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Handbook of Pragmatics (2012)

NEUROLINGUISTICS

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1. Definition

Neurolinguistics is the study of language-brain relations. Its final goal is the comprehension and explanation of the neural bases for language knowledge and use. Neurolinguistics is by its nature an interdisciplinary enterprise, and straddles the borders between linguistics and other disciplines that are connected to the study of the mind/brain (mainly cognitive psychology, neuropsychology and cognitive neuroscience). When approached from the point of view of the neurosciences, neurolinguistics focuses on how the brain behaves in language processes, both in healthy and pathological conditions; conversely, from a linguistics standpoint, neurolinguistics aims at clarifying how language structures can be instantiated in the brain, i.e. how patterns and rules exhibited in human languages are represented and grounded in the brain. In addition, neurolinguistics has a fundamental clinical impact for assessment and treatment of patients suffering from aphasia and other language pathologies.

The field was officially opened up by the nineteenth-century neurologist Paul Broca with his observations of the correlation between language disturbance and brain damage. Since then, over 100 years of investigation into the organization of language in the brain were based on a lesion-deficit approach, in a localizationist perspective. The significance of a brain area was deduced through observation of deficits following a lesion to that brain region, and the exact localization of the lesion was verified through post-mortem examination. The aphasiological era developed a functional model of language production and comprehension that highlighted the role of frontal and temporal regions (and connections between them) in the left hemisphere, a model that has informed diagnosis and research up to date. The state of knowledge began to change in the 1990s, with the advent of new methodologies for the functional exploration of the living brain. Today it is possible to identify the cerebral regions involved in the on-going performance of a specific linguistic task, and to relate brain activity to specific processing stages unfolding over time. With the contribution of functional neuroimaging and neurophysiology techniques, along with significant advances in clinical investigations, the field of neurolinguistics has substantially broadened. On the one hand, the original model of language organization in the brain is currently undergoing a process of revision, which emphasizes the role of distributed cerebral networks, rather than specific isolated areas, with differences in regional involvement and relative order of recruitment related to specific language sub-functions. On the other hand, scholars have started to investigate subtler questions than the production and comprehension dichotomy, approaching the representation of components such as phonology, syntax, semantics, and more recently pragmatics.[1]

While the field is relatively old and can be traced back to the nineteenth century, the term 'neurolinguistics' is quite recent. During the aphasiological era, what we now call neurolinguistics was entrenched in the province of neurology, thus lacking a specific characterization. Only after the late 1960s the study of language-brain relations attracted the linguists' interest, promoting the circulation of the term. Roman Jakobson was probably the first linguist to realize the potential relevance of neurolinguistic research for linguistic theories. Jackobson pointed out the importance of aphasia for understanding how language is instantiated in the healthy brain, and for confirming or disconfirming grammatical models stemming from theoretical linguistics (Jakobson 1941). The year 1985 witnessed the birth of the *Journal of Neurolinguistics*, presented as "the first and only journal that bears the name of this relatively new but fast developing field called NEUROLINGUISTICS" and "the only journal concerned with the interface of neurology and linguistics, an interdisciplinary realm of specialization that takes upon itself the exploration of brain function in language behavior and experience" (Whitaker 1985). Nowadays the term neurolinguistics has become popular and stands aside other labels, among which "neuroscience of language" and "neurobiology of language", depending on the emphasis placed either on the linguistic or on the neuroscientific perspective.

This chapter aims at presenting the major methodological trends and scientific achievements in neurolinguistics, from the dawn of the field to the open challenges. The chapter is organized as follows. After basic information on the anatomy of the human brain (Section 2), the issue of the cerebral localization of linguistic processes is addressed in a historical perspective, from the founding fathers in the aphasiological tradition (3.1–3.2) to contemporary findings in the functional neuroimaging literature (3.3–3.5). Section 4 switches from the 'where' issue to the 'when' issue, and tackles the time course of language processes in the brain, reviewing the major evidence obtained with neurophysiology techniques. As for the neural correlates of pragmatics, although the interest emerged only a few decades ago, nowadays this research domain is totally integrated and indeed a very vital area in the neuroscience of language (Bambini ed. 2010). As such, hints into the localization and timing of pragmatic processes in the brain are provided in Section 3 and 4, along with the other components of the language system.

2. The human brain

The physical seat for the representation and processing of language is hosted in the brain. A side view reveals three major divisions in the human brain: the cerebrum, which is the largest part and constitutes what is usually referred to as the "brain"; the cerebellum, which lies behind the cerebrum and is primarily a movement control center with connections with the cerebrum and the spinal cord; the brain stem, which forms the stalk from which the cerebrum and the cerebellum sprout and serves to relay information to and from the spinal cord, and to regulate vital functions such as breathing. The cerebrum is divided into two cerebral hemispheres (left and right) by the longitudinal fissure, connected by a band of cross fibers (corpus callosum). The surface of the hemispheres is covered with a layer of grey matter, the cerebral cortex, made up of nerve cell bodies (neurons), while the inner layer, the white matter, consists mostly of long axons. While grey matter is mainly responsible for information processing, white matter is responsible for information transmission, carrying nerve electrical signals throughout the brain and the rest of the body. Clinical and experimental evidence indicates that the cortex is the primary seat of human reasoning and cognition, including most aspects of language. Considering its prominence in the human brain, the cortex deserves further description.

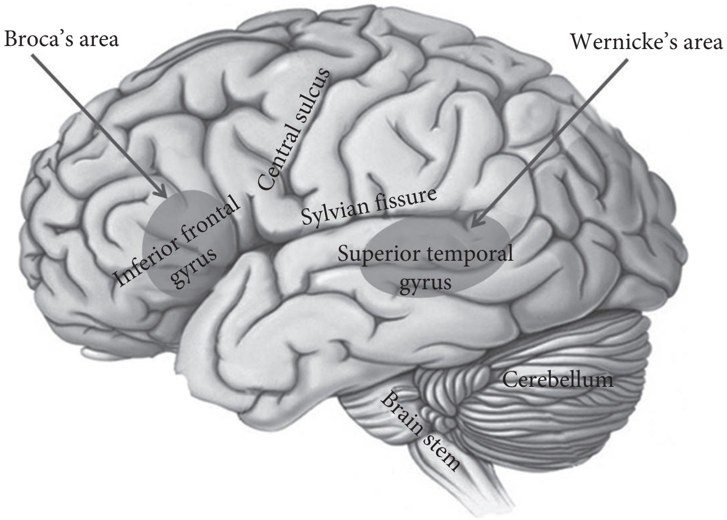

Figure 1. *Lateral view of the human brain (left hemisphere)*

The human cortex measures about 1100 cm^2 and is tightly corrugated to fit the confines of the skull. The folded structure of the cortex is functionally motivated: it increases the surface area, allowing for a greater number of cells in the same volume. The ridges are called gyri, the indentations are called sulci or, when especially deep, fissures. The precise pattern of gyri and sulci varies across individuals, but the main structure is constant, and used as reference point for delimiting the lobes of each hemisphere. In addition to the already mentioned longitudinal fissure separating the two hemispheres, two other fissures are the most prominent: the lateral sulcus, or Sylvian fissure, and the central sulcus, or Rolandic fissure. The former separates the frontal from the temporal lobe; the latter separates the frontal from the parietal lobe. A fourth lobe, the occipital, lays at the very back of the cerebrum, separated by the parieto-occipital fissure.

A frequent shorthand to refer to cerebral regions is Brodmann's numbering system. In 1909 Korbinian Brodmann produced a cytoarchitectonic map of the cortex identifying approximately 50 distinct cortical fields on the basis of different cell architectures (Brodmann 1909). He referred to these regions by numbers from

1 to 52, according to the order in which he studied them. These numbered areas are usually referred to as Brodmann Areas (BAs).

Although all structures of the brain interact, language is traditionally thought to be implemented in the cerebral cortex. The portions of the cortex especially involved in language processes are located in the frontal and temporal lobe of the left hemisphere, and especially the inferior frontal gyrus and the superior and middle temporal gyri (respectively, Broca's and Wernicke's area; see Figure 1). Recent research has highlighted the role of the right hemisphere too: initially linked to pragmatic and emotional aspects of language, right hemisphere areas are indicated as complementing the left in processing standard aspects of language too (Lindell 2006).

In addition to the cerebral cortex, the cerebrum includes subcortical structures, grey matter structures that lie deep with in the cerebrum, among which the basal ganglia that control movement; the hippocampal formation, involved in diverse memory functions (e.g. declarative memory formation); and the amygdaloid nuclei that seem to be very important in processing emotions/ regulating emotional states. Recent evidence suggests that subcortical structures participate in language processes too: specifically, the basal ganglia are involved in motor articulation of speech, as well as in grammatical processing; the hippocampus contributes to lexical storage, and the amygdala to the verbal expression of emotions.[2]

3. The localization issue (Where matters)

The central topic in the history of neurolinguistics is the localization of the cerebral structures responsible for the different linguistic processes. The quest of mapping language onto the brain crucially depends on the methodological resources available. Two main eras can be identified, differing in leading methodologies and functional models: the aphasiology era, which started in the 19th century and produced the classical model articulated in centers and pathways in the left hemisphere, and the neuroimaging era, started in the Nineties and still expanding, which has forced researchers to rethink the classical model, moving towards a widely distributed representation of language in the brain. Another important issue concerns what aspects of language are mapped onto the brain. While early studies tended to focus on modality distinctions (especially production vs. comprehension), modern research has engaged in disentangling the brain regions implicated in the different levels of the linguistic structure, from phonology to semantics and pragmatics, including finer-grained distinctions such as the noun-verb or the animate-inanimate distinction.

3.1 The aphasiology era

On April 18, 1861 the French surgeon Pierre Paul Broca reported revolutionary findings to the Anthropological Society of Paris: he presented evidence from a patient showing profound speech disorders and right hemiparesis after a lesion to the left frontal lobe. The patient, whose name was Leborgne, is known in the literature as ‘Tan’, as “tan” was the only syllable he could produce, while his comprehension abilities were relatively spared. Post-mortem examination of Leborgne’s brain showed the lesion to be confined mostly to the lower areas of the left frontal lobe (in the third frontal convolution), very close to motor regions. From this and other clinical cases, Broca concluded that articulated speech is localized in the frontal lobe of the left hemisphere, and that lesions therein cause *aphémie* (Broca 1861a–c; for English translation, see Grodzinsky & Amunts 2006), later renamed aphasia by Armand Trousseau (Trousseau 1864). The area identified by Broca became famous as Broca’s area, and difficulties in language production fell under the label of Broca’s aphasia (also known as “motor aphasia” or “expressive aphasia”).

Broca’s hypothesis was reinforced by a remarkable observation made in 1874 by the German neurologist Carl Wernicke. He described the cases of two patients whose speech was relatively fluent (although with unusual semantic features), but who showed a profound deficit in oral comprehension. Post-mortem examination led Wernicke to state that the comprehension deficit was caused by a lesion in the posterior division of the superior temporal convolution of the left hemisphere, close to the primary auditory cortex (Wernicke 1874). Later this area became known as Wernicke’s area, and difficulties with language comprehension became known as Wernicke’s aphasia (also known as “sensory aphasia” or “receptive aphasia”).

The early neurologists assumed that, for language to occur, the production center and the comprehension center needed to interact somehow, and this was claimed to be possible by means of connecting pathways. Wernicke postulated the existence of a direct connection between the production and the comprehension center, whose lesion was predicted to cause a type of aphasia characterized by normal production and normal comprehension, but impaired repetition ("conduction aphasia"). Later, another German physician, Ludwing Lichtheim, assumed that, for linguistic input to be processed and for linguistic output to be generated, a semantic node was also needed, which he referred to as the concept center, and hypothesized an additional pathway between Wernicke's and Broca's areas through the concept center. Lesion to the concept center was thought to be responsible for anomic or semantic aphasia. A diagram displaying all the centers and the connections involved in language processes was produced by Wernicke and later modified by Lichtheim, becoming popular as the "Lichtheim's house" (Wernicke 1874; Lichtheim 1885).

The discoveries made by Broca and Wernicke were reinforced by other lesion-deficit investigations carried out at the end of the 19th century. Additional areas and connections were proposed to account for normal and impaired reading and writing, connecting linguistic regions to visual regions (Dejerine 1891). All this provided the empirical basis for what is still considered the classical model, based on the idea that there are domain-specific centers in the brain for language (localizationism), and that linguistic functions are the results of associative connections between the relevant areas of the brain (connectionism).

Even if the localizationist-connectionist approach was very successful because it allowed for the best clinical predictions, other forms of aphasia occurred which did not fit the Wernicke-Lichtheim diagram. Certain data indicated that regions other than the ones marked in the classic diagram were responsible for language disorders, and doubts arose about a strict localizationist view. In the early 20th century, the localization approach had to face strong attacks from scientists such as Pierre Marie, Arnold Pick, Henry Head (who sarcastically referred to localizationists as "the Diagram Makers"), Kurt Goldstein and Hughlings Jackson. Although from different perspectives, they all contributed to an antilocalizationist and holistic view which assumed the existence of a fundamental language factor, dependent upon total brain functioning and not on special language centers in the brain. During the first half of the century, the influence of Behaviorism in psychology further weakened localizationism, by emphasizing the role of learning and the plasticity of the brain. The classical view was revived in the 1960's, with the advent of Cognitivism and the crucial contribution of Norman Geschwind and his followers.

3.2 The classical model

Norman Geschwind is credited with overcoming purely behavioral explanations of cognitive processes and bringing the study of cognition back into the framework of neurology. He carefully reviewed the neurological literature of the 19th century and exported its insights – especially the connectionist perspective – into modern research, emphasizing the role of connective pathways between different parts of the brain (Geschwind 1965; Catani & ffytche 2005). He extensively described the disconnection syndromes that follow the disruptions of the pathways, affecting knowledge (agnosia), action (apraxia), and language (aphasia). For what concerns language, his proposal represents an extension and refinement of the classical Wernicke-Lichtheim diagram, and became popular as the Wernicke-Geschwind model. Its fortune is also linked to the so-called Boston School, a group of researchers connected to the Aphasia Research Center in Boston, strongly influenced by Geschwind's clinical studies and by Chomsky's formal and nativist approach to grammar (Goodglass & Kaplan 1983).

The main claims of the (neo)classical approach to language functioning can be schematically summarized as follows:

1. there are two primary seats in the brain for language: Broca's area (located in the inferior frontal gyrus, corresponding to BAs 44 and 45), and Wernicke's area (located in the posterior superior temporal gyrus, roughly corresponding to BA 22 and posterior part of BA 21), which are connected through the arcuate fasciculum, a fiber tract running in the white matter; other connections link these regions with the visual and auditory systems;[3]
2. each area is dedicated to a specific modality: Broca's area sub-serves production, Wernicke's area sub-serves comprehension;
3. lesions to each area lead to specific types of aphasia: Broca's aphasia and Wernicke's aphasia; disconnection of the two areas leads to conduction aphasia.[4]
4. A fourth claim made by the classical model follows from the tenets above, namely the lateralization of linguistic functions in the left hemisphere. Data showed that the left hemisphere is dominant for language functions in about 96% of right-handed and in 70% of left-handed adults; of the remaining left handers, half have right dominance, and half have a bilateral representation (Rasmussen & Milner 1977). Several investigations carried out since the second half

> of the 20th century supported the lateralization hypothesis, showing functional and structural asymmetry between the two hemispheres (Gazzaniga & Sperry 1967; Geschwind & Levitsky 1968). In this view, a stroke to the dominant hemisphere was predicted to cause an aphasic syndrome, while a lesion in the right hemisphere should not be associated with language disruptions. Apparently in contrast with this, by the end of the Seventies clinicians started to notice a number of language deficits that followed right hemisphere lesions. These deficits, however, although affecting language, did not fit classic aphasic classifications: first described as high-level linguistic disorders, these were later grouped under the label of pragmatic disorders (Joanette et al. 1990; Tompkins 1995). The observation of right hemisphere language deficit, thus, far from disconfirming the claim of the left hemispheric dominance for language, strengthened it as to include a pragmatic appendix: the two hemispheres were assumed to differ markedly in their importance for language functioning, with the left being responsible for standard linguistic processing, and the right housing paralinguistic and communicative-pragmatic abilities (Paradis 1998).

The main tenets of the classical model, including the corollary of the right hemisphere for pragmatics, were radically imposed and still feature in most textbooks in neuroscience. Unquestionably, this model has been immensely useful both heuristically, to stimulate research in neurolinguistics, and clinically, to guide diagnosis. However, its assumptions have not survived the test of time and technology, at least not in the original form.

3.3 Functional neuroimaging: Basics

Until very recently it was not possible to examine the brain in intact human beings with anatomical precision. This has become feasible in the last decades, thanks to the advent of non-invasive techniques such as positron emission tomography and functional magnetic resonance imaging, usually referred to as “functional neuroimaging”, as they provide picture images of the living brain, of both its physical and its functional anatomy (i.e. the areas involved in a specific task). Unlike the lesion method, functional neuroimaging techniques are not confined to the regions that have been damaged, but allows for the observation of the distributed cerebral systems underlying cognitive functions, thus crucially advancing the study of mental activity, both in normalcy and in pathology. Research on the neurobiological basis of language has greatly benefited from the imaging revolution. No longer limited to experiments on nature for defining the scope of their investigations, researchers can combine these new techniques with creativity and sound methodological designs to deepen our knowledge on the cerebral representation of language. In what follows essential remarks on functional neuroimaging techniques are provided, along with some information on pioneering applications into the study of language. Next, we will consider the impact of this new technological horizon on neurolinguistic research.[5]

Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) measure changes in blood flow related to different cognitive processing conditions. PET was the first high-resolution technique to examine functional activity in the living human brain, beginning in the mid-1970. FMRI was developed later during the 1990s, as an extension and refinement of structural magnetic resonance imaging (sMRI), and has become the leading methodology in the field of cognitive neuroscience. The logic at the core of both techniques is straightforward. When subjects perform a task, neural activity in specific areas of the brain increases. This causes greater need for glucose and oxygen, both of which are met by increasing blood flow. Blood flow functions as an indirect marker of neural activity, allowing for the identification of the cerebral areas activated in performing a particular task, and, by inference, of the cognitive functions mediated by those areas. While PET measures blood flow by employing a very short lived radioactive tracer injected into the blood, fMRI detects changes in magnetic fields associated with hemodynamic adjustments, i.e. the relative concentration of oxy and deoxyhemoglobin in the blood. This is known as blood oxygen level-dependent (BOLD) signal. Saying that a region is “activated” means that it shows a greater BOLD response in one condition relatively to another.

In order to detect hemodynamic changes, most experimental paradigms using PET/fMRI include measurements from at least two conditions. This method derives from the studies of mental chronometry by the Dutch physiologist Franciscus Donders (Donders 1868) and is based on the comparison of two states: the task condition and the control (or baseline) condition, with the former representing the presence of some factor, and the latter representing the absence of this factor. The factor under investigation is by hypothesis believed to elicit a certain additional information processing effort. The subtraction of the control condition from the target condition allows for the identification of the additional processing components related to the task, without affecting global processing. In the case of PET and fMRI, the subtraction aims at identifying the cerebral areas where activity significantly differs in response to the cognitive factor under investigation (Friston 1997; Price et al. 1997).

The landmark study applying functional neuroimaging to language is Petersen et al. (1988). The experiment was hierarchically designed in order to allow for the subtractive analysis of the PET data. In the first level comparison, single word presentation (both visual and acoustic) was contrasted to fixation point presentation in order to identify the neural correlates of passive sensory processing. In the second level comparison, word repetition was contrasted to word presentation, aiming at isolating the neural correlates of articulation. In the third level comparison, word generation (e.g. to produce a verb relative to a given noun) was compared to word repetition, in order to identify the neural correlates of semantic association and syntactic reanalysis. Collectively, the results highlighted a number of brain regions not expected in the neoclassical framework (e.g. right perisylvian cortex and cerebellum for repetition, as well as Broca's area in semantic association), and failed to report the involvement of some of the regions predicted by the canonical model (e.g. Wernicke's areas for semantic processing). These early results – and the many that followed – questioned the specific functions of the traditional language areas and suggested that language processing involves more regions and more complex interconnections than those posited by the Wernicke-Lichtheim model.

3.4 Rethinking the classical model I

Functional neuroimaging techniques began to be extensively used for research purposes in the 1990s, a period designated as "the decade of the brain", and their impact on neurolinguistics was enormous. The profusion of data produced in the last two decades has proven that the classical model was indeed correct in assuming that the cortical areas around the Sylvian fissure (Broca's and Wernicke's areas, but also their vicinity, including the underlying insula) are central for language. The variety of the results, however, questioned the functional specificity of these areas, and imposed the revision of the traditional assumptions. Below the main claims of the (neo)classical model as listed in Section 3.2 will be considered one by one, and re-discussed in light of the neuroimaging findings. After the *pars denstruens* comes the *pars construens*: the next section will include a state of the art presentation of emergent trends towards a renewed architecture of language.

1. *Brain regions involved in language processes: More than two centers*. While the classical model clearly assumed three main physical seats in the brain for language (Broca's area, Wernicke's area and the arcuate fasciculum), when it comes to functional neuroimaging the whole brain seems to be involved: "depending on the task, experimental design, population in question, and/or protocols used in a given laboratory, virtually every region of the human brain has been implicated in at least one language activation study" (Bates & Dick 2000: 19). In addition to the left perisylvian areas, there is robust evidence for the involvement of many other cortical and subcortical brain structures in normal language processing, among which at least the following are worth mentioning: prefrontal areas, temporal areas of various kind (the anterior superior temporal sulcus; middle temporal gyrus, the temporal poles, the temporo-parietal junction), frontal and temporal regions in the right hemisphere (especially the homologues of Broca's and Wernicke's areas), and (where possible to detect) cerebellar and subcortical sites, especially in the basal ganglia. Recently, in addition to the arcuate fasciculum, another fiber tract connecting Broca's and Wernicke's areas has been brought to light. This pathway runs parallel and lateral to the classical pathway, and touches the inferior parietal lobule, in what has been called the "Geschwind territory" (Catani et al. 2005; Catani & Mesulam 2008). This discovery was made possible by recent developments in magnetic resonance imaging, namely diffusion tensor imaging (DTI) tractography, which can reconstruct white matter pathways in the living human brain, thus providing an important contribution for understanding the connections operating in the brain networks (see below).
2. *Linguistic categories relevant for the brain: Beyond the production-comprehension dichotomy*. According to the classical model, production and comprehension are supported by clearly distinct regions in the brain. Nowadays it is well established that production and comprehension cannot be separated and straightforwardly associated to Broca's and Wernicke's areas respectively. A number of studies shows the involvement of the left inferior frontal gyrus in comprehension, and of temporal regions in production (Stowe et al. 2005). Besides, the production-comprehension distinction is no longer the only focus of attention. The last decades have witnessed an increasing interest toward more linguistically and cognitively

relevant characterizations of the language-brain relation. Today, much attention is devoted to the test whether the brain makes distinctions among the different levels of linguistic representation, namely phonology, syntax and semantics and more recently pragmatics. Below we will briefly discuss how research perspectives evolved, as the issue bears special relevance to the linguistic viewpoint.

As clinicians, Broca, Wernicke and the other early scholars viewed language as a collection of activities practiced in the service of communication: most of all speaking and listening, but also reading, writing, naming, and repeating. Since the 1960s, due to the strong influence of Generative Grammar and modular theories of cognition, a new perspective emerged. Language was no longer seen as a set of activities but as a body of knowledge organized into different components and levels of representation and analysis. A number of behavioral and clinical experiments in the 1970s showed that the componential approach was worthwhile, providing evidence that the brain made such distinctions, and all this promoted a new interpretation of the brain centers, not related to activities but to linguistic representations. Specifically, neuropsychologists began to explore the extent to which the different components are selective with respect to types of aphasia. In their seminal study, Caramazza and Zurif (1976) showed that Broca's aphasics suffered from a selective disruption of the syntactic component. They also showed that this disruption affected not only production, but comprehension too, and introduced the notion of "overarching agrammatism", challenging the standard assumption that Broca's aphasia is associated with unimpaired comprehension. Similarly, a modality-overarching semantic difficulty was claimed for patients with Wernicke's aphasia, and an alternative theory gained credit, according to which Broca's area was taken to house syntax, in the service of both comprehension and production, and Wernicke's area was believed to be responsible for semantics, in the service of both comprehension and production. Soon, however, it became clear that unitary profiles are difficult to trace. Syntactic impairments are not unique to Broca's aphasia, or to any clinical group; semantic impairments are not unique to Wernicke's aphasia, or to any clinical group. The debate on agrammatism is still lively (Grodzinsky 2000), but what is important here is that neuropsychologists (and psycholinguists as well) showed that the modality-based model was too rudimentary, and that the functional characterization of language in the brain requires also explicit consideration of distinct and to a certain extent modality-neutral levels of representation (Swinney 1999).

The componential model quickly became the leading framework in neuroimaging too. Although pioneering PET/fMRI studies concentrated on single-word processing in distinct input and output modalities (recall Petersen et al. 1988), later research spent a great effort in unraveling the neural basis of phonological, syntactic, and semantic operations. By the end of the 1990s many authors reported increased activity in Broca's area for syntactic processing, while semantic elaboration seemed to activate many other areas, among which Wernicke's (Ni et al. 2000). Others put the syntactic-semantic distinction in relation to different portions of the left inferior frontal gyrus: while BA 44 was thought to be involved in syntax, semantics was located in BAs 45 and/or 47 (Dapretto & Bookheimer 1999). Again, further research revealed a much more complex scenario. Frontal areas may participate in semantic tasks; posterior areas may be recruited in syntactic processing (Stowe 2005). The leading paradigm in functional neuroimaging has radically changed since, and the center perspective has been abandoned in favor of large-scale brain networks (see below): again, the important aspect to note is the focus on the components of the language system, rather than on the production vs. comprehension distinction. Indeed, modality-based distinctions are not to be dismissed, as different input and output modalities proved to engage different computational centers. The modality and the componential perspective are much informative when combined, in order to get a full picture of the neural substrates of language knowledge and use, from articulatory planning to meaning retrieval (for a combined approach, see Price 2010).

As a further step in detailing the linguistic categories relevant for the brain, it is worth noting that from the 1980s onward neuropsychology and brain mapping have also approached finer-grained distinctions than the main components of language, and especially grammatical classes and semantic categories. A major area of research is represented by the noun-verb dichotomy (Laudanna 2002; Vigliocco et al. 2011). Neuropsychologists observed that impairments in verb retrieval tend to occur in patients with damage to the left frontal cortex, while noun deficits follow damages to the left temporal lobe (Damasio & Tranel 1993). Functional neuroimaging studies confirmed this separation (Shapiro et al. 2006). Another well-documented distinction separates animate from inanimate entities. Observations of double-dissociation reported in the clinical literature (Capitani et al. 2003) found support in PET/fMRI studies. The most robust result is an increased occipital activation for names of animals compared with names of tools, with refined distinctions related to specific categories of objects (Perani et al. 1999; Martin & Chao 2001; Martin 2007). The list of the linguistic distinctions possibly relevant for the brain is wide open, and every day new studies are published exploring new facets of the language system. This notwithstanding, according to Poeppel and Embick (2005), we are still scarcely more sophisticated than Wernicke was more than a century ago, as the field of neurolinguistics suffers from a "granularity mismatch problem", that is a mismatch between the elemental concepts of linguistics and the elemental concepts of neuroscience. A profitable research program should thus concentrate on finding the right linguistic primitives to link the conceptual apparatus of linguistics (elements such as "syllable", "noun phrase", "clause", and operations such as "concatenation", "phrase-structure generation", "semantic composition", etc.) with the primitives of neurobiology (elements such as "neuron" and "cortical column", and operations such as "oscillation", "synchronization", etc.). On this problem, see also Grimaldi (2012).

3. *The syndromes: Beyond the strict lesion-syndrome view*. According to the classical model, lesions to Broca's area lead to impairments in production described as aphasia of Broca's type, while lesions to Wernicke's area lead to impairments in comprehension described as aphasia of the Wernicke's type. Contrary to this view, refinements in neuropsychological research revealed the rigidity of the modality-specific classification. The early claims made by Broca and Wernicke were based on lesions that actually affected much larger regions than initially thought. High resolution magnetic resonance inspections of the preserved brains of two Broca's patients (Leborgne and the less-known Lelong, whose brains are deposited in the Dupuytren Museum in Paris) revealed lesions that extend well beyond the canonical Broca's area, extending significantly into medial regions, i.e. towards the imaginary midline dividing the two hemispheres (Dronkers et al. 2007). Likewise, it has been argued that one of Wernicke's two historic patients was indeed demented (Mathews et al. 1994). After years of collecting data on chronic aphasics, it has been shown that, when lesions are restricted to the centers labeled as Broca's and Wernicke's areas, they do not always result in the two classical types of aphasia (Dronkers 2000): only 50–60% of patients with lesions in Broca's area have a persisting

Broca's aphasia, and approximately 30% of patients with lesions in Wernicke's area exhibit a persisting Wernicke's aphasia. Conversely, only 85% of patients with chronic Broca's aphasia have lesions in Broca's area, and only 65% of patients with chronic Wernicke's aphasia have lesions in Wernicke's area. Conduction aphasia tends to follow not from lesions in the arcuate fasciculus, but rather in the superior temporal gyrus and inferior parietal lobule. In sum, the classical lesion-syndrome correspondences remain very useful for clinical purposes, but in fact fail to capture a large part of clinical cases. The experiments of nature are complex and irregular, resulting in a variety of impairments that can scarcely fit into classified profiles (Caramazza et al. 2005). This has led to a greater consideration of single symptoms rather than syndromes (i.e. group of symptoms), and to a great diffusion of single-case studies. Also, much interest in modern aphasiology is devoted to the understanding of the specific cognitive-linguistic component that motivates the linguistic deficit: different patterns observed in patients might derive by different disruptions at the cognitive-linguistic level (Hillis 2007). Finally, fine-tuning the classification of language disorders and variants (e.g. primary progressive aphasia: Gorno-Tempini et al. 2011), as well as the consideration of language impairments occurring in the context of a general decline of cognitive functions, e.g. in dementing illnesses (Grossman 2008), represent major research areas in modern aphasiology, and has led to a refinement in classification and approach.

4. *Lateralization: The role of the right hemisphere*. In listing the loci of activation figuring in neuroimaging experiments on language (see point 1 above), we included the right hemisphere, as most experiments run on right-handed subjects, whatever linguistic ability and whatever modality are tested, show bilateral activations with a weak (or even without) asymmetry (see Démonet et al. 2005 for a qualitative synopsis). This is blatantly in contrast with the assumptions of the classical model, and right activations came indeed as a "big surprise" for neuroscientists of language (Gazzaniga et al. 2002). Despite left hemispheric dominance remains one of the most robust evidence in the field, it is now well documented that the right hemisphere, far from being non-verbal, participates in processing all levels of the linguistic structure. As for pragmatics, a shockwave came in the opposite direction: a number of left hemisphere activations for pragmatic tasks are reported in the neuroimaging literature. This suggests that processing the pragmatic aspects of language is not confined to the right hemisphere, but rather results from bilateral, concerted brain activity (Stemmer 2008). Consistently, also clinical pragmatics have been reporting cases of pragmatic deficits following not only

right hemisphere damages, but also left hemisphere damages, dementia and autism, among others. Moreover, as in the field of aphasiology in general, also in the study of communicative disorders the attention is moving from the descriptive to the causal level, in the attempt to identify multiple and disorder-specific explanations, from mind-reading deficits in autistic patients to executive dysfunction in the Alzheimer's population (Martin & McDonald 2003).

3.5 Rethinking the classical model II

Combining data from neuroimaging studies, researchers have begun to breathe new life into the investigation of the language-brain relation. Although inconsistencies remain over the findings reported in the literature and debates on the usefulness of neuroimaging are open (Van Lancker Sidtis 2006; Cappa 2006), convergent observations encouraging for the proposal of more refined models can be found across the body of studies. Here we draw out the major points of consensus, along with some of the most vital and promising research lines.

1. *Linguistic processes are actuated by distributed brain networks*. Early neurologists thought of the brain in terms of function-specific localized centers. Over time, investigators observed that there is evidence for the localization of functions, but these functions, especially when complexity increases, are not confined to discrete anatomical centers, but rather broadly distributed across several brain areas. A new paradigm emerged in cognitive neuroscience, which moves beyond 1:1 mapping of cognitive functions into brain areas, and assumes the interplay of brain areas working together as large-scale networks (Mesulam 1990; Bressler & Menon 2010). This has fostered the revision of the centers-and-pathways model for language. Linguistic abilities too do not map in a 1:1 fashion into neural centers, relying instead on the concurrent activations of multiple areas forming interconnected and widely distributed networks. In this scenario, much effort has been devoted in the past two decades to identify the distributed networks underpinning each level of linguistic representation. Before going through an ultra-concise overview of the most common findings across the literature, domain by domain, it is worth noting that great impulse and promises in the research on brain organization come from the study of the connectivity, i.e. the connections that link brain areas, both in terms of anatomical connections (through diffusion tensor imaging (DTI) tractography; recall the pathway in the

> Geschwind territory mentioned above) and functional connections (through refinements in the analysis of neuroimaging data). This would allow to best describe how brain areas are organized in large-scale networks, and to explore the mechanisms of functional integration (Friston 2003).

There is robust evidence that *phonological processing*, as part of auditory speech perception, is supported by a neural system located in the superior temporal lobe, including the superior temporal gyrus and the superior temporal sulcus, bilaterally (Hickok & Poeppel 2007). Its activation is observed both in studies comparing speech stimuli with non-speech signals, and in investigations tapping phonological properties of processing (Hickok 2009). Much debate actually concerns what portions of the superior temporal sulcus are involved. Some researchers argue for a specific involvement of the left side, and specifically the anterior portion in processing intelligible speech. (Scott 2012).

Much effort has also been made to discover the neural basis of *morphological* processes, comparing regular versus irregular inflection (Ullman 2001), and inflectional versus derivational morphology (Marangolo et al. 2006). Overall, it seems that words created through rule-based combinations engage a left-lateralized fronto-temporal system, specialized in grammatical computation, while lexicalized and unpredictable forms engage a bilateral system, which underpins lexical assess (Bozic & Marslen-Wilson 2010).

The main focal areas involved in *syntactic* processing are located in the left inferior frontal gyrus, including Broca's area (and notably the *pars opercularis*) and its vicinity (Embick et al. 2000; Moro et al. 2001; Cappa 2012). Several other sites have been consistently reported in syntactic tasks, among which the more robust are located in the basal ganglia, especially the left caudate nucleus and the insula (Moro et al. 2001; Monti et al. 2009). A fruitful research line focuses on grammar rules, by comparing possible (non-rigid, hierarchical) and impossible rules (rigid, linear) in artificial language (Tettamanti et al. 2002), in learning real languages (Musso et al. 2003) and even in processing symbolic visual sequences (Tettamanti et al. 2009). Results indicate that only hierarchical rules specifically activate Broca's area and the neighboring ventral premotor cortex, which suggests a cortical signature for Universal Grammar (Tettamanti & Perani 2012).

The brain network supporting *semantic* processing appears extremely distributed (Binder et al. 2009; Cappa 2012). It seems that frontal activations are quite standard, i.e. modality and content independent, while in the temporal and parietal lobe separate foci of activity are related to specific categories of concepts (Bookheimer 2002). Although there is no consensus on the loci for each category, activations seem to be spatially proximal to brain regions with strong sensory or motor association with the conceptual category (Martin & Chao 2001; Martin 2007). One region that has received much attention lately is the anterior temporal pole, which might function as a semantic hub and with a crucial role in causing semantic dementia (Patterson et al. 2007).

Currently, most fMRI studies on *pragmatics* report extensive bilateral patterns of activations, predominantly in the frontal and temporal lobes (Stemmer 2008; Bambini 2010). This seems to hold for the comprehension of non-literal meaning (Papagno & Romero Lauro 2010) as well as for discourse management (Mason & Just 2006). As a general trend, interest is moving beyond debating over the right versus left hemispheres towards disentangling the functional architecture of the brain networks activated by pragmatic processes. For metaphor, for instance, it is claimed that the network involves conceptual operations in the frontal areas as well as mind reading abilities in regions along the superior temporal sulcus and attentional resources in the prefrontal cortex (Bambini 2011). For discourse, special emphasis has been put on the dorso-medial prefrontal cortex for inference and coherence building, the parieto-medial cortex for the updating of situational and discourse representation, and the anterior temporal lobes for integrating clausal information (Ferstl 2010).

2. *Linguistic processes rely on extra-linguistic systems*. While unraveling the brain substrates of the language system and its components, it cannot go overlooked that the use of the language faculty relies on and is constrained by more general and transversal cognitive functions, such as memory (of various types), attention and others (Démonet et al. 2005; Kutas 2006). An important research line aims at sorting out the bounds between the language system and general cognition. For instance, phonological awareness is supported by short term memory storage, while lexico-semantic operations engage a collection of mechanisms that reflect the amalgam of information used to store semantic knowledge in long term memory.

Recently, much attention has been devoted to investigate the involvement of the motor system in language processing, as a result of a ground-breaking discovery in the field of neurophysiology. In the 1990s researchers described a class of neurons in part of the ventral premotor cortical area 6 (also known as area F5c) of the macaque monkey that discharges not only when the monkey performs a particular action but also when the monkey observes a similar action being performed by another individual. As these neurons appear to ‘reflect’ actions performed by others, they were named “mirror neurons” (Di Pellegrino et al. 1992; Gallese et al. 1996). A consistent body of literature provides evidence in favor of the existence of the mirror neuron system in humans too (including the premotor cortex and Broca’s area), and reports activations in the mirror neuron network in response to a number of cognitive and social tasks, among which language. This has been motivated in terms of sensory-motor processes, thus assuming a form of embodied simulation in language functioning. Up to now, the participation of the motor component has been especially explored in two linguistic domains (Gallese 2007): the vehicle level, pertaining to phono-articulatory aspects of language (Fadiga et al. 2002), and the content level, pertaining to semantic aspects of language, and especially action semantics (Pulvermüller 2012), while the coupling of motor system and syntax is still controversial (Tettamanti & Moro 2012). However, the debate on the issue is very lively: some authors acknowledge some involvement of the motor system in language processing but cast doubt on the extent of this involvement (Hickok 2008), and some others question the existence of mirror neurons in humans (Lingnau et al. 2009).

Another crucial topic in the exploration of language and its relation with the other cognitive systems concerns the role of Theory of Mind, that is the ability to attribute mental states to others. The issue is of special interest in the pragmatic perspective, as it has been claimed that Theory of Mind is what implements the recognition of communicative intentions and meanings, and thus what actually ignites and makes the communicative exchange possible. The Theory of Mind network is especially extended (Van Overwalle 2009), and includes the medial prefrontal cortex, the superior temporal sulcus and the temporo-parietal juncture bilaterally, and the precuneus (an area in the postero-medial parietal lobe). This network has been proved to be activated for the comprehension of communicative intentions (Bara & Ciaramidaro 2010), independently of modality, i.e. both verbal and gestural (Enrici et al. 2011). Also, parts of this network show up in specific linguistic tasks demanding efforts in recognizing speakers’ meaning, among which metaphor comprehension (Bambini et al. 2011), as well as monitoring the discourse perspective (Mason & Just 2006).

3. *Linguistic processes are modulated by subject-dependent factors*. The cerebral representation of language varies considerably among individuals. Activation patterns are influenced by both wired-in factors, especially age and handedness, and environmental factors, such as literacy and experience (Démonet et al. 2005). Although up to now the majority of PET/fMRI studies has tested young and highly educated subjects, a growing body of research takes into account specific populations in order to assess the role of specific subject-dependent variables. Starting with the age factor, neuroimaging data are revealing important mechanisms of brain maturation and plasticity. Data show that adults make use of a more confined language network than children (Brauer et al. 2011); with aging, compensatory recruitment of additional resources takes place to support good performance (Stine-Morrow & Shake 2009), as for instance in metaphor comprehension (Mejía-Constaín et al. 2010). Gender, on the contrary, has produced non-conclusive findings, suggesting that the male and the female brain work the same in representing and processing language (Wallentin 2009). Also experience can drastically modify the way information is processed in the brain (Ansari 2012). Literacy (i.e. the acquisition of orthographic language skills) seems not only to augment the visual response in the occipital cortex, but also to enhance the left-hemispheric network for spoken language (Dehaene et al. 2010). Going further, specific linguistic expertise might modify the cerebral response, with effects even on brain morphology: for instance, expert phoneticians – highly trained to analyze and transcribe speech – showed increased size in the left *pars opercularis* of the inferior frontal gyrus with respect to controls (Golestani et al. 2011). Interesting modifications at the functional level occur when the brain has to deal with more than one language. Although the core language network doesn't seem to vary from the dominant to the weaker language, there seems to be additional neural recruitment related to attentional and cognitive resource (Abutalebi et al. 2009).

The agenda of neurolinguistics is to piece together all these results, from contributor mechanisms to individual variability, to outline models of the language-brain relations that are both theoretically grounded and biologically sensible. Yet, so far one important variable for charting the map of language in the brain has been left aside, namely time.

4. The timing issue (*When* matters)

Research in functional neuroimaging has shown that the brain elaborates language in different brain regions and networks, specializing for processing different components of language, from sound to meaning. All this needs to be coordinated in time in order to achieve successful comprehension and production, and a comprehensive description of language in the brain must take into account not only the anatomical correlates but also the temporal dynamics of the processes. PET and fMRI have good spatial resolution throughout the entire brain volume, but poor temporal resolution compared to typical neural firing rates of neurons, due to the sluggishness of the hemodynamic response. In order to capture cognitive processes as they unfold over time, we need to rely on neurophysiological techniques and the use of electroencephalogram (EEG) and event-related brain potentials (ERPs), which can measure the postsynaptic electrical activity of large neural populations with a millisecond accuracy.

While EEG measures spontaneous brain activity and provides overall information about a person's mental state, ERPs capture temporal patterns of activity that are time-locked to classes of specific processing events: this has become the leading methodology for investigating the neurocronometry of mental functions. The history of ERP research is closely linked with the development of technologies that allow for their extraction from the background EEG oscillations, which are usually much larger in amplitude (around 50 microvolts versus few (5–10) microvolts), and therefore tend to obscure them. During modern EEG recording, the tiny electrical signals naturally produced by the brain are picked up by electrodes hooked up to the subject's scalp and transmitted to bioamplifiers. Here, information about voltage changes is converted to a digital signal and stored on a computer. In order to isolate the information in the EEG that is related to specific processing events, EEG portions time-locked to the onset of the stimuli are then averaged, extracting the ERP (Coulson 2007; Stemmer & Connolly 2011).

The ERP is a waveform containing a series of deflections appearing as positive and negative peaks, which are referred to as "components" (Picton et al. 2000).

ERP components are characterized by polarity (positive or negative), peak latency (post stimulus-onset time at which largest amplitude is reached), and topography or scalp distribution (the pattern of amplitude across electrodes sites). Accordingly, components are traditionally named with a letter denoting the polarity and a number denoting either the peak latency value (e.g. the N400 is a negative component peaking at 400 ms), or the ordinal latency of the component (e.g. the P3 is the third positive peak in the waveform).

ERP studies on language have been especially directed at identifying the components reflecting linguistic processing, the type of linguistic information modulating them, and their relative ordering. A fundamental question in ERP research concerns the distinction between syntax and semantics, due to the importance this issue had in psycholinguistics since the Seventies, where modular views were opposed by interactive theories. ERP research allowed researcher to address the syntax/semantics distinction with great methodological advance with respect to traditional psycholinguistic methods: reaction time can only say how long the performance of a given task takes, whereas ERP, by reflecting ongoing activity before, during and after the task, can reveal whether distinct processes are used, thus providing evidence on domain-specificity and relative ordering of such processes.[6]

The standard procedure in ERP studies involves recording activity elicited by minimally different sorts of stimuli and looking for components that vary accordingly. The dominant paradigm is to compare the effects generated by words or phrases that produce a violation, either by failing in meeting semantic expectations or by violating grammatical rules, and to compare them to the responses recorded for correct stimuli. In this approach, a violation is assumed to produce extra-processing specifically drawn at the linguistic component disrupted. A differential response to two kinds of violation is thus taken to reflect a distinction between syntactic and semantic processing. In their benchmark study Kutas and Hillyard (1980) contrasted congruous and incongruous sentence completions such as “He spread the warm bread with *butter*” versus “He spread the warm bread with *socks*”. By averaging the signal elicited in the two conditions, they observed systematic differences in the brain’s electrical response to congruous versus incongruous sentence-final words. Specifically, they revealed a negative waveform that peaks about 400 ms after the presentation of the word over centro-parietal electrode sites and shows much amplitude in case of incongruous words. They referred to this waveform as to the N400 component, and interpreted it as an index of semantic processing.

Since Kutas and Hillyard (1980), it is common opinion that the brain integrates lexico-semantic information in a stage that occurs between 300–500 ms, reflected in the N400. The N400 effect has been replicated across different languages and different modalities, opening the way to unraveling the neurochronometry of language processing. The inventory of syntax-related effects is more articulated (Friederici 2004). Syntactic violation elicit a number of ERP components that differ from the N400. The most widely-reported are left anterior negativities (LANs) and a later positivity component (LPC or P600). The latency of the negativities seems to depend upon the violation type. Phrase-structure violations (such as word category violation) elicit an early LAN (ELAN) peaking around 200 ms, while agreement violation (mostly subject-verb agreement) and verb-argument violation produce a LAN with a latency range similar to that of the N400 (300–500 ms from stimulus onset), but distributed differently, i.e. over left anterior sites. As for the LPC, it starts around 500 ms after presentation of the syntactically critical word, and persists for several hundred milliseconds. This component is registered in a wide range of syntactic phenomena, including constituent movement and garden-path sentences, and is usually taken as indexing late syntactic integration and possibly re-analysis and repair.

The interpretation of the ERP data is not straightforward, and the above components may be explained in different terms. For instance, the LAN component has been related to working memory usage (Kluender & Kutas 1993). The syntactic P600 has been claimed to be a different manifestation of the P300 component recorded for improbable events (Coulson et al. 1998; but counterarguments in Osterhout & Hagoort 1999). Recent literature is providing a more fine grained account of the N400 effect, distinguishing between cases where it indexes semantic integration in the working context and cases in which reflects lexical access and retrieval from the long-term memory (Lau et al. 2008). Despite the debate over interpretation, ERP data show that the brain responds differently to syntactic and semantic anomalies, which is consistent with accounts that include such a distinction, and possibly a seriality of the processes. This does not entail that semantics and syntax are distinct modules in a strict sense, i.e. informationally encapsulated. It means that these two types of processing are to an interesting degree not overlapped, and suggests a domain-specificity for semantic and syntactic operations (Hagoort 2000). Based on this and other evidence, coupling anatomical and temporal information has become possible, and four-dimensional models of language in the brain are being proposed, among which Friederici's model (Friederici 2002; 2011) and Hagoort's Memory Unification and Control framework (Hagoort 2005; Hagoort & Van Berkum 2007).

In recent years, pragmatics has entered the scene in a much articulated way, being associated to more than one component. A number of studies report N400 effects in response to pragmatic manipulations, mainly for figurativity and for beyond-the-single-sentence phenomena (Coulson & Van Petten 2002; Van Berkum et al. 2003). These findings have been interpreted in terms of early contextual influence, against the traditional, Grice-inspired hypothesis that pragmatic processing occurs after an initial, literal elaboration stage. Recently, evidence has emerged that pragmatic facts are reflected not only (and not always) in the N400 but also in the later P600/LPC component (Regel et al. 2011; Schumacher 2011), which is in line with the hypothesis of the P600 indexing not only syntactic but also meaning operations (Bornkessel-Schlesewsky & Schlesewsky 2008). A nice proposal comes from Schumacher (2012), with a distinction between contextual effects (indexed by the N400) and content enrichment and updating based on pragmatic considerations (reflected in the P600/LPC). It is possible, thus, that pragmatic operations unfold in different stages, without principled separation from lexical/semantic access and syntactic parsing, but rather adapting to the contextual and communicative environment (Kutas 2006). Furthermore, as in functional neuroimaging, also in ERP research increasing attention is being paid to the role of subject-dependent factors in modifying the flow of real time comprehension, among which experience and aging (Kutas 2006; Wlotko et al. 2010). Interestingly, also linguistic typology is being considered, to explore whether the components are universal manifestations or rather language-specific modifications can intervene (Bornkessel & Schlesewsky 2006).

A recent line of investigation addresses induced changes in the ongoing EEG, i.e. the brain's natural oscillatory activity, measured in terms of spectral amplitude or power (David et al. 2006). This type of activity is believed to serve as a mechanism for the temporal synchronization of neurons from different brain regions, and can be fruitfully employed to investigate the formation and activation of brain networks. The application of oscillatory research to the study of language is still in its infancy, but different oscillatory dynamics have already been observed for lexical information as opposed to semantic unification (Bastiaansen & Hagoort 2006), and for speech processing (Giraud & Poeppel 2012).

5. Final remarks

At the end of this detour through the maps of language in the brain, if we turn back, we clearly see how much we owe to the founding fathers of the field, and how their legacy is still fertile for current research programs. The most mentioned brain area in modern day neurolinguistic investigations is the very same area who inaugurated the field, the area that bears Broca's name. Research carried out with different methodologies and from different perspectives seems to converge towards Broca's area, or sub-parts of it. Activations in Broca's area are reported for all levels of the linguistic structure, from phonology to pragmatics, and its involvement is advocated in key models such as Universal Grammar and embodied cognition. Yet Broca's legacy hasn't exhausted its fruitfulness, as the precise functional characterization of Broca's area is still to understand, possibly playing a crucial role in orchestrating brain networks. Wernicke's legacy has been fundamental too. He was the first in proposing a large-scale model with centers and pathways, which, *mutatis mutandis*, we are still elaborating upon today. Looking forward towards the future of neurolinguistics, we see that the greatest promises seem to come from methodological refinements and advances. The study of brain connectivity, neural oscillations, the combination of different techniques, their application to more differentiated populations, including patients, are all exciting areas for future research. Crucially, linguistic theorizing hasn't lost its appeal: we need models and grids to shape experimental paradigms and formulate hypotheses, in a strict cooperation between linguistic-cognitive modeling and experimental practice.

The vitality of neurolinguistics finds a special hub in the domain addressing the neural basis of pragmatics. Large scale proposals of language in the brain are beginning to include a contextual space, and to consider pragmatic processing. One of the major challenges is indeed to overcome the "white room effects" and the artificiality of experimental settings, to increase the ecological validity of linguistic stimulations and address language mechanisms as displayed in real use. Issues such as the coupling of production and comprehension in dialogue, the inferential chains, even the emotional and esthetic aspects of meaning are now possible topics for scientific investigation.

As a very final note, the practical impact of neurolinguistics in treating language impairments should be stressed. In a world where the median age of the population increases constantly, the prevalence of pathologies related to aging, among which language deficits, is escalating, affecting the quality of life of the patients and their care-givers. Refinements in modeling the language-brain relations can ultimately lead to fine-tunings in the assessment and treatment of language disorders. Here too pragmatics proves to be a fundamental aspect to consider, as evaluating and potentiating not only the formal aspects of language but especially the communicative effectiveness is of primary importance from the social point of view.

Notes

* I wish to thank Marcella Bertuccelli Papi, author of the previous version of this entry, for precious suggestions. Thanks are also due to Donatella Resta and Marta Ghio for useful comments.

1. See Ahlsén (2006) for an introduction to neurolinguistics, and Stemmer and Whitaker (2008) for a comprehensive text. See also Joanette and Small (2000) for a snapshot of neurolinguistics entering the new millennium.
2. On the human brain, see Kandel et al. (2000) and Bear et al. (2006).
3. Broca's area corresponds posteriously to BA 44 (which roughly corresponds to the *pars opercularis* of the inferior frontal gyrus) and anteriously to BA 45 (*pars triangularis*). Some authors extend Broca's area to include another portion of the inferior frontal gyrus frequently involved in language processing, i.e. BA 47 (*pars orbitalis*). For a detailed discussion on the cytoarchitectionic characteristics of Broca's area, see Grodzinsky and Amunts (2006). Wernicke's area is usually associated to posterior BA 22 in the superior temporal gyrus; other areas frequently included are posterior BA 21 and parts of BAs 37, 39 and 40. Indeed, the anatomical identification of Wernicke's area has been quite elusive since the beginnings (Bogen & Bogen 1976): indeed Wernicke himself provided a functional definition of the area, rather than an anatomical one.

4. See Obler and Gjerlow (1999) and Ahlsén (2006) for a more detailed taxonomy of the classical aphasic classification. For an updated reference in clinical linguistics, see Ball et al. (2008).

5. For more accurate descriptions of the functional neuroimaging techniques, see Cacioppo et al. (2007) and Perani (2008).

6. On the on-line methods to study of sentence comprehension, from behavioural measurements to ERP technique, including eye movements recording, see Carreiras and Clifton (2004).

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