

HISTORICAL INTRODUCTION

You may not have heard about neurolinguistics before, but you may have heard of neuromania: the recent fascination with anything neuroscientific, especially if accompanied by colorful pictures of the brain “in action.”¹ Is neurolinguistics yet another case of neuromania? The short answer is no. So far as one can tell, there is no general fad for language in the brain, and whatever interest there is in it has a long and rich history, predating many developments in cognitive neuroscience (the study of human brain structures and functions) and linguistics (the study of human languages). Research on language in the brain did not need a mature linguistics and a mature neuroscience to get started. In fact, some of the early results in neurolinguistics were instrumental in launching the enterprises of modern linguistics and modern cognitive neuroscience.

A comprehensive history of neurolinguistics has yet to be written, and the origins of the term *neurolinguistics* are still largely undocumented.² We may identify three major turning points in the history of speculation and, eventually, research on language in the brain. The first was an empirical breakthrough: the discovery by Paul Broca around 1860 that damage to certain parts of frontal cortex can be accompanied by impaired speech production. The second was a theoretical breakthrough: the proposal by Noam Chomsky and others around 1960 that language is a computational system, formally defined by a finite vocabulary plus a finite set of rules that can be used to generate an infinite set of sentences. The third was a technological breakthrough: the introduction and diffusion around 1980 of methods for in vivo neural measurements in humans and of computers for the analysis and simulation of experimental data.

For better or worse, neurolinguistics today is shaped by those theoretical and methodological choices. We still view language as a computational component of the human mind, we still try to map specific linguistic processes to specific areas of the brain, active at particular times, and we still rely on high-tech measurements and data processing techniques for getting, analyzing, and modeling experimental results. Let us review in more detail how neurolinguistics became what it is.

The Pioneers and the “Diagram Makers”

The idea that speech and language are manifestations of specific capacities of the human organism dates back to antiquity.³ Descriptions of cases of speech disorders in the presence of traumatic head injuries became relatively more frequent during the Renaissance and early modern period,⁴ but it was only in the nineteenth century that a connection between speech disorders and brain lesions was proposed. Franz Joseph Gall (1758–1828) was likely among the first who made that connection explicit. His version of “faculty psychology” was original and influential.⁵ Gall argued that the mind is organized as a hierarchy of faculties that (1) are defined by their content (e.g., language, mathematics, music), (2) may be innate in humans or other species, (3) are distinct from and independent of each other, and (4) are localized in parts of the brain distinct from and independent of each other. Gall also noted that there are disorders limited to the “faculty of speech,” and that would be impossible if speech was not localized in a particular part of the brain.⁶ Gall put forward a simple idea that—in virtue not of being right but of being testable using the methods available at the time—contributed to the emergence of early empirical research on the brain bases of language.

The neurological doctrines circulating in the early nineteenth century included the thesis that any region of

the hemispheres can take up a given function (equipotentiality), proposed by Jean Pierre Flourens (1794–1867), and the law of symmetry by Xavier Bichat (1771–1802), implying that if a brain area for speech or language exists, it should be an area in both hemispheres—a “bilateral area.”⁷ At that time, the question was not so much where precisely in the brain language and speech would localize. The issues were rather whether they would localize at all and whether they would localize in areas of one hemisphere but not the other. Different positions were possible, depending on how one would frame and answer each of those two questions. For example, Jean-Baptiste Bouillaud (1796–1881), on the basis of analyses of the site of brain lesions in patients with impaired speech, proposed that speech would be localized in the frontal lobe of the brain and concluded that Gall was correct. However, Bouillaud assumed that the human brain was symmetrical. Therefore, if speech could be localized, it would be in the frontal lobe of both hemispheres.

Paul Broca (1824–1880) is usually credited with the discovery that aspects of speech or language are not just localized in the frontal lobe; they are also lateralized to the left hemisphere. Others before Broca, including Marc Dax (1770–1837), had argued that spoken language was in the left hemisphere. But Broca had the data, and he published them at what retrospectively seem to have been the right time and the right place. In a series of communications to

the Anatomical Society in Paris in 1861, he described the cases of two patients, Leborgne and Lelong, who had enormous difficulty producing speech, except for a very few “articulated sounds that are always the same and always produced in the same manner.”⁸ Broca reported that both men could “hear and understand” spoken language, could easily produce “vocal sounds” and move their tongues and lips more “expansively and energetically” than is required to articulate speech, and were “fully intelligent.”

These observations allowed Broca to conclude that, in both patients, what appears to be compromised are not input (auditory) and output (motor) systems but rather the “faculty of articulated speech.”⁹ Broca examined Leborgne and Lelong’s brains on autopsy and he observed that both had extensive damage to the left frontal cortex in a region he referred to as the “third frontal convolution” (figure 1). “The integrity of the third frontal convolution, and perhaps of the second, seems indispensable to the exercise of the faculty of articulate language. In Leborgne and Lelong the lesion lies behind the middle third, opposite the insula and precisely on the same side” (the left), Broca concluded.¹⁰

Did Broca aim to test the hypotheses that speech is localized in the frontal lobes *and* lateralized to the left side? And did he actually claim he had evidence for both? This is not the place for historical controversy, but it may be worth mentioning that Broca’s views evolved in the years between 1860 and 1865. Broca had never been a

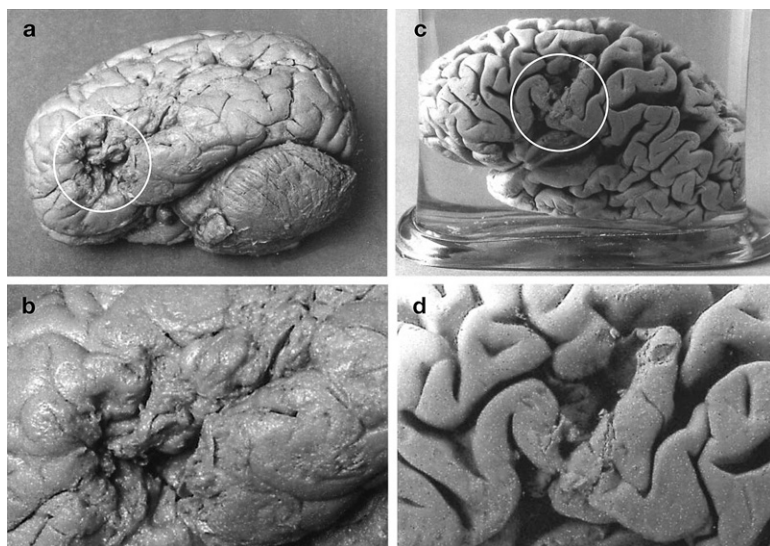


Figure 1 Photographs of the brains of Leborgne (a, b) and Lelong (c, d).

fervent supporter of the localization and lateralization theses: his “conversion” was “slow and effortful,”¹¹ and he detached gradually from the doctrines of equipotentiality and symmetry of Flourens and Bichat. For him, the Leborgne and Lelong cases were one opportunity to test Bouillaud’s hypothesis that speech resides in the frontal lobes or the prediction that a patient who was unable to speak would present frontal lesions. It was not an issue whether the faculty of language could be localized frontally or at

all, or whether the faculty of speech was left lateralized. Broca did claim that the frontal injury in Leborgne and Lelong was “the cause of loss of speech,” confirming Bouillaud’s view.¹² However, he was also careful to avoid general claims about the language faculty, and he only eventually accepted the possibility that speech could be lateralized to the left hemisphere.

It was the task of the next generation of researchers to study other components of speech and language in the brain. Carl Wernicke (1848–1905) could examine cases of patients with different symptoms and lesions compared to Broca’s patients, who presented limited ability to produce speech but had good comprehension—what became known as “Broca’s aphasia.” Wernicke described patients whose speech is rapid and effortless but may lack relevance and coherence, and whose speech comprehension abilities are impaired; this pattern became known as “sensory aphasia” or “Wernicke’s aphasia.” Wernicke also described patients who could still articulate and understand speech, but where repetition was impaired—“conduction aphasia.” As the title of his landmark 1874 publication indicates (*Der aphasische Symptomencomplex*), Wernicke was aware that there was a “symptom complex” of aphasia, not a single or uniform disorder, awaiting explanation.¹³ Wernicke’s answer was the first model of language in the brain (figure 2), which was bound to have a huge impact, lasting to this day.

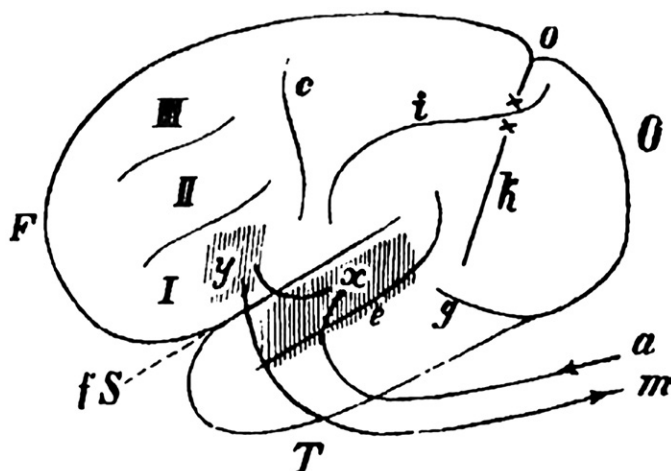


Figure 2 Wernicke's diagram model of speech processing in the brain.

For Wernicke, spoken language is supported by a set of interconnected centers: gone is the notion that a single “grand region” of the cortex is the basis for a single “mental faculty.”¹⁴ These are a center for “motor images” of words, corresponding to the left frontal cortex, as identified by Broca (figure 2, *y*), and a center for “auditory images” of words in the posterior superior temporal gyrus (figure 2, *x*). These centers are connected anatomically (Wernicke also put forward a hypothesis concerning the fibers that would provide the link), they receive inputs from auditory nerves (*a*), and they relay outputs through motor nerves (*m*).

These centers and connections can be damaged, and each lesion can cause a specific speech or language disturbance.¹⁵ Disruption of acoustic nerves (a) can cause deafness, while disruption of motor nerves (m) can cause paralysis of speech—not aphasic symptoms. Damage to the motor images center (y) can cause Broca’s aphasia, where speech is not correctly articulated. Damage to the auditory images center (x) can lead to sensory aphasia, where speech cannot be decoded and made intelligible. Finally, damage to links between the motor and auditory centers can cause conduction aphasia: if the transfer of information between these centers fails, the patient has difficulty expressing the intended thoughts or repeating words that are spoken to them.¹⁶

Wernicke is the last pioneer of neurolinguistics and the first of the so-called “diagram makers,” as Henry Head (1861–1940) would later call the early aphasiologists.¹⁷ His everlasting contribution is the first connectionist model of language in the brain, with both predictive and explanatory power. Today we view the language system effectively as a network of brain regions that collectively perform certain functions or tasks and where individual regions participate in several functions or tasks. Wernicke was responsible for an early shift toward this view, away from strict localization. He also believed that concepts would be distributed across the brain and so would not be localizable, as motor and auditory centers were.

Ludwig Lichtheim (1845–1928) adopted and developed this insight.¹⁸

Versions of Wernicke’s model—also known as the Broca-Wernicke-Lichtheim model or the Broca-Wernicke doctrine—were advanced until recently. Sometimes these were genuine and substantial updates of the model, as in a proposal by American neurologist Norman Geschwind (1926–1984).¹⁹ But others were caricatures popularized as “the” standard neurological model of language. A recurrent simplification is that Wernicke’s auditory images center is the brain’s speech comprehension center, while the motor images center is the brain’s speech production center. His view was instead that the two centers (plus the distributed concept centers) contribute different processes to speech production, which is always the result of the joint operation of several nodes in the network.

Much modern aphasiology was a sustained attempt at testing and revising Wernicke’s model—a series of footnotes to Wernicke, one might say. But was nineteenth-century research on the brain bases of speech really neurolinguistics, or was it “just” neurology or aphasiology? The ideas and results of Broca, Wernicke, and others were not yet neurolinguistics, but they provided the initial impulse to its development before they could be integrated with linguistic theories during the twentieth century. Early attempts at integration were made with structuralism: the theory of language as a system of signs, such

as sound-meaning pairings, formulated by Swiss linguist Ferdinand de Saussure (1857–1913).²⁰ But a leap forward came only with generativism, the theory that language is a computational system—a finite set of rules for generating sentences—made precise by linguist Noam Chomsky.

Neurolinguistics and the Cognitive Revolution

At the turn of the twentieth century, it must have seemed clear to discerning linguists that language was in some sense “in” the brain. For example, Saussure remarked in his *Cours de linguistique générale* (1916) that language exists as a “sum of imprints deposited in each brain.”²¹ But recognizing that it is so is an altogether different matter from proving it with the methods of the sciences. Broca, Wernicke, and others had shown that productive and receptive speech had their seat in the brain. But they left the much bigger issue of the localization of the general faculty of language untouched, as Broca readily conceded as soon as 1861. Approaching that question required a better understanding of language, specifically of syntax and semantics, than was available for most of the nineteenth century. Aphasiology and the neurology of language had to morph into neurolinguistics proper.

How that happened is a complex and untold story, but there were three critical junctures. First, John Hughlings

Jackson (1835–1911), among others, noted that identifying the anatomical causes of a symptom is not the same as localizing a function. This paved the way for inclusion of psycholinguistic methods into aphasiology, in particular of controlled lab experiments outside the clinic. Second, it became clear that speech and language were about phrases and sentences, not just words. Heymann Steinthal (1823–1899) was among the first to distinguish word-level (aphasia) and sentence-level (acataphasia) disorders.²² Adolf Kussmaul (1822–1902) introduced the term *agrammatism* for a spectrum of deficits relating to the syntactic organization of sentences. Third, linguistics began to penetrate aphasiology, for example, through the work of Roman Jakobson (1896–1982), who argued that output deficits in Broca’s aphasia reflect the breakdown of the syntagmatic (sequencing) axis of language, while input deficits in Wernicke’s aphasia reflect the breakdown of the paradigmatic (lexical selection) axis.²³ Jakobson’s linguistic approach to aphasia, in particular its structuralist emphasis on language as a formal system, today seems much more sophisticated than that of most of his contemporaries.²⁴ But it is only with subsequent developments in linguistics, in the mid-twentieth century, that neurolinguistics could start to get a firmer grasp of syntax and semantics in the brain.

One breakthrough came in the 1950s in a series of papers by Chomsky, where he combined techniques from

logic and mathematics with earlier analyses by Zellig Harris (1909–1992) on so-called syntactic transformations, such as the rules that transform active sentences (“The boy ate the candy”) into passive ones (“The candy was eaten by the boy”). Chomsky proposed transformational-generative grammar as a theory of linguistic syntax—eventually, just generative grammar (GG). A GG is unlike the grammars we were taught in school. At bottom, a GG is a procedure for constructing sentences.²⁵ Initially, it was a finite set of rewrite rules; for example:

A. $S \rightarrow NP VP$

B. $NP \rightarrow Det N$

C. $VP \rightarrow V NP$

where S is a sentence, NP a noun phrase (e.g., “the boy”), VP a verb phrase (e.g., “ate the candy”), Det a determiner, N a noun, and V a verb (rewrite rules where words are the terminal symbols may also be included—for example, $Det \rightarrow the$, $N \rightarrow candy$, $N \rightarrow boy$, $V \rightarrow eat$). A rule $X \rightarrow Y$ allows us to rewrite the left-hand symbol X as the right-hand symbol Y , for example, a sentence S as a sequence of a noun phrase and a verb phrase $[NP VP]$, applying rule A. Let us gloss over the question whether this toy GG generates all and only the well-formed sentences of English

(it doesn't), and consider how it generates the syntactic structure of "The boy ate the candy." We start from the symbol:

S

We apply rule A to S, and we obtain:

[NP VP]

Then we apply rule B to NP and rule C to VP, and we get:

[Det N] [V NP]

Finally, we apply rule B to NP again:

[Det N] [V [Det N]]

Each application of a rewrite rule leaves a trace in the final structure: the brackets [] are the fingerprints of the generative procedure. The final structure is *hierarchical*, as each phrase (e.g., [Det N]) can be embedded inside some other phrase (e.g., [V [Det N]]). The procedure is *recursive*, as each rule can be applied to the result of applications of itself or other rules: rule B is used twice, recursively, in the derivation. This formal approach can be extended beyond syntax—for example, to phrasal and sentential semantics.

Before the advent of generative grammar, logicians and philosophers were already developing formal systems and languages for various purposes. But it was Chomsky, in the 1950s, who designed formal systems that could be used to capture key properties of natural language syntax (it had not been tried before) and who, in the 1960s, wed the formal approach to a view of “generative grammars as theories of human linguistic competence” (earlier research on formal languages was decidedly antimentalistic).²⁶ This blend of formalism and mentalism in linguistics contributed to the emergence of the so-called computational theory of mind and eventually cognitive science: the interdisciplinary study of mind, embracing areas of philosophy, psychology, linguistics, and neuroscience. Some have dared call these developments a “cognitive revolution,”²⁷ while others have argued that it was in fact a return of linguistics and psychology to their (European) “mentalistic roots.”²⁸ Many would agree that the computational theory of mind has changed how scholars and educators understand human cognition—its structure and its capabilities.²⁹

What did that imply for neurolinguistics? In essence, it brought to completion and fruition the movement toward a mature neurolinguistics initiated several decades earlier. First, innovative experimental techniques were developed by psycholinguists, including George A. Miller (1920–2012) at Harvard, a close associate of Chomsky. Aphasiologists gradually adopted those new methods, for

example, at the Boston Aphasia Research Center, established and led by Norman Geschwind and Harold Goodglass (1920–2002). Second, the emphasis shifted from words to sentences and from stimulus-response associations to the formal, hierarchical structure of complex cognition and behavior. Third, linguistic theories were actively used as predictive and explanatory tools in studies of language processing and acquisition. For the first time, in the late 1960s and early 1970s, it became possible to ask questions on the “psychological and neural reality” of specific operations posited by theoretical linguistics (such as transformations).³⁰

In the 1960s, the term *neurolinguistics* emerged,³¹ the first “grand synthesis” of linguistics and neurobiology was proposed by Eric Lenneberg (1921–1975),³² and the community began to organize itself, with the founding of societies and the journal *Brain and Language* in 1974. The editorial of the first issue, by Harry Whitaker, reads: “The nascence of such fields as physiological psychology or, more recently, neurolinguistics, is simple evidence that many recognize the value of an enlarged conceptual base and new analytical tools in the complex area of language, the brain, and the interrelationships between them.”³³ With much foresight, Whitaker saw that a radical technological transformation was coming to the field of neurolinguistics: “the development of new techniques and refinements of old ones which presage even more remarkable advances

and insights in the future: event-related slow potentials of the brain, three dimensional X-ray analysis of brain tissue, mathematico-logical systems for linguistic analysis and psycholinguistic analyses of aphasia” are only a few examples of the technologies and methods that would shape neurolinguistics as we know it today.

Neurolinguistics and the Technological Revolution

During the 1970s, researchers in neurolinguistics began to use methods for recording electrical brain activity online in healthy participants (electroencephalography, EEG) and for measuring variations in the electrical currents (event-related potentials, ERPs) generated by the brain in response to external events (e.g., stimuli) or internal actions (e.g., decisions). In the 1980s and 1990s, scholars in Europe and the United States showed that some of these signals changed rapidly and in systematic ways in response to experimental manipulations of linguistic stimuli—for example, if a sentence ends with a word that is unexpected in that context (“... we eat bread and socks”) or if a sentence contains a grammar error (“... they throws the toy on the ground”).³⁴ It turned out that the brain produces different responses, at different times, to anomalies of linguistic form and content. This led researchers to speculate on the separability of systems

for meaning and grammar in the brain: a topic of considerable debate even today (more in the next three chapters). EEG and ERP methods were extensively tested, perfected, and applied over the past three decades to several questions concerning language processing and acquisition in various populations and age groups. Other techniques for tracking neural responses to language have been adopted by many neurolinguists, including magnetoencephalography (MEG), electrocorticography (ECoG), and other direct measures of electrical brain activity, such as intracranial EEG (iEEG). These methods can provide detailed information on the timing of linguistic processes and, increasingly, on the underlying physiological mechanisms.

In the 1980s, it became possible to detect changes in the concentration of glucose or oxygen and hemoglobin in brain tissue with positron emission tomography (PET) or functional magnetic resonance imaging (fMRI) and to build maps of active brain regions, superimposed on anatomical three-dimensional scans. With the wider diffusion of these tools taking off in the mid-1990s, neurolinguists could finally “see” how the human brain responds to language, in vivo, noninvasively, and in exquisite spatial and temporal detail.³⁵ Reassuringly, the first imaging experiments on language comprehension were compatible with the neurolinguistic lore. For example, an fMRI study by Marcel Just and colleagues, published in 1996 in the journal *Science*, showed that Broca’s area (in the left inferior

frontal cortex) and Wernicke's area (in the left posterior superior temporal cortex) were active as a function of the syntactic complexity of the sentences that participants were processing. Such activation was overall stronger in the left hemisphere in these two regions than in their right-hemispheric counterparts.³⁶ Hundreds of fMRI experiments on language have been published since then, and fMRI remains a prime imaging method in many areas of human neuroscience, including neurolinguistics.

Most EEG and fMRI data sets contain millions of data points: millions of different numbers organized into a matrix or a higher-dimensional structure. Collecting and analyzing (and storing) so much data would be impossible without digital computers. The computer is the protagonist in the recent history of neurolinguistics: as a mathematical concept, it inspired the computational theory of mind, and as a physical object, it enabled experimental research on larger samples, longer laboratory sessions, and better-controlled conditions than was previously possible. Neurophysiology and computing have changed the whole research pipeline in neurolinguistics and, more generally, in psychology and neuroscience: data and ways to handle them today shape every step of inquiry, from study conception to publication.

The technological revolution has also changed how theory is developed and tested: it has become common to construct computer models of various linguistic processes,

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such as a program that learns to assign a syntactic structure to a given sentence, and to use such models to generate or “simulate” data that are then compared to experimental observations. The social structure of the field has evolved too: research on language in the brain today is performed by large, interdisciplinary teams of highly skilled specialists, working in different countries on short-term grants. Broca, Wernicke, and arguably even Jakobson would find today’s computer-aided neurolinguistics alien in comparison to the solitary, low-tech efforts that characterized their daily work.

We have come to the conclusion of our brief history of neurolinguistics. A few remaining gaps will be filled later. Consider now the picture that emerges from the narrative. The “neuro” aspect is a thoroughly experimental enterprise that uses the latest technologies to measure brain activity and synthesize these recordings in the form of models: spatiotemporal representations of activation waves in the brain. The “linguistics” aspect is an intensely formal project that produces logico-mathematical accounts of how complex linguistic structures can be derived from simple elements. Can these very different modes of inquiry and spheres of reality—biology and mathematics, matter and mind—be integrated instead of only juxtaposed? The adventure of contemporary neurolinguistics begins here.

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