch, 1978; Rosch and Mervis, 1996; Smith and Medin, 1981), biases and heuristics in natural reasoning and decision-making (Kahneman, Slovic & Tversky, 1982; Kahneman and Tversky, 1972, 1973, 1979), memory (Tulving and Thompson, 1973), abstraction (Posner, 1978) motion perception (Johansson, 1973), cognitive conceptual development in the child (Carey, 1985; Keil, 1979; Markman, 1989; Spelke, 1985, 1988), learnability theory (Osherson, Stob & Weinstein, 1986), and the theory of Government and Binding (Chomsky, 1981). [35]

A major paradigm shift was in the offing, however, in the revival of biologically inspired approaches to cognitive science. Beginning with the efforts of a group in San Diego, the "connectionist" movement has made major inroads in a large number of fields previously dominated by the views first emphasized by Newell and Simon. A critical focus of this approach was its assertion, sometimes explicit, sometimes implicit, that cognitive models should look more closely at biology. Instead of emphasizing the symbolic level that had been the bread and butter of cognitive science since the mid-1950s, this approach claims to eschew symbols altogether, focusing instead on distributed representations and learning algorithms (Rumelhart, McClelland & Group, 1986). Connectionism as a concept is an old idea – Hebb (1949) referred to it in his book. The label resurfaced in the mid-1980s as the name for a new approach to neural networks, one that has had a major impact on the domain of cognitive science in the past 20 years. Initially developed by John J. Hopfield in 1982, neural networks were abstract entities (later to be also implemented by physical hardware) that were explicitly inspired by real neuronal circuitry, and were capable of automatic learning, rule extraction and generalization (Hopfield, 1982). Hopfield showed how the mathematical simplification of a neuron could allow an analysis

[35] The theories of conceptual development, categorization (Rosch, 1973; Rosch, 1978; Rosch and Mervis, 1996; Rosch, Mervis, Gray, Johnson & Boyes-Braem, 1976; Smith, Osherson, Rips & Keane, 1988; Smith and Medin, 1981) and psychological similarity (Shepard, 1962, 1964, 1994; Tversky, 1977; Tversky and Gati, 1978) see the special issue of BBS on the work of Roger Shepard for a recent synthesis) combined with the theories of, and experiments on, lexical acquisition in the child, and with lexical semantics, opened the way to an integrated theory of conceptual and linguistic development, at the interfaces between phonology and syntax, syntax and the lexicon, syntax and semantics (Bloom, 2000; Gopnik and Meltzoff, 1998; Jackendoff, 1983, 2002; Jackendoff, Bloom & Wynn, 1999; Landau and Gleitman, 1985; Levin and Pinker, 1991); with a dissenting view by Fodor (Fodor, 1994, 1998).

of the behavior of large scale neural networks, modeling progressive descents on an energy surface, thereby mimicking automated learning and automatic feature extraction from a corpus of different, but related, stimuli. Under an assortment of training procedures, with artificial equivalents of reinforcement and punishment, and with "backpropagation" from one layer of terminal nodes back to layers of "hidden" nodes (a powerful improvement that could solve some of the problems of older perceptrons), the remarkable potential of these artificial networks created a sensation. Cognitive scientists, in a number of places, paid very close attention and began to challenge the modularist-innatist theory of mind, and the very idea of dedicated mental rules and representations. The efficiency of such connectionist networks in extracting common features from certain families of inputs could equal, or even surpass, that of humans, as Stephen Grossberg of Boston University had noticed some years before (Grossberg, 1976). In spite of the adjective "neural", and in spite of the liberal use of terms borrowed from biology (evolutionary landscape, fitness, adaptive behavior etc.), the real proximity to "wet" neurobiology remained questionable [36].

The rise of connectionism in cognitive science goes hand in hand with neo-Piagetianism, touting the virtues of general intelligence and multi-purpose cognitive mechanisms powered by processes called stepwise abstractions, categorizations, thematizations and generalizations. Renewed invitations to go "beyond" innatism and modularity (Bates & Elman, 1996; Elman, 1989; Elman et al. 1996; Karmiloff-Smith, 1992, 1993, 1994; Karmiloff & Karmiloff-Smith, 2001) show how pertinent the arguments and counter-arguments developed at the Royaumont

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[36] It is noteworthy that, since the mid-Eighties, physicists in France (Marc Mézard and Gérard Toulouse), in Israel (Daniel Amit and Gabriele Veneziano) and in Italy and Argentine (Giorgio Parisi, and Miguel Virasoro) developed germane mathematical models for the so-called spin glasses (amorphous magnetic lattices in which each node is occupied by an element with a magnetic dipole – spin – that interacts mostly, but not exclusively, with its immediately adjacent neighbors, with a statistical tendency to propagate local dipole alignments to larger regions, in search of global minima (attractors) in the resulting energy surface) (for a comprehensive synthesis, see (Mézard, Parisi & Virasoro, 1987). Inspired by models of ferromagnetic lattices developed in the 1920s by the German physicist Ernest Ising (Brush, 1967), and temperature-sensitive probability decay functions initially proposed by Ludwig Boltzmann, the theories of spin glasses and Hopfield's models soon began to converge, jointly establishing many basic analogies between idealized magnetic lattices and idealized neural nets. The formal equivalence between spin glasses and neuronal networks, no matter how elegant and intellectually satisfactory at an abstract level, engendered in some neurobiologists doubts concerning the real applicability of these models to real brain circuits.

conference remain. The often feisty debates between proponents of these two approaches to cognitive science continue to this day.

A conception of learning, one radically different not only from the connectionist models but also from almost all previous models of learning, has been developed, ever since the early 80s, in a new approach to the study of first-language acquisition (notice that even the word "learning" has been expunged). Commandeering and reorganizing an array of studies on many languages and dialects in a series of lectures at the Scuola Normale in Pisa (Italy) in 1980, and then in the published book (Chomsky, 1981), Chomsky introduced the model called "principles and parameters" (PP for short). In essence, this model reduces all the differences between human languages to a small universal set of syntactic nodes (parameters) for each of which there is a choice between only two admissible values. The binary "values" for each parameter are labeled as "+" (the marked value) and "– " (the un-marked or default value). Under this idealization, the "task" of the child learning his/her native language consists in appropriately "fixing" the binary values of all the parameters in conformity with the set of values implicitly chosen by the surrounding community of speakers. James Higginbotham has summarized this idealization as the positioning of a set of "switches" on a mental "panel" (Higginbotham, 1982). [37] [38]

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[37] At the time (and until the mid-90s) the nature of these parameters was conceived as quintessentially syntactic. Under the guidance of specific hypotheses about the parameters, researchers applied real acquisition data (and vast pre-compiled corpora) to their theoretical predictions of the subtle cascades of manifest consequences on linguistic expressions that the different possible parametric values were expected to produce. This kind of linguistico-developmental "parametric" literature started to grow steadily (and still continues to the present date), but the early results were not always neat, and many intense discussions ensued. In 1995 the "minimalist program" (Chomsky, 1995) shifted the localization of the parameters from the syntax proper, to the morpho-lexical component of language. The problematic re-interpretation of older data, and a new flurry of experiments carried out under this different model have blurred some of the simple and elegant contours of the initial experiments. This has stimulated some, but also disappointed other, researchers, who presently feel the need of a reappraisal of the very ideas behind the PP model. Whatever the ultimate destiny of the PP idealization, it has given a very productive impulse to the development of detailed non-inductivist models of learning. Novel kinds of fixation mechanisms have been introduced and equally novel kinds of interactions between the linguistic external inputs and these mechanisms. One quick and relevant measure is a steady increase in the number of scientific communications inspired by this approach presented each year at the Boston University Conference on Language Development. The Conferences started in 1976. Their proceedings from 1994 to the present have been published by Cascadilla Press (Somerville, Massachusetts).

An entire family of new mechanisms was proposed to account for non-inductive learning and the fixation and stabilization of rules and concepts in the child's developing mind-brain: the sub-set principle (Berwick, 1985), greediness, conservativity, locking capacity, triggers, default

The Emergence of Cognitive Neuroscience: Some Exciting Developments

Progress in cognitive neuroscience during the last decades has been nothing short of phenomenal, owing in large measure to the development of neuroimaging techniques that have made it possible to study the human brain during various cognitive activities. The use of electroencephalographic methods with humans has a long history, but such methods involving surface recordings have inherent limitations, most specifically related to the spatial localization of the recorded signals. The use of many more recording sites, and sophisticated analytic tools has engendered a new generation of such methods, most prominent in the domain of event-related potentials (ERPs), where recordings are synchronized to cognitive events of interest so that patterns of brain activation specifically related to those events can be identified. Such ERP methods have yielded considerable insights, especially in the temporal domain. However, spatial localization remains a problem. This is where the emergence of new neuroimaging techniques has been most productive. The critical insight here was the realization that methods could be

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values (Gibson and Wexler, 1994; Wexler and Borer, 1986; Wexler and Culicover, 1980; Wexler and Manzini, 1986). A close constructive dialogue was established between formal theories of "learnaibility" (Gold, 1967; Osherson, Stob & Weinstein, 1986; Pinker, 1979; Pinker, 1990) and empirical data on language acquisition in children in a variety of languages (for an early synthesis, see (Wanner and Gleitman, 1982) and for a recent one see (Guasti, 2002)). Arguably, the most remarkable property of these hypotheses, besides their non-inductivism, is to constitute a cumulative concrete attempt by many of these researchers to build a detailed selectional (as opposed to instructional) frame for language acquisition across languages. Selective models of the growth and development of the nervous system can be traced back to the paradigm of stabilization of developing synapses through selective activation, as initially established by Hubel and Wiesel's experiments on the development of the visual system in selectively deprived kitten (see text). Pasko Rakic and Patricia Goldman-Rakic (Goldman-Rakic, 1985; Goldman-Rakic, 1987; Rakic, Bourgeois, Eckenhoff, Zecevic & Goldman-Rakic, 1986), and Purves and Lichtman, among others, later extended and refined a model based on the overproduction of synapses in the developing cortex, followed by a massive trimming of the inactive connections. The wider implications of such selective models for neurobiology, cognitive science and beyond were soon highlighted by J.-P. Changeux,and G. M. Edelman (Changeux and A., 1974; Changeux, Heidmann & Patte, 1984; Edelman, 1987; Edelman and Mountcastle, 1978; Edelman and Reeke, 1982) (for a recent reconstruction and wide philosophical consequences of selective theories, see (Changeux, 2002)).

[38] It is to be expected that at least some of these new ideas will find a suitable place in future theories of learning and acquisition, possibly even beyond the domain of language. Over and beyond the interest of the PP model per se, this is a case study of a deep connection between the neurosciences and the study of the mind, one of many that have shaped modern cognitive science.

devised to track metabolic and other consequences of neural activity in humans. The first widely used method, positron emission tomography (PET) depends upon the use of radioactive substances and the uptake of these materials by recently active neural tissue. More recently, a less invasive method, functional magnetic resonance imaging (fMRI) has been developed as an alternative. This method takes advantage of the fact that blood oxygenation levels change as a function of neural activity, and that oxygenated and de-oxygenated blood (or more precisely, hemoglobin) have different magnetic properties. This permits the detection, with powerful magnets, of those areas of the brain mobilized by some form of cognitive activity. Yet another method, magnetoencephalography (MEG) depends upon the very small, but measurable, magnetic fields engendered by neural activity. This method, though depending on considerable analysis to extract signals from noise, offers great promise given its ability to couple the real-time dynamic response (on a scale of milliseconds) with accurate spatial localization. Finally, trans-cranial stimulation (TMS) has emerged as a method to stimulate, or, mostly, selectively inhibit, areas on the cortical surface, and has been productively used to study in a very precise way the role of these surface structures in various cognitive functions.

Considered together, these methods have brought about a considerable explosion of research on the brain mechanisms of normal human cognitive function [39]. Where previous studies were limited to pathological cases, and involved the problematic analysis of function from the deficits caused by pathology, these methods provide an entirely new window onto the human mind. Not surprisingly, they have in the first instance confirmed many of our hard-won assumptions about which parts of the brain are engaged by what kinds of cognitive activity. Imaging studies have also shifted the focus of explanation away from reliance on discrete "centers" of cognitive function towards the notion of an interaction between multiple brain areas. While some might argue, even at this stage, that neuroimaging is merely a modern-day version of phrenology (activations in the head, rather than bumps on the skull) (Bates & Dick, 2000), clever researchers are beginning to develop new paradigms that offer the promise of real advances that would have been impossible with earlier techniques. Finally, the combination of neuroimaging with more traditional single and multiple neuron recording and with selective

[39] Many have contributed to this set of exciting developments, but the St. Louis group of Marcus Raichle, Peter Fox, Steve Peterson and Michael Posner, instrumental in getting things started, deserve special mention (Posner, Petersen, Fox & Raichle, 1988).

chemical labeling methods offers the promise of combining the insights that these approaches can offer [40].

The productive use of more traditional methods has by no means ceased: consider for example the discovery in monkeys of the so-called "mirror neurons" (Rizzolatti and Craighero, 1998). These neurons demonstrate a remarkable property: the same neuron is active when the animal either engages in an action, or observes another animal engaging in the same action. Th existence of such neurons raises questions of great import to philosophers of mind (Goldman and Gallese, 1998). The possible role of a system of mirror neurons in the creation of internal mental models is obvious, and the implications of these findings for theories of the emergence of language is under active discussion (eg., Rizzolatti & Arbib, 1998, 1999). Another major advance concerns the development of methods for simultaneously recording from many individual neurons, making it possible to study the activity of neural ensembles. These methods have been quite productively applied to the study of hippocampal "place cells" (Wilson and McNaughton, 1993), where it has been possible to demonstrate that patterns of activity observed during a rat's daily activity have a high likelihood of recurring during a subsequent sleep episode.

New findings from developmental neuroscience and neuroanatomy have overturned the long-accepted view that nerve cells cannot be formed after the earliest stages of life (Gould and Gross, 2002). This, and other findings from the study of memory and perception, have reminded neuroscientists of the incredible dynamism of the brain. A major challenge for the future, at the very heart of the cognitive science enterprise, is to figure out how the stable world our minds construct, as pointed out by Craik, can be instantiated in a biological substrate that is constantly changing. Or, to put it as McCulloch (and Shakespeare) did: "What's in a brain that ink might character" (McCulloch, 1964).

Thanks to the stunning discovery of systematic errors in spontaneous reasoning and decision-making, notably by Amos Tversky and Daniel Kahneman, a progressive integration has begun between cognitive science and economics (for a pioneering survey, see (Thaler, 1991, 1992)). The recently explored neuronal bases of decision-making, both in pathological cases

[40] This combination is currently being explored most productively by Nikos Logothetis and his group at the Max Planck Institute in Tübingen (Saleem, Pauls, Augath, Trinath, Prause, Hashikawa & Logothetis, 2002).

(Adolphs, Tranel, Bechara, Damasio & Damasio, 1996; Bechara, Damasio & Damasio, 1994; Bechara, Damasio, Damasio & Lee, 1999; Damasio, 1994; Damasio, Damasio & Christen, 1996), and in normal subjects (Breiter, Aharon, Kahneman, Dale & Shizgal, 2001) has suggested that a whole new domain, called Neuroeconomics (McCabe, Houser, Ryan, Smith & Trouard, 2001; Smith, in press) (McCabe, article "Neuroeconomics" in this encyclopedia) may be just around the corner. The need to integrate standard economic analyses with what cognitive scientists have discovered about spontaneous heuristics and biases is now reported in the popular press [41].

The modern era

Among the most striking changes in cognitive science in the past 10-20 years has been the shift in what is open to study. As we noted earlier, cognitive science started with the view that cognition is limited to those things humans can be conscious of. This position has been totally abandoned, and much of the domain is now concerned with phenomena that lie behind the veil of consciousness. Whether or not they are conscious, animals and animal research are very much a part of modern-day cognitive science. One prominent example concerns the study of emotion. Great strides have been made in linking emotion to traditional views of cognition, thereby returning the field to the point at which Craik left it more than 50 years ago. Finally, the grand-daddy of them all, consciousness itself, has become the focus of intense research interest within cognitive science (and beyond) in recent years [42].

Cognitive Science has now reached the stage where one sees the production of integrated textbooks (Bechtel and Graham, 1999; Osherson, 1990/1995; Posner, 1989; Stillings, Feinstein & Garfield, 1987) and the publication of a concise encyclopedia (Wilson and Keil, 2000) Neuropsychology and cognitive neuroscience also now have their comprehensive sourcebooks (Gazzaniga, 1984, 2000; Kosslyn and Andersen, 1992; Posner, 2001)

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[41] For instance, among many more, the following articles:*The New York Times*, March 30,1997; *The New York Times Magazine*, February 11, 2001, *The Washington Post*, January 27, 2002.

[42] This resurrection was initiated perhaps by researchers in cognitive psychology and neuropsychology (eg., Moscovitch, 1995), but it has now been embraced by a much wider, interdisciplinary, network. A series of large multidisciplinary conferences on consciousness has been held at two year intervals in Tucson, Arizona since 1994, attracting each time more than a thousand participants ranging from poets to physicists to physiologists.

Having grown into a rich and multi-faceted domain, it's normal that cognitive science has witnessed, is witnessing, and will continue to witness, disagreements, schisms, partial reconciliations and yet further splits in theories and methodological criteria. If we decide, with some simplification, to characterize as "mainstream" or "classical" cognitive science the individualist, largely innatist, modular and representational-mentalist (RTM) conception of the mind that characterized much of the 80s and 90s, there are clear signs that we may be entering a post-classical cognitive science (Piattelli-Palmarini, 2001). The innovative turn introduced by connectionist models in the mid-80s has revamped an anti-modular and general-purpose conception of the mind-brain, soon contested by "classic" cognitive scientists (Pinker and Mehler, 1988) The last few years have witnessed a partial (only partial, but not irrelevant) rapprochement between the two camps: many connectionists now countenance initial sets of pre-wired connections, and can explain the spontaneous tendency of parallel networks to locally cluster into modules (these modules are, however, conceived as emergent a la Piaget, not pre-wired (Elman et al. 1996; Karmiloff-Smith, 1992, 1994). Symmetrically, on the other front, several linguists and developmental psychologists rooted in the generative tradition are presently searching for inductive (even statistical) components of early language acquisition, and report finding some that may play a crucial role (Nespor, 2001; Newport, Bavelier & Neville, 2001; Ramus, 2002 (in press); Ramus, Nespor & Mehler, 1999).

Critics of modularity are also to be found in cognitive neuroscience, notably in the analysis of pathological deficits heretofore depicted as paradigms of modularity (prosopagnosia, for instance, with contrasting views, and contrasting observations, championed by Isabel Gauthier (Gauthier, Skudlarsky, Gore & Anderson, 2000; Gauthier, Tarr, Anderson, Skudlarsky & Gore, 1999; Gauthier, Tarr, Moylan, Skudlarsky, Gore & Anderson, 2000)on one side, and by Nancy Kanwisher and Morris Moscovitch (Kanwisher and Moscovitch, 2000) on the other. The nature and significance of earlier discoveries of specific language variants and deficits, from savants (Smith and Tsimpli, 1995) to Williams syndrome (Bellugi, Lichtenberger, Mills, Galaburda & Korenberg, 1999; Bellugi and StGeorge, 2000; Bellugi, StGeorge & Galaburda, 2001; Bellugi, Wang & Jernigan, 1994; Stevens and Karmiloff-Smith, 1997), to sign-languages (Kegl and McWorther, in press; Kegl, Neidle, MacLaughlin, Bahan & Lee, 2000; Klima and Bellugi, 1979; Petitto, 1987; Petitto and Marentette, 1991) (Emmorey and Lane, 2000), to SLI (Specific Language Impairment, (Gopnik, 1990, 1994; Van der Lely, 1997; Van der Lely and

Stollwerck, 1996; Wexler, 2002) is being questioned by researchers who conceptualize language as a specialization of general cognitive and communicative functions (Bates and Dick, 2000; Bates, Elman, Johnson, Karmiloff-Smith, Parisi & Plunkett, 1999; Karmiloff and Karmiloff-Smith, 2001; Karmiloff-Smith, 1998; Volterra, Caselli, Capirci, Vicari & Tonucci, 2002 (May 1-5); Volterra and Erting, 2002) Even the legitimacy of combining data from language pathologies in the adult with data on developmental deficits in the child is being criticized in principle (Karmiloff-Smith et al. in press for BBS).

Theories of language evolution that revise the approach of generative grammar (Pinker, 1994; Pinker and Bloom, 1990) [43], only pay lip service to it (Deacon, 1997) or fly in the face of decades of research in generative grammar (Dunbar, 1999; Lieberman, 2000; Tomasello, 1999) have recently been published. The age-old attempt to derive linguistic structures from motor control, considered moribund (cf. the exchange between Chomsky and Piaget on this point at the Royaumont debate described earlier), is being revamped under a different guise (Rizzolatti and Arbib, 1998, 1999). Cognitive innatism is re-analyzed at its roots, and allegedly more promising alternatives are being offered (Cowie, 1999, 2000; Elman, Bates, Johnson, Karmiloff-Smith, Parisi & Plunkett, 1996).

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[43] The 1990 article in BBS by Pinker and Bloom has been received with warm, albeit sometimes cautious (Deacon, 1997), assent by many who have only general sympathy for generative grammar, or accept only parts of it, or remain prudently agnostic about the enterprise as a whole. The reconciliation between generative grammar and a neo-Darwinian adaptationist account of the evolution of language, so eagerly explored by Pinker and Bloom (for later developments and refinements see their subsequent books (Bloom, 2000; Pinker, 1994, 1997), reassures those who are reluctant to follow Chomsky all the way in his defense of radical discontinuity and the punctate appearance of the language faculty exclusively in humans. It assuages their fear that Chomsky's theses may involve an appeal to an evolutionary miracle, an exceedingly improbable "hopeful monster". The radical adversaries of generative grammar, predictably, have found no reason to be interested in this reconciliation, noting that the generative camp harbors embarrassing internal disagreements. Generative grammarians have, in the main, remained unabatedly critical of all extant adaptationist accounts of language evolution {see Note 25}, including the one offered by Pinker and Bloom (see the peer commentaries accompanying the BBS article), and some have brought into evidence the convergent critiques of adaptationist explanations independently and authoritatively developed by Stephen J. Gould and Richard C. Lewontin in evolutionary theory proper (one of the main targets of Pinker and Bloom was a paper by Piattelli-Palmarini (Piattelli-Palmarini, 1989) in which this convergence between antecedently separate contributions was made explicit). At an international meeting in Venice (Italy), with Gould in the audience, Paul Bloom confessed with humor that he and Pinker would have felt uncomfortable challenging Chomsky on language and Gould on evolution, but felt reasonably comfortable challenging Chomsky on evolution, and Gould on language.

The cognitive sciences today expand in every direction, as can be seen in the wide range of articles included in these volumes. Neuroscience has been drawn back into the fold, and the area of cognitive neuroscience is one of the major growth industries in the field. We will let the articles in this volume speak for themselves in filling in our history. Among these articles are biographies of a variety of pioneers (now deceased) whose contributions were critical to the emergence of cognitive science. Also among these articles are a number of overarching reviews that attempt to address large domains within cognitive science, such as memory, perception, representation, development, and the like.

It is impossible to anticipate the paths that cognitive science is going to take in the years to come. We are entering a post-classical era and there are reasons to believe that it will prove as productive and as innovative as the one that preceded it. These volumes offer a complete and complex picture of the discipline up to the present. What will happen in the future will almost certainly surprise us. It will be the task off the forthcoming online version of the encyclopedia to report on these developments.

Putting together the encyclopedia has been a challenge but also an opportunity, and the same can be said about looking into the history of the field. It is a fascinating history, peopled by intellectual giants, and ruminations about the big issues that have concerned thinkers for several millennia. A complete history of these times remains to be written; perhaps a reader of this encyclopedia will be sufficiently excited by its contents, and the genesis of these ideas, to take on that task.

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