Review

Toward a neural theory of language: Old issues and new perspectives

Mirko Grimaldi

Centro di Ricerca Interdisciplinare sul Linguaggio (CRIL), University of Salento, Lecce, Italy

A R T I C L E   I N F O

A B S T R A C T

The cognitive neuroscience of language is an exciting interdisciplinary perspective that suffers from unresolved epistemological and methodological issues. Despite the impressive amount of neural evidence accumulated until now, the field of research results fragmented and it is quite difficult to reach a unit of analysis and consensus on the object of study. This frustrating state of the art results in a detrimental reductionism consisting in the practice of associating linguistic computation hypothesized at theoretical level with neurobiological computation. However, these two entities are at the moment ontologically incommensurable. The problem lies in the fact that a theory of language consistent with a range of neurophysiological and neuroimaging techniques of investigation and verifiable through neural data is still lacking. In this article, I focus on the main issues, questions, and concerns that prevent the integrated study of language and brain and I explore a feasible way for linguistics to pursue a theory susceptible of neuroscientific testability in the light of recent neurocognitive models and of data on the functional-anatomic organization of language in the brain. Finally, I discuss a possible interdisciplinary program in order to achieve a theory capable of predictions on the real-time neural constrains characterizing the biological bases of language.

© 2012 Elsevier Ltd. All rights reserved.

E-mail addresses: mirko.grimaldi@unisalento.it, grimaldi.mirko@alice.it.

The mind sees and the mind hears. The rest is blind and deaf.
Epicharmus, 450 BC
What is troubling us is the tendency to believe that the mind is like a little man within.
Ludwig Wittgenstein
The only laws of matter are those which our minds must fabricate, and the only laws of mind are fabricated for it by matter.
James Clerk Maxwell

1. Introduction

Let me begin with two quotations:

> Linguistic structure is no less real then speech, and no less amenable to study. Linguistics signs, although essentially psychological, are not abstractions. The associations, ratified by collective agreement, which go to make up the language are realities localized in the brain.

> The distinctive features would be more than a universal schema for classifying phonemes in all their diversity across languages; the features would be 'real' in the sense of being universal neural mechanisms for producing and for perceiving sounds of speech.

The most relevant point of these statements is the opposition between the terms "psychological", "abstractions" and "schema" and the terms "real", "brain", and "universal neural mechanisms". I would like to draw attention to this dichotomy, which at first glance, as we will see below, merely describes a terminology-based conflict. The essential point to note for now is that this opposition is based on the idea that language can be investigated in terms of the physiological properties of the brain (i.e., in correlation with the brain mechanisms that form the basis for language processing). This perspective is, of course, endorsed by contemporary scholars in the field of cognitive neuroscience. Crucially, the scholars who stated these phrases are, respectively, the linguists Ferdinand de Saussure (1986 [1916], p. 15) and Roman Jakobson (Jakobson & Waugh, 1979, p. 123).

As a linguist, it is interesting to note that Saussure's and Jakobson's works were in some way stimulated by contributions from neuroscience during their lives. Moreover, following the view of Baudouin de Courtenay (1895), who suggested that a study of language pathology may contribute to the understanding of language structure, Jakobson was the first linguist to apply linguistic theory to aphasia research (Jakobson, 1941, 1956, 1964, 1970). The early interest of leading linguists on the neural correlates of language seems symptomatic of the developments that, between the end of the 20th and the first decade of the 21st century, have led linguistics to the promising field of the cognitive neuroscience of language (CNL). Although the entry of linguistics into the field of cognitive neuroscience has been of extreme importance for the potential development of an integrated discipline, this progress has raised some crucial issues and controversies due to a problematic dialogue resulting from the different scientific traditions involved.

The purpose of this article is to explore the intersections between research in linguistics and cognitive neuroscience. After focusing on the main issues, questions, and concerns that limit the joined study of language and the brain, I will propose a possible way to pursue a linguistic theory that is susceptible to neuroscientific testing. Contrary to the brain-centric approach, a possible program of integration will be proposed that enables the testing of assumptions and predictions based on real-time neural constrains that characterize the functional-anatomic organization of language in the brain.

1.1. Linguistic meets cognitive neuroscience

To better clarify the problems raised by this article, we need to briefly outline the field of research and discuss the role of linguistics and other disciplines in cognitive neuroscience. The CNL is a part of the wide multidisciplinary field of cognitive science, which emerged through a long period of gestation between the late 1950s and the 1980s by renewing and further developing very old issues that culminated in the scientific revolution of the 17th century. The cognitive science involves different disciplines, including psychology, computer science, neuroscience, linguistics, philosophy, and

anthropology, that converged at a particular stage in their history to study what human cognition is, what it does, and how it works. Indeed, most of the preparatory developments that led to this convergence previously occurred in the computer sciences, psychology, and neuroscience. In the last phases of this gestation, with the birth of generative grammar, Noam Chomsky transformed linguistics by placing it coherently within the field of cognitive science (cf. Bechtel & Graham, 1998). The turning point in this transformation was the rejection of the behaviorist's account of language (Chomsky, 1959) and the emphasis placed on the assumption that the faculty of language is embedded within the broader architecture of the mind–brain. Chomsky's incursion into psychology generated a number of controversies that are still ongoing (and we will see that such disputes remain within the relationship between linguistics and cognitive neuroscience). However, the generative grammar framework has had a broad practical impact for the maturation of cognitive science because it initially offered a model that was coherent with a variety disciplines, such as psychology and artificial intelligence, that attempted to answer the question of how mental representation and computation work together.

While disciplines such as psychology and linguistics contributed to the birth of cognitive science only after undergoing internal revolution and artificial intelligence had already been created, 19th century neuroscience first developed the idea that the brain was not merely an organ where mental processes occurred, but a system of integrated components performing different and specific mental functions. The past and future challenges of neuroscience are to divide the brain into its functional components and (a more difficult task) to determine how they work together as a system. Information on the distinct functions performed by the brain could be used to corroborate or guide the development of psychological models of cognitive processes (Bechtel & Graham, 1998, pp. 24–33).

Notwithstanding this advantage, neuroscience was excluded from the constellation of disciplines converging onto cognitive science for a period of time. First, there were pragmatic reasons for this exclusion because the questions asked and the tools used in most neuroscience research were remote from the inquiries being conducted in cognitive psychology. Additionally, the success of artificial intelligence minimized the relevance of neuroscience. The belief was that the relationship between psychology and neuroscience could be a relationship similar to the one that exists between hardware and software. The computer raised the exciting possibility that the mind could be understood almost entirely independently of the brain; if the operations of the mind are akin to the execution of a program, then almost all of the relevant aspects of the mind could be captured by that program, independent of whatever was running it, be it transistors or neurons. The reasons for neglecting the brain were challenged beginning in the 1980s due to the neuroscientist's interest in the study of cognitive systems, such as vision and memory. Finally, the emergence of several sophisticated neural recording techniques (e.g., PET, fMRI, and MEG) and updated applications of the older EEG (ERPs) and non-invasive techniques to stimulate the cortex (TMS) resulted in the communication and collaboration between neuroscientists and cognitive scientists.

With respect to the CNL, starting with the Broca–Wernicke–Lichtheim classical model (reviewed and modified by Geschwind, 1967), the first decade of the 21st century has seen psychologists, neuroscientists, and linguists make an impressive range of efforts to test, evaluate and investigate the neural correlates of language and to develop new, functional-anatomic models of language and speech (Ben Shalom & Poeppel, 2008; Poeppel & Hickok, 2004). The 'holy grail' of language research is thought to be in the brain, and the research undertaken will allow us, for the first time, to solve all of the conundrums that have conflicted scientists for centuries.

1.2. A problematic perspective

By reassembling the pieces of the puzzle, one can legitimately think that in the current state of research, a common program exists by which psychology, neuroscience and linguistics are unified by the aim to jointly investigate the nature of the knowledge of language, the acquisition processes of language, the biological mechanisms that permit the elaboration and the use of such knowledge and the neural computations involved in these processes. In short, it is possible that a sort of neurobiological research program exists that attempts to elaborate a unified model able to make predictions on the innate ability of language and its use in the world from an interdisciplinary perspective. This program could be summarized as follows:

(a) A theory of language capable of explaining how listeners convert sounds into meanings by perception and how speakers convert meaning into sounds by production must be consistent with a range of neurophysiological and neuroimaging techniques so that the theory may be verified through empirical data.

Unfortunately, a cohesive correlation between language theory and neuroscientific methods is extremely complex. Currently, this exciting interdisciplinary perspective suffers from unresolved epistemological and methodological questions, and a coherent research program has not yet been formulated. Scholars from the different disciplines involved in the study of CNL separate sounds, words and sentences. Others "[…] investigate not linguistic units, but activities, such as speaking, listening, reading and writing. It is quite difficult to home in on a unit of analysis on which consensus (one that would hopefully reflect understanding) exists" (Grodzinsky, 2003, p. 551). As stated by Grodzinsky, the study of language is unique compared to the study of the visual system. Debates within the field of vision research exist; however, there are no debates concerning the basic unit of analysis. In contrast, within the study of the neural basis of language, little is agreed upon.

Nevertheless, in contrast to vision and other cognitive abilities, we have to consider that language is characterized by both perception processes and the intricate interrelation between perception and production processes. Language is unique in that it combines a set of finite meaningless sound units in a potentially infinite manner, forming increasingly complex units that are given meaning and establishing complex structural relations among these units (this generative nature of language is shared with music and mathematics: see Zatorre, Belin, & Penhune, 2002; Patel, 2003; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Gelman & Butterworth, 2005 for a discussion). Thus, the continuous, varying acoustic waveforms involved in the speech signal can be converted into discrete neural representations through a series of appropriate computations. Crucially, this process is correlated with different types of memory instantiated in the brain. Importantly, following its emergence, language has become a social object, i.e., language occurs pragmatically within a social context, where speakers and listeners implement sets of conversational strategies to contribute to the success of communication (also including gestures, facial expressions, and the direction of an individual's gaze to amplify or better convey the message involved in the acoustic signal).

However, these almost intuitive assumptions can only partially justify the difficulties in solving the epistemological and methodological issues present within the field of CNL. To the special status of language, one has to add the above-mentioned fact that when different disciplines are integrated to enhance cognitive science, they already have existing models for analyzing cognitive processes involved in language. These toolboxes contain different (and in some cases incompatible) instruments, and the enthusiasm for the enterprise has not been accompanied by an effort to integrate assumptions, models and techniques within a coherent framework. Therefore, the results produced in this area of research seems, in some ways, confused and sterilized.

2. Two different scientific models

Although Chomsky's perspective has facilitated and stimulated the birth of cognitive science, this occurred at the cost of the neuroscientific perspective. From its birth, the generative approach to language (specifically the notion of Universal Grammar) theoretically separated the study of linguistic representations from the study of the neurophysiological process producing them. This separation was based on the idea, developed by the scientists of the 17th century (in particular by Descartes), that the mind is wholly distinct from the body and from physical objects of any sort (Chomsky, 1986, 2000a, 2006). Chomsky (2000b, pp. 16–17) better specified this issue:

The world has occult properties, which we try to comprehend as best we can, with our highly specific forms of intelligence, which may leave much of nature a mystery, at least if we ourselves are part of the biological world, not angels. There is no longer a "mind–body problem," because there is no useful notion of "body," of the "material" or "physical" world. The terms simply indicate what is more or less understood and assimilable in some manner to core physics, whatever that turns out to be. For individual psychology, the emergence hypothesis of

contemporary neuroscience becomes a truism: there is no coherent alternative, with the abandonment of materialism in any significant sense of the concept.

After solving the mind–brain problem, one can consider language as a component of the human mind–brain, the specialized "language organ" (the *faculty of language*), in addition to other cognitive systems (Chomsky, 2005). In this way, we are authorized to make inferences with respect to physical properties (i.e., of the brain) through theoretical assumptions and empirical verification based on the cognitive outputs of such properties, i.e., the utterances produced by native speakers.

From this point of view, Universal Grammar mirrors the properties of the brain projected onto the mind. Language is a component of the mind–brain that yields experienced-based knowledge of language. An explicative model, based on an effective formal apparatus, would be able to capture the mental computations underlying language. The explanatory power of a formal apparatus permits an implicit knowledge of language structure and language rules. Starting from the awareness of mind activity correlated, for example, to sentence formation, it is possible to verify the predictions of theory on language computation. Separating competence from performance (see Section 3.1), the abstract, underlying structure of universal human language can be investigated using the principle of the native speaker's intuition on the grammaticality of sentence formation as a criterion. For linguists, grammatical judgments represent experimental data in some respects (Marantz, 2005). This issue, which has contributed to the disconnect between formal linguistics and psycholinguistics (see Ferreira, 2005; Walenski & Ullman, 2005), will be further discussed in the next section.

Cognitive neuroscience is, by contrast, an anti-dualistic field. The guiding assumption of this field is that the mind is instantiated in the nervous system and that the neurophysiological processes and spatial images of neural network activity are identical to the mind at work. Although basic theoretical assumptions are required, the data prevail over predictive theorization and are acquired through controlled experiments that apply performance measures through an impressive array of methodologies. The neurocognitive approach aims to describe how properties of language are established in the brain. The starting point is the hypotheses on the observed language phenomenon that one intends to study, followed by a set of conditions with alternative possible outcomes excluding one or more of the hypotheses. Afterward, an experiment—based on an appropriate set of stimuli to induce cognitive activity—is designed to test the hypotheses in a suitable number of subjects, minimizing measurement errors and artifacts. The statistical analysis of the data will eliminate the hypotheses on the basis of discrepancies between the predicted and the observed outcomes. Finally, an interpretation correlating the hypotheses to the results is subsequently developed. Thus, the focus of cognitive neuroscience is shifted to empirical data. Any time a new molecule is discovered, a new technology to capture a new synaptic connection is developed, and the changeable activity of a neuronal network is connected to a specific cognitive activity; thus, brain areas are mapped, and neuroscientists celebrate a victory. In the past few years, the victories have been numerous and increasingly important. This, however, causes a stunning accumulation of data that has not been verified within a framework of the mind–brain.

These divergent attitudes are a result of the different scientific models followed by the two disciplines. Modern linguistics, and the Chomskyan approach in particular, derives from a theoretical tradition that occurs at a highly abstract level. As in physics, this abstract inquiry should develop hypotheses that lead to the discovery of physical mechanisms exhibiting specific properties (Chomsky, 1988). Conversely, for cognitive neuroscience, the knowledge of the world is reachable through the observation of macroscopic empirical data, which can simultaneously lead to microscopic observations and, as a consequence, to the building of a theoretical model (for example, see how neuroscientists used the implications associated with neural damage to elaborate the Broca–Wernicke–Lichtheim–Geschwind model).

To summarize, on one hand, linguistics presents a powerful theoretical apparatus that can be verified through empirical data that are not neurocognitive in nature and cannot be controlled in an experimental environment. On the other hand, the CNL has developed fine experimental methodologies to study the brain architecture of language and has accumulated an impressive amount of neural data that is not based on a predictive framework of brain functionality. It follows that the data linguists use to capture representations and computations of language in the mind–brain cannot be directly integrated with those obtained from neurocognitive experiments. In other words, in linguistics and cognitive neuroscience, two incompatible types of empiricism evolved, which were differently

modulated by divergent theoretical traditions. We need to better understand this dichotomy in order to attempt a feasible way of integration.

3. Principal conflicts between linguistics and cognitive neuroscience

3.1. Traditional levels of analysis and neural properties of language

First, we must note that during the development of linguistics, the levels of analysis proposed—phonetics, phonology, morphology, lexicon, syntax, semantics and pragmatics—appear to be abstract notions that are not immediately suitable to describe the biology of human language. In fact, their status as autonomous, explanatory elements in mental and cerebral processing is no longer clear. These terms may not reflect the neural properties of language (cf. Lancker Sidtis, 2006, pp. 279–280).

According to Poeppel and Embick (2005, pp. 2–5) this issue raises two problems: the Granularity Mismatch Problem (GMP) and the Ontological Incommensurability Problem (OIP). The GMP states that linguistic and neuroscientific studies of language operate with objects of different granularity. In particular, linguistic computation involves a number of fine-grained distinctions and explicit computational operations, whereas neuroscientific approaches to language operate in terms of broader conceptual distinctions. Assembling phonemes into syllables, morphemes into lexical items, forming larger syntactic objects out of smaller syntactic chunks, and applying transformation rules that express the displacement property do not have direct neural correlates. The OIP states that the units of linguistic computation and the units of neurobiological computation are incommensurable. Consider for example the sentence in (1):

(1) The astute detective solved the case.

The classical syntactic structure of this sentence is composed of two syntagmatic components: a Noun-Phrase (NP) and a Verb-Phrase (VP). Within a neuroscientific perspective, it makes little sense to assume that we have the NP in mind–brain when we utter and perceive 'The astute detective'. A neuroscientist may accept that structure is represented in terms of a system of components, but he immediately will ask himself whether we have to assume that this is the form in which grammatical information is represented in the brain, namely, in the cerebral cortex. While the static (mathematical) representation offered by a tree diagram has been very useful for forceful linguistic theory, it serves little function in capturing the algorithmic compositions of neural units correlated to language structure configurations. In fact, these configurations turn into a state of synchronized neural activity and maintain this state for approximately a few hundred milliseconds, forming a connected network of neural assemblies without any consciousness for the speaker/listener (Fuster, 2003; Pulvermüller, Shtyrov, & Hauk, 2009; Schnelle, 2010).

Another problem concerns the previously cited competence/performance distinction introduced by Chomsky (1965). The core assumption is that a generic system exists that is composed of a set of mental forms that constitute linguistic competence, whereas performance refers to the production of actual utterances. How these functions are actually implemented, i.e., in terms of the processes underlying performance, is irrelevant to this goal. Although Chomsky thought that studies on performance might be of interest (at least in Chomsky, 1965), the competence/performance dichotomy was maintained in the time. Thereby, the goal of most theoretical linguistics seems to be to determine the formal mathematical functions (mental forms) that underlie language. Within the perspective assumed here, it becomes clear that the competence/performance dichotomy is an awkward distinction, especially if one discards the notion of mathematical grammar in favor of a more procedural, algorithmic grammar that takes into account the flow of information in real-time processing. By avoiding grounding formal descriptions within some external reality (the neurophysiological brain processes), linguistic research risks becoming theory-internal with no way of developing a fertile integration with cognitive neuroscience. Clearly, at the moment, a direct link between theoretical linguistics and neuroscience is difficult to imagine (as well as between theoretical linguistics and the branch of psychology dealing with neuroscience).

3.2. The nature of grammaticality judgments

In the opinion of Marantz (2005, pp. 430–432), this disconnection is imputable to "a public relations problem rather than a fundamental methodological confusion" (see also Jackendoff, 1988). For example, Marantz assumes that judgments of grammaticality are essentially behavioral data, and the connection between such data and linguistic theory should follow the standard scientific methodology of cognitive science. Because linguists generally do not present their data as the result of a behavioral experiment, Marantz tries to show how, when properly construed, all well-formed judgments with a possible sound/meaning connection are measured through data from behavioral experimental designs (see Phillips, 2011 for a recent defense of this position and Gibson & Fedorenko, in press for a critique). Finally, Marantz suggests that linguists must always follow the methodology of experimental psychology when the languages being discussed lack native speakers who are linguists. Without a linguist who performs the experiment on him/herself, the investigator must be careful to sample from a representative set of sentences, explain the nature of the judgments required, and check across speakers of the same language/dialect possible variables of the same sentence (see, however, Manzini & Savoia, 2007; Rizzi, 2004 for a generative approach considering many representative variables of a sentence obtained from native speakers).

Jackendoff (2007a, p. 354) better clarifies Marantz's assumption stating that the intuitions and grammatical judgments used by linguists "are akin to well-known visual demonstrations such as the Necker cube, the duck–rabbit, the Kanizsa triangle, Escher's 3-dimensionally anomalous drawings, and Julesz's random-dot stereograms—all of them made-up examples. They are quick and dirty experiments for which the results are (purportedly) robust enough as to require no statistical analysis" (but see Schütze, 1996 for a discussion on statistical methods of analysis based on grammatical judgments).

Along this line, Sprouse (2007, 2011), Sprouse and Almeida (submitted for publication), deeply studied whether traditional acceptability judgment collection methods are lower unreliable then formal collection protocols (familiar from experimental psychology). They tested 469 data points from an introductory syntax textbook (Adger, 2003) in formal experiments using 440 naïve participants, the magnitude estimation and yes-no tasks, and three different types of statistical analyses. The results showed that the maximum replication failure rate between the traditional acceptability judgments for those 469 data points and the formal judgments for those 469 data points is 2%, suggesting that traditional methods are a well-powered methodology for syntax (see also Featherston, 2009; Phillips, 2009; Bader & Häussler, 2010 for similar conclusions). Thus, the authors propose that the choice of the useful methodology has to be related with the goals of particular research questions. It is possible that over the time the (potentially) increased sensitivity of experimental syntax will lead to the collection of a body of data that will motivate dramatically different theoretical architectures. However, it is worth noting that the focus on abstraction and formal systems can lead linguistics to consider empirical analysis as an afterthought. Most theoretical linguistic research seems inclined to work with relatively small sets of data and relies only on the intuitions of native speakers with respect to grammaticality judgments.

Two immediate problems follow: (1) How can we be sure that what we are examining in the world has any link to the hypothetical activities presumed to be in operation within the idealized cognitive environment of the speaker? (2) How can we establish and study these links empirically?

3.3. The Minimalist Program within the cognitive neuroscience perspective

Marantz (2005) suggests that the Minimalist Program (MP) offers a straightforward and testable dynamical model that uses neurocognitive experiments (see also Rizzi, 2012, for a similar proposal). In the MP (Chomsky, 1995 and later works) syntax is simply viewed as a recursive procedure that constructs objects (i.e., structures) that are processed and evaluated by two interfaces (i.e., the sensory-motor and the conceptual-intentional components) through their own conditions and procedures. According to this approach, the syntax-phonology interface prepares syntactic structures to be further processed by the sensory-motor component. This preparation involves (a) the linearization of the syntactic structure and (b) the mapping of the syntactic objects onto phonological objects. Linearization concerns the translation of the hierarchically organized syntactic structure into the relevant

linear order. The mapping procedure deals with the organization of sentence elements into prosodic constituents within and/or across which phonological operations occur.

In agreement with Jackendoff (1994, 2007a), Marantz (2005) proposes rehabilitating the Derivational Theory of Complexity (DTC, Foss & Hakes, 1978) in light of the MP. The DTC assumes that the behavioral complexity of processing a sentence directly corresponds to the number of transformations necessary to generate the surface structure of the sentence. This approach led an increase in the interest between psycholinguistics and linguistics theory in the early days of generative grammar (see Pylkkänen, Feintuch, Hopkins, & Marantz, 2004; Pylkkänen & Marantz, 2003). Unfortunately, as noted by Ferreira (2005, pp. 368–370), this approach did not survive tough experimental scrutiny (see Fodor, Bever, & Garrett, 1974, but also the discussion in Bever & Poeppel, 2010) and negatively affected all of the attempts to link linguistics and psychology at this time. Notwithstanding this failure, linguists remain deeply interested in the issue of psychological reality (as is evident from their attention to the problem of language acquisition), and psychologists need to make assumptions about the types of structures being processed (see Phillips & Wagers, 2007).

However, Marantz (2005, pp. 439–440) maintains that the MP "allows for more straightforward testing and falsification of linguistic hypotheses" and that "the syntactic computations described in the theory are necessary to the representations that they derive and thus speakers and listeners must carry out these computations". At the same time, as observed by Jackendoff (2007a, p. 382), although Marantz deals with the compositionality issue, he does not shows how a Minimalist derivation is to be interpreted during processing.

For her part, Ferreira (2005, pp. 369–371) manifests some perplexities on the real link between, for example, modern psychology and linguistics. She finds the MP "highly unappealing from the point of view of human sentence processing"; for example, in the MP, the derivation begins with the most deeply embedded lexical items (usually on the right) and works up to the topmost node. This is difficult to reconcile with left-to-right incremental parsing, which decades of research have confirmed to be the way people actually parse (see Phillips, 2003 for an attempt to deal with this challenge). According to Ferreira (2005) and Jackendoff (2007a), the MP architecture makes it difficult to account for syntactic reanalysis based on a semantic anomaly because at the point in the derivation where semantic information can be evaluated, syntactic information is no longer relevant. This seems to be "a case where a basic mechanism of minimalism is completely incompatible with known facts about human processing (which were published in mainstream journals more than a decade ago)" (Ferreira, 2005, p. 371). Although Phillips and Lau (2004, p. 11) acknowledge the necessity of incremental processing, they state that "If real-time processes build only well-formed structure, and if the grammar defines well-formedness in terms of possible constituents, then we might expect that structure building should occur only when a string is identified that forms a possible constituent". That is, they see anticipatory or predictive structure building as theoretically problematic. This is because, as Jackendoff (2007a, pp. 31–32) notes, in the MP, the rules of grammar can create structure only by merging two constituents; there can be no open structures waiting to be filled by elements yet to come. Phillips and Lau (2004, p. 16) cite experimental evidence suggesting that speakers build anticipatory structures, and they find most theoretical approaches wanting in this respect. However, they concluded, "[…] the main challenge for unification in this area involves the question of how to build structures accurately and incrementally in real time. This challenge could be viewed as the 'Logical Problem of Language Processing', and it remains somewhat mysterious under most theoretical approaches."

Trying to modernize the generative model in an attempt to synchronize it with the field of cognitive neuroscience and social cognition, Jackendoff (2002, 2007a, 2007b) has suggested a parallel cognitive architecture of language. First, he introduced the notion of the f-mind (functional mind) to correct Chomsky's main idea of abstract structures as mental phenomena. This implies that the analysis of the mind should be interpreted by a framework in which the discoveries of brain properties should have a more direct bearing on its functional properties. Instead of specifying a single combinatorial structure for syntax, Jackendoff's framework suggests the combination of multiple parallel sources for phonology, syntax and semantics, which are sub-divided into sub-domains that are mutually correlated by rich systems of interfaces. For each of the three domains, which obviously hint at phonology (including prosody), morphosyntax and semantics, there is a domain-specific structure-determining system. Finally, Jackendoff incorporated the possibility of coherently analyzing the pieces of meaning

that are not evident at the word-level or at the sentence-level. The effort of reintegrating the semantic level in a formal model of language is important, as Generative Grammar has advocated the autonomy of syntax since its birth, a position that has been recently mitigated by the MP (for example in Manzini & Savoia, 2007; see also the very interesting attempt of Pylkkänen, Brennan, & Bemis, 2011 to theoretically ground the cognitive neuroscience of semantics). In fact, the hypothesis of a core syntactic module whose operations are constrained by both the semantic system and an output (phonetic) system (see Hauser, Chomsky, & Fitch, 2002) is also very difficult to translate into neurocognitive terms (see Bates & Goodman, 1997; Levelt, 1999; MacDonald, 1993; Pulvermüller, 2012).

However, although Jackendoff's framework seems to offer promising ways of integration with cognitive neuroscience, as noted by Schnelle (2010, p. 192), it is based on limited references to brain organization and architecture. Currently, only Hagoort (2005a, 2005b) has discussed some data related to Jackendoff's model, and Schnelle (2010, pp. 154–180) attempted to neurally integrate the model from a theoretical perspective. To the best of my knowledge, until recently, no other studies have tried to implement and verify Jackendoff's model through neurocognitive experiments.

Is it possible that neurocognitive investigations could facilitate a resolution of the issues raised here? This is unlikely until a unified neurobiological theory of language with notions and levels of analysis is created.

4. To reduce or not to reduce?

4.1. The seduction of neural data and the brain-centric approach

Recently, Weisberg, Keil, Goodstein, Rawson, and Gray (2008) studied whether irrelevant neuroscience information in an explanation of a psychological phenomenon may interfere with an individual's ability to critically consider the underlying logic of this explanation. Surprisingly, the authors have elegantly demonstrated that naïve adults who are not experts in neuroscience (among which students in a neuroscience course were included) judge that explanations with logically irrelevant neuroscience information are more satisfying than explanations without logically irrelevant neuroscience information.

This allure is in somehow unmotivated. Although hemodynamic and electromagnetic techniques represent a scientific advance to address old questions in new ways and uncover new concerns about brain function and behavior, they show also some limits due (i) to the nature of the signal captured; (ii) the physiological basis exploited by the technique; add (iii) the experimental design that is required (see Fedorenko & Kanwisher, 2009; Lancker Sidtis, 2006; Poeppel, 1996a, 1996b; Poldrack, 2006, 2010; Yarkoni, Poldrack, Van Essen, & Wager, 2010). fMRI offers high spatial resolution (1 mm in-plane resolution), but low temporal resolution (on the order of 1 s). Conversely, EEG and MEG capture brain activity with a millisecond resolution, but they have limits in calculating the source of brain activity: In fact the spatial resolution is on the order of 5–20 mm (cf. Poeppel & Marantz, 2000). Thereby, even with the conviction that further improvements of the hemodynamic and electromagnetic techniques will help to better understand brain mechanism, the seduction so far emerged should be mitigated in the awareness that a multimodal approach is necessary for the study of the brain function and dysfunction. Such an approach must include the problematic integration of different techniques available, but it also requires a profound understanding of the neural basis of hemodynamic responses and a tight coupling of human and animal experimentation (cf. Logothetis, 2008).

The seductive allure of neural data seems also to occur between linguistics and cognitive neuroscience, with the conviction that hard science methodology may give the evidence for concepts, representations, and processes independently motivated within the linguistic research field (Poeppel & Embick, 2005, p. 5). This frustrating state of research results in a detrimental reductionism. As sharply pointed out by Poeppel and Embick (2005), it consists of directly connecting linguistic categories or linguistic processes to neurobiological categories or processes to imply a direct computational connection between the two. This is an ingenuous inter-theoretic reductionism because, as noted above (in Section 3.1), the current notions of linguistic computation at the theoretical level is incommensurable with notions at the neurobiological level.

It is very problematic, for example, to find a neurobiological notion that directly corresponds to the 'phoneme' notion. The phoneme notion attempts to account for the fact that speakers/listeners are able to convert an acoustic signal into discrete elements that are hierarchically organized into the basic functional units of language. However, this useful (although in some respects controversial) notion in linguistics cannot be directly translated into an equivalent neural notion, as a highly intricate and synchronized cluster of cortical and subcortical areas (bilaterally distributed) is activated during the production and perception of words (Guenther, 2006; Hickok & Poeppel, 2007; Scott, McGettigan, & Eisner, 2009). Thus, what is captured in the idea of a phoneme involves neurally distinct processing subroutines that are synchronized at a spatial and a temporal level.

The reductionist approach simply focuses on how a component or a process of language is realized in the brain: an approach still pursued by some CNL research, under the opinion that sub-domains of language are in somehow holistic parts that can be functionally localized (see, for example, Hagoort, 2005a, 2005b). This includes how and where in the brain various linguistic functions occur (localization). Considerable progress has been made in the former, whereas less progress has been made in the latter (see Pulvermüller, 2010 for a discussion). For example, with respect to linguistics research, the brain-centric approach asks where in the brain a certain linguistic process occurs. The answer to this question is valuable in its own right (this is the *cartographic imperative*, according to the Poeppel's (2008) definition). Because it does not stem from a process-centered approach, such information has limited value in what it can tell us about the underlying processes at a cognitive level. It also cannot tell us what that process does given a particular input or what the output of that function should or could be. It is possible that this may eventually be achievable and we may come to understand a simple cognitive process by an inspection of the underlying neurophysiology. However, at present, it is crucial to understand that the state of neuroscience is nowhere close to realizing that ability.

We have to consider that the kind of incommensurability within linguistics and cognitive neuroscience is more problematic. With respect to Poeppel and Embick (2005), consider, for example, the linguistic units 'distinctive feature', 'syllables', and 'morphemes', and try to find the corresponding neurobiological terms. As hypothetical counterparts, we will encounter notions such as 'dendrites', 'neuron', and 'cell-assembly', i.e., we cannot find neurobiological terms that correspond to the linguistic terms. If others scientific domains can share the same terms but not the same interpretations of the terms, linguistics and neuroscience do not even share the same terminology, i.e., there are no linguistic terms that may be interpreted as neurobiological terms. The idea of the 'distinctive feature' may better exemplify this problem. Linguistically, this idea identifies the basics for lexical representation and phonological computation; namely, it captures the idea that words are represented in the mental lexicon in terms of sequences of discrete segments (see Calabrese, 2012 for more details). Neurally speaking, we can describe distinctive features in terms of the anatomical parts of the brain or in terms of the neurophysiological answers, i.e., the temporal characteristics of specific EEG components, to build the neural functional architecture involved in speech perception and production. Thus, a fine-grained notion in linguistics corresponds to coarse brain functional-anatomical parts and neurophysiological responses.

Moreover, if we compare the semantic fields of the linguistic notions with the neurobiological notions mentioned above, we would easily discover that the linguistic notions are connoted by abstract meanings, while the neurobiological notions are described by concrete meanings. It is clear that this has important epistemological implications: The same reality, observed from two different perspectives, generates irreconcilable ontologies. It is therefore possible that the superstructures contributing to the building of a theory influence the knowledge of the world observed. Thus, different theories not only produce incommensurable terminology, but they also may generate incommensurable ontologies.

However, within the epistemological analysis a perspective has been developed that advocates integration rather than reduction (Darden & Maull, 1977). This view presupposes an inter-field theory that integrates and bridges fields rather than establishing one complete, unified theory. Inter-field theories can be generated when two fields share an interest in explaining different aspects of the same phenomenon in order to build solid knowledge and relations between the fields. Taking into serious consideration the cautionary observations of Chomsky (2000b) that the unification of chemistry and physics in physical chemistry (not the reduction of the former to the latter) happened only after chemistry and physics established a rich body of doctrine, the integration perspective seems the

more suitable for redefining a linguistic and cognitive neuroscience research program with the final aim of describing how language is instantiated in the human brain.

What we cannot agree upon, I think, is Chomsky's (2000b, p. 16) position that "The world is simply not comprehensible to human intelligence, at least in the ways that early modern science had hoped and expected" (see also the whole arguments contained in that paper). As pointed out by Feyman (1994, pp. 18–20), we can discuss the world at various hierarchies or levels, looking at the whole structural interconnection of the thing: "And today we cannot, and it is no use making believe that we can, draw carefully a line all the way from one end of this thing to the other, because we have only just begun to see that there is this relative hierarchy. […] The great mass of workers in between, connecting one step to another, are improving all the time our understanding of the world, both from working at the ends and working in the middle, and in that way we are gradually understanding this tremendous world of interconnecting hierarchies".

4.2. From linguistic theory to neurophysiological world

By working at both the end and the middle of linguistics and cognitive neuroscience, we must assume—contrary to the tacit assumption peculiar to current linguistic theory—that there is no distinction between the neurophysiological world and the world addressed by linguistic theory. This view, as noted at the beginning of this work, may have been already implied at the early stage of modern linguistics, but was not fully developed for historical reasons.

For example, interconnecting hierarchies can be observed by considering that human motor abilities (e.g., grasping or moving an arm or a hand) require a set of representations and computations (Arbib, 2008; Gallese, 2003; Wolpert & Ghahramani, 2000) similar to the way in which representations and computations are required to manipulate grammar. The (not insignificant) difference consists of the fact that moving a hand to grasp an object (or seeing others doing the same acts) only requires a set of representations and computations necessary for the motor act, whereas speech acts (and linguistic thoughts) require two levels of representation and computation: one connected with the generation of the speech-specific motor acts and another to deeply correlate any grammatical elements with each other and to the world implied by the language as a set of symbols (I put aside here the additional implications concerning the evolution of language; for a description of these, see Arbib, 2005; Hauser et al., 2002; Pinker & Jackendoff, 2005).

Experimental evidence suggests that complex cognitive functions and functional and behavioral acts are organized at a global level in the brain (i.e., at large-scale cortical and subcortical networks) and that they arise in real time from operations organized into interconnected brain areas (Bressler & Kelso, 2001; Damasio & Damasio, 1994; Luria, 1966). It therefore seems highly possible that motor control, grammatical processing and other kinds of cognitive abilities are executed in the brain in real time (for example, see the discussion in Bromberger & Halle, 2000; Calabrese, 2005; Calabrese, 2012). From this point of view, representations do not derive from neurally produced computations; instead they are the same entity differently realized by the dynamic, distributed and continuously interconnected cortical and subcortical activities of the brain at spatial and temporal levels. Simultaneously, we have to avoid considering computations as an abstract component of the language faculty, such as generative syntax seems to presuppose (Poeppel & Embick, 2005).

By focusing on language, guided by assumptions and notions developed within a theory, we are authorized to think that one can begin with the computations performed in the brain to make inferences on the biological principle regulating this particular cognitive ability, inasmuch as we have now methods and technologies to do so (although with the constrains mentioned in Section 4.1). Importantly, neuroscientists working on language processes frequently need to support their data with linguistic theories to improve the predictive power of their data, as in the case of the discovery of mirror neurons, where the motor theory of speech perception was considered suitable for interpreting neural data (Liberman & Whalen, 2000; see D'Ausilio, Craighero & Fadiga, 2012; but see Hickok, 2009b; Hickok, Holt, & Lotto, 2009 for a critical analysis of strong evidence against the idea that mirror neurons provide the basis of action understanding and speech perception). This natural tendency could already be seen as an implicit requirement of theoretical-empirical integration. However, to bridge fields and reach an inter-field theory integration, linguistic theories need to be amended from the critical issue

discussed above; in particular, these theories need to be amended to reduce the propensity for formal abstractness, the limitation in describing language as a set of formal functions and not in terms of neuronal functions, and the negligence in considering the performance level of language.

Thus, it is quite helpful to use all of the data and methods at hand to solve these problems, including information about processes and their implementation. In practical terms, we can use an incomplete (and likely incorrect) model of language to begin to study language; through the scientific process, the model can then be further refined. Then, the central question we need to answer is the following: how are neuronal structures specialized to produce human linguistic computations? Namely, how is human grammatical language computed in the brain? Within this perspective, it is necessary to go from a physiological description to a more functional description, increasing the consistency of linguistic theory and the empirical methods of analysis.

5. Examining the linguistic brain at work: reallocating the study of linguistics representation and computation within the brain

The necessity of proceeding in this way is more explicit if we reexamine recent neurocognitive data with the aim to provide a more integrated view of the functional brain anatomy of language and suggest hypotheses about functional anatomy and the computations associated with particular brain regions. To accomplish this task, I will concentrate on the crossroads of classical notions of language processing that are strongly established and empirically well supported within linguistic theory: e.g., syntactic and semantic interface, hierarchical syntactic structures, recursion procedure, phonological processes and speech perception. Following Ben Shalom and Poeppel (2008) and Hickok (2009a), I will discuss these levels considering three distinct operations connected with them, namely, analysis, memorization and retrieval of stored items, as well as combinatorial operations. Finally, I will try to correlate them to the frontal, temporal and parietal lobes, i.e., the anatomical cortical areas traditionally hypothesized to be involved in these processes (see Fig. 1).

5.1. The frontal lobe

The frontal lobe recently received a more detailed specification with respect to the classical model. Friederici (2002, 2004) argues that the frontal operculum and BA 44/45 in the inferior frontal gyrus (IFG), the anterior portion of the superior temporal gyrus (STG), the basal ganglia (a group of
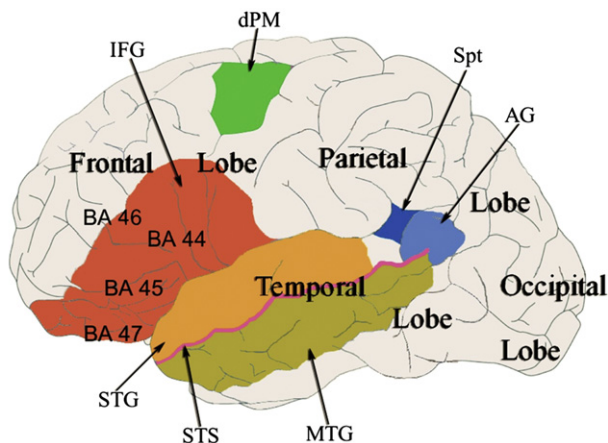

Fig. 1. The neural network that controls language processing is schematically represented in this figure. The areas involved show a gradual distribution of processes from superior to inferior plane: Phonetic/phonological information being distributed in dorsal field, syntactic information in the middle, and semantic representations more ventrally (Ben Shalom & Poeppel, 2008). BA = Brodmann area; IFG = inferior frontal gyrus; dPM = dorsal premotor cortex; STG = superior temporal gyrus; STS = superior temporal sulcus; MTG = middle temporal gyrus; Spt = superior planum temporale within the supramarginal gyrus; AG = angular gyrus.

subcortical structures collocated deep in the brain) and the posterior portion of STG support the processing of memory-demanding complex sentences (see also Newman, Ikuta, & Burns, 2010; Snijders et al., 2009; Tettamanti et al., 2005). Furthermore, a recent functional imaging study suggests that at least a portion of Broca's area supports syntactic processing via a working memory function (Rogalsky, Matchin, & Hickok 2008).

A neural network for semantic processes is involved in BA 45/47 in the IFG together with the posterior portions of the middle temporal gyrus (MTG) and the STG, respectively (see also Moro et al., 2001; Musso et al., 2003; Tettamanti et al., 2002, 2009). In addition, Friederici (2002, 2004), discussing exhaustive data, identifies four neurophysiological responses that reflect sentence-processing stages: i.e., the early left anterior negativity (ELAN), the left anterior negativity (LAN) (indexes of early syntactic structure building), the N400 (related to lexical-semantic processing) and the P600 (correlated with repair and reanalysis processes). These studies demonstrated that the (E)LAN was presented independent of the semantic factor but that the P600 can vary as a function of both (see Gouvea, Phillips, Kazanina & Poeppel, 2010 for a recent discussion; but see also Pulvermüller et al., 2009, wherein early neurophysiological indexes of lexical, syntactic and semantic processing are hypothesized). Taken together, these findings, in Friederici's view, indicate that syntactic and semantic processes are independent during the early processing stage and that interaction takes place during a stage of late integration. Thus, Friederici's (2002) model draws a distinction between the identification of word-level syntactic and semantic information in the temporal lobe and syntactic and semantic relation-building in the frontal lobe. This differentiated functional pathway was recently supported by studies that observed the white matter fiber tract connecting the frontal and temporal lobes in healthy and impaired subjects (e.g., Friederici, 2009; Papoutsi, Stamatakis, Griffiths, Marslen-Wilson, & Tyler, 2011).

However, is still unclear whether the anterior temporal lobe is specifically involved in performing syntactic computation or whether it is involved in semantic integration within sentences or else in combinatorial semantics, i.e., the process of integrating the meaning of words with their position in a hierarchical structure (Hickok, 2009a). Recently, in an fMRI study, subjects were asked either to monitor sentences for syntactic violations (*The flower are in the vase on the table*) or for combinatorial semantic "violations" (*The vase is in the flowers on the table*). It was found that most of the anterior temporal lobe sentence responsive region was modulated by both attention tasks, suggesting sensitivity to both syntactic and combinatorial semantic processes, although a sub-portion was only modulated by the semantic attention task (Rogalsky & Hickok, 2009). Furthermore, Friederici, Bahlmann, Friedrich, and Makuuchi (2011), comparing recent neuroimaging studies, concluded that the left BA 44/45 is mainly activated in the processing of hierarchically complex sentences, whereas hierarchically structured mathematical formulae strongly recruit the more anteriorly located region BA 47 (see also the interesting works of Santi & Grodzinsky, 2007, 2010; Snijders et al., 2009; and, in particular, the work of Pallier, Devauchelle, & Dehaene, 2011). Friederici et al. (2011) suggest that speakers are predetermined to compute linguistic recursions and propose two different computational systems in the lateral prefrontal cortex: one system determined by cognitive control that follows the posterior-to-anterior gradient and one system confined to Broca's area that is able to process complex hierarchies in language efficiently.

Nevertheless, Bookheimer (2002), on the basis of a meta-analysis of functional neuroimaging studies, suggests that the left inferior frontal cortex should be divided into three different areas: (i) a more dorsal area (the superior posterior region of the inferior frontal cortex, i.e., BA 44/46), which is specialized in phonological processes and assembling syllables, within and between words, in order to synthesize phonological information (see also Kotz et al., 2010); (ii) a middle area (the central mid-inferior frontal cortex, that is, BA 45/44), which is involved in computing the syntactic relationships between different words; (iii) and a more inferior area (the inferior anterior frontal cortex BA 47/45), in which processing semantic relationships between different words are executed (see also Burton, 2001; Grodzinsky & Amunts, 2006; Hagoort, 2005b; Hickok & Rogalsky, 2011; Rogalsky & Hickok, 2011; Sahin, Pinker, Cash, Schomer, & Halgren, 2009; Thompson-Schill, 2005). This view, as noted by Ben Shalom and Poeppel (2008), presupposes that the three left frontal areas are implicated in synthesizing combinatorial and compositionality operations between phonological, lexical and semantic items.

5.2. The temporal lobe

Recent evidence supports the recruitment of the superior posterior temporal lobe, part of the Wernicke's area, in the analysis of speech sounds and during the identification of the phonological word form (Blumstein, Myers, & Rissman, 2005; Chang et al., 2010; Desai, Liebenthal, Possing, Waldron, & Binder, 2005; Desai, Liebenthal, Waldron, & Binder, 2008; Flinker, Chang, Barbaro, Berger, & Knight, 2011; Friederici, 2002; Friederici, Kotz, Scott, & Obleser, 2010; Leaver & Rauschecker, 2010; Leff et al., 2009; Obleser et al., 2006; Obleser, Zimmermann, Van Meter, & Rauschecker, 2007; Osnes, Hugdahl, Hjelmervik, & Specht, 2011; Rimol, Specht, Weis, Savoy, & Hugdahl, 2005; Sabri et al., 2008; Skipper, Goldin-Meadow, Nusbaum, & Small, 2007; Turkeltaub & Coslett, 2010; Zheng, Munhall, & Johnsrude, 2010). In line with these results, the model proposed by Hickok and Poeppel (2000, 2004, 2007) argues that superior parts of the temporal lobe are the origin of the dual streams that mediate speech perception. In particular, the areas of the STG, adjacent on the dorsal surface, are suggested to be involved in spectrotemporal analysis, while regions in the posterior half of the superior temporal sulcus (STS) are implicated in phonological-level processes. The ventral stream is bilaterally organized with a weak left-hemisphere bias: the posterior middle and inferior portions of the temporal lobes serve as a lexical interface that links phonological and semantic information, whereas the more anterior locations correspond to a combinatorial network (see also Lau, Phillips, & Poeppel, 2008). Conversely, the dorsal stream seems strongly left dominant. The posterior region of the dorsal stream, the superior planum temporale (Spt), which was identified by Hickok, Buchsbaum, Humphries, and Muftuler (2003) and involves a triangular area lying posterior to Heschl's gyrus and posteriorly contiguous with the parieto-temporal operculum, is proposed to be a sensorimotor interface.

The more anterior locations in the frontal lobe, likely involving Broca's region and a more dorsal premotor site —i.e., the anterior inferior temporal sulcus (aITS), the anterior middle temporal gyrus (aMTG), the posterior inferior frontal gyrus (pIFG), and the premotor cortex (PM)— correspond to portions of the articulatory network and interface between auditory and motor processing. This viewpoint has important implications, as it offers a potential resolution to a long-standing open question (cf. Liberman & Whalen, 2000), i.e., the dual nature of distinctive features as both auditory and motor (articulatory) units (Ben Shalom & Poeppel, 2008, p. 122; see also ; D'Ausilio et al., 2009, this issue; Rogalsky, Love, Driscoll, Anderson, & Hickok, 2011; Schwartz, Basirat, Ménard & Sato, 2012 Scott, 2005; Scott et al., 2009 for an integrative proposal). Then, Hickok & Poeppel's model predicts that the superior temporal lobe (bilaterally) performs acoustic-phonetic mapping and that the inferior temporal lobe is implicated in the mapping from sound to meaning (for this last point, refer to the evidence in Anderson et al., 1999).

This perspective is consistently integrated with the latest research that studies how speech sounds are processed in human auditory cortical fields (ACFs), i.e., particular fields that compose the auditory cortex and differ from each other in both structure and function (before now, studied only in animals). Woods et al. (2010), and in particular Woods, Herron, Cate, Kang, and Yund (2011), compared the stimulus preferences and the absolute activation magnitudes to speech sounds (CVCs) and non-speech sounds (with spectra identical to those of CVCs) in different ACFs in humans. Consistent with previous reports, the study suggested the involvement of the STG and the STS in the phonological processing of speech sounds. Strong response preferences were found for CVCs in lateral belt fields and parabelt fields. This CVC preference was not dependent on attention: similar CVC preferences were seen for unattended sounds. Additional analysis suggested that in both medial belt and lateral belt fields, there was an increase in stimulus preferences from posterior-to-anterior regions of the auditory cortex. This result is compatible with the what/where dichotomy that has been reported in many studies of the auditory cortex (Rauschecker & Scott, 2009), with posterior cortical regions being more responsive to the spatial location of stimuli and anterior regions being more sharply tuned to the complex acoustic features that characterize particular stimulus categories. Finally, as ACF preferences showed similar patterns for attended and non-attended sounds, Woods et al. (2011) suggested that medial regions of the human auditory cortex are tuned to the processing of aspects of environmental sounds, whereas lateral regions are tuned to the processing of the spectrotemporal features of vocalizations, even in the absence of attention.

However, the temporal lobe seems also involved in the processing of syntactic information. Indefrey and Levelt (2004), through an extensive meta-analysis, suggested that the mid middle temporal lobe is recruited during the selection of word-level syntactic information (e.g., the category of words). This hypothesis seems compatible with Friederici's (2002) model, in which the temporal cortex can control the retrieval of word-level syntactic information, whereas the frontal cortex is involved in coordinating relations between basic items (see also Ben Shalom & Poeppel, 2008). Overall, these data support Hickok and Poeppel's (2007) view of a dorsal-to ventral gradient in the temporal lobe, with the more dorsal region subserving phonological processing, the middle areas subserving morpho-syntactic processing, and the ventral areas subserving retrieval of (lexical) semantic representations (see also Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004; Simonyan & Horwitz, 2011).

5.3. The parietal lobe

For the parietal lobe, neuroimaging and studies of deficit lesions patterns support Price's (2000) model, which proposes the involvement of the angular gyrus (i.e., inferior ventral parietal cortex) during semantic processing. Price, Moore, Humphreys, and Wise (1997), comparing conscious semantic and phonological decision tasks, demonstrated the activation of the angular gyrus during conscious semantic decision making (e.g., whether an item denotes a living or nonliving concept), which requires the analysis of sublexical-semantic information. At the same time, during conscious phonological decision making (e.g., counting the syllables of an item), the supramarginal gyrus (superior ventral parietal cortex) was activated. According to Hickok and Poeppel (2004, 2007) and Ben Shalom and Poeppel (2008, p. 125), "this area seems to be necessary for sublexical acoustic-phonemic processing" (see also Hartwigsen et al., 2010). This area may be compatible with the above-mentioned Spt in terms of location and function. In fact, the Spt is argued to be involved in phonological working memory (see also Griffiths & Warren, 2003; Shapleske, Rossell, Woodruff, & David, 1999; Tian & Poeppel, 2010; van Wassenhove, Grant, & Poeppel, 2005). However, recently, Marangolo, Piras, Galati, and Burani (2006) studied a morphological derivation and carefully showed increased morphological brain activation during verb derivation versus verb repetition in left parietal regions, including the angular and supramarginal gyri. Using these results and extending the patterns in the frontal and temporal lobes, Ben Shalom and Poeppel (2008) tentatively hypothesized that an area in the middle ventral parietal lobe (between the angular gyrus and the supramarginal gyrus) would show activation during morphological analysis.

5.4. Summary

The correlation of different data and the comparison of the models discussed above do not suggest the existence of a faculty of language as hypothesized in the classical Generative Grammar perspective but rather a differentiated neural network that controls language processing. To summarize, within this network, the temporal lobe controls memorizing operations (learning new and retrieved stored linguistic primitives), the parietal lobe controls analyzing sublexical linguistic units and converts sensory subunits to motor subunits, and the frontal lobe integrates linguistic units in motor sequencing with the lateral prefrontal cortex, and Broca's area in particular is specialized to process complex linguistic hierarchies efficiently (see also Price, 2010; Xiang, Fonteijn, Norris, & Hagoort, 2010).

The present picture for the language domain does not preclude, of course, the involvement of the frontal, temporal, and parietal lobes in other processing domains. Taking as an exemplificative case the frontal lobe, and Broca's area in particular, Broca area may also be involved in visual-event sequences (Bahlmann, Schubotz, Mueller, Koester, & Friederici, 2009), in the processing of action sequence (e.g., Pulvermüller & Fadiga, 2010), in the processing of abstract action rules (e.g., Badre, Kayser, & D'Esposito, 2010), or in the processing of hierarchically ordered control signals (e.g., Koechlin & Summerfield, 2007), as well as in rhythmic perception (see the discussion in Embick & Poeppel, 2006). Thus, Broca's area may be seen as part of a functionally complex neural network, part of which involves old processing and part of which involves new cognitive processing that evolved over the base of the old structures.

6. An integrated model to study language and brain

The functional approach sketched above can be seen as the converse of the brain-centric reductionist approach: In fact localization does not provides per se the explanation of the observed phenomena, because the underlying higher cognitive functions depend on how neural processes are organized. Cognitive functions necessitate and likely emerge from the formation of distributed computational operations in a common format, as a type of meta-representations. Meta-representations have become possible through the evolution of higher-order cortical areas that process the output of lower order areas in the same way as the lower order areas process their sensory inputs. As supposed by Edelman (1989, 1992), this has been possible because of the emerging of reentrant circuitry throughout subcortical and cortical regions that enable relating phonological symbols to concepts forming words and to manipulate words forming syntax. To account for the combinatorial flexibility required for the production and perception of speech and language, these meta-representations have to consist of dynamically associated assemblies of neurons rather than individual specialized cells. Neurons are grouped into assemblies, and their responses are connected through a binding mechanism based on the transient and precise synchronization of their discharges and active brain states.

From a descriptive point of view, the data and models discussed in the previous section led us to develop preliminary hypotheses on the effective linguistic operations that are related to complex anatomical neural assemblies: We found some strong evidence that support a generalization of different linguistic analysis executed by the lobes that are concentrated in a prevalent anatomical network. In particular, as suggested by Ben Shalom and Poeppel (2008), dorsal areas comprehending the inferior parietal lobe, the inferior frontal lobe, and the entire temporal lobe are involved in phonological processing, middle area in morpho-syntactic processing, and ventral areas in semantic processing. Nevertheless, in spit of these useful anatomical specifications, we are not yet able to make predictions on what kind of computations in the brain forms the basis for linguistics representations and operations. That is, we need a theory so grounded on biological basis that it is able to make explicit predictions on linguistic computations mirrored in a functional-anatomical network.

To build such neural theory of language we need to assemble in a fertile way the pieces available: that is, a linguistic theory and a set of diversified experimental methods, that, although with the limits above discussed, permit us to obtain brain data of linguistic representations/computations correlated to functional-anatomical assemblies. Thus, the large body of evidence already accessible on the basic functional neuroanatomy of language processing can help us to formulate more detailed hypotheses about how assumptions and notions on linguistic levels of analysis (already deeply investigated within linguistic theory) may be grounded in the physical world. Then, these hypotheses will be verified through experimental methods in order to progressively develop finalized predictions on how linguistic computation and processing are neurally assembled (i.e., functionally distributed in neural circuitries). For example, the fact that the temporal cortex seems control the retrieval of word-level syntactic information, whereas the frontal cortex seems involved in coordinating relations between basic items might help to make hypotheses on syntactic operations as Merge and Search postulated within the MP (see Rizzi, 2012 for more details). In particular, evidence for the presence of Merge and Search operations should exhibit the selective recruitment (also temporally differentiated) of temporal and frontal areas during this particular linguistic computation.

On the side of speech perception, a promising perspective was developed by Poeppel, Idsardi, and van Wassenhove (2008), which was previously proposed in Poeppel and Embick (2005). The authors suggest reconsidering traditional linguistic assumptions concerning this issue at the interface of neurobiology and linguistics. It is generally accepted that speech perception forms the basis for the transformation of physical signals into the representations used for computation in the brain, but how the continuous acoustic signal is transformed into abstract, discrete representations that generate further linguistic computations is currently under debate. To approach the problem, Poeppel et al. (2008) adopt Marr's (1982) model of visual perception that distinguishes three levels of description when investigating computational systems in cognitive neuroscience: namely, computational, algorithmic and implementational levels. At the basis of this different program of research, the authors suggested the following questions: what are the primitives for speech, and how can we build defensible linking hypotheses that bridge these domains? Consequently, three steps were discussed because

they are essential for transforming signals into interpretable internal representations: (i) multi-time resolution processing in the auditory cortex as a computational strategy to fractionate the signal into appropriate 'temporal primitives' that are commensurate with concurrently processing the auditory input on a segmental and a syllabic scale; (ii) analysis-by-synthesis as a computational (algorithmic) strategy linking top-down and bottom-up operations in the auditory cortex, which is conceptually related to the idea of internal forward models in cognitive neuroscience and to the Bayesian classification approach in the terminology of automatic speech recognition (see also Poeppel & Monahan, 2011); and (iii) the construction of abstract representations (distinctive features) that form the computational basis for both lexical representation and transformations between sensory and motor coordinates in speech processing (see Calabrese, 2012, for an alternative proposal).

Within this perspective, perception and recognition processes have a number of bottom-up and top-down steps. Specifically, these processes imply a mechanical (forward) calculation of perceptual candidates based on very precisely guided synthesis steps. First, the system attempts a quick reduction (primal sketch) of the total search space for lexical access by finding the somewhat coarsely specified landmarks (Stevens, 2002) through articulator-free (major-class, place-less) features (Halle, 2002). Secondly, once the phonological primal sketch is constructed, a cohort-type selection is elicited from the articulator-bound (place) features. In this way, it is possible to capture the (gross) neighborhood and (gross) cohort-model effects (Poeppel et al., 2008, p. 1074). As the authors noted, this proposal is similar to the Featurally Underspecified Lexicon (FUL) model of speech recognition (Lahiri & Reetz, 2002, 2010). In fact, a growing body of neurophysiological research (and, more rarely, neuro-imaging studies) has preliminary demonstrated the possibility of probing the neural representation of distinctive features, although from different perspectives (Aaltonen et al., 2008; Cornell, Lahiri, & Eulitz, 2011; Dehaene-Lambertz, 1997; Eulitz, 2007; Eulitz & Lahiri, 2004; Friedrich, Lahiri, & Eulitz, 2008; Idsardi, 2007; Kazanina, Phillips, & Idsardi, 2006; Lipski, Lahiri, & Eulitz, 2007; Näätänen et al., 1997; Obleser, Lahiri, & Eulitz, 2004; Philips, 2001; Phillips et al., 2000; Pulvermüller et al., 2006; Sörös et al., 2006; see also the studies reviewed in Näätänen, Kujala, & Winkler, 2011; Näätänen, Paavilainen, Rinne, & Alho, 2007; Pulvermüller & Shtyrov, 2006; Winkler, 2007). In particular, the findings of these studies provisionally hint (a) that representations of sound categories are abstract, (b) that not all phonological features are stored in the mental lexicon, and (c) that a top-down influence of the language-specific phonological system exists for the fine structure of phonological representations.

Finally, Poeppel et al. (2008) have provided evidence for a functional cortical architecture of speech perception (see Section 5. below for more details) and have discussed it with respect to multi-time resolution processing and analysis-by-synthesis—internal forward models and lexical representation of distinctive features. According to the authors, the three attributes of speech representation (features) and processing provide a way to think about how it might be possible to more explicitly link the acoustic signal to the internal abstractions of words.

We can graphically represent the viewpoint discussed in this Section by Fig. 2. The model in the figure assumes that the cognitive neuroscience of language must be informed by theory interconnected with all of the other levels of analysis. A theory that makes predictions based on observable linguistic phenomena needs to be empirically verified with respect to brain processes that have been hypothesized to inform linguistic representations and computations. I suppose that these representations and computations occur in real time in the brain as entities that are anatomically and temporally realized within a neural network. The integration of linguistics and cognitive neuroscience will be step-by-step reached by mapping between the dynamic structure of neural assemblies and the linguistic computation performed. Actually, this integration not only requires the acquisition of new data, but also necessitates the functional synthesis of the data within a comprehensive theory. This will avoid the dispersive accumulation of thousands of neural pieces of evidence derived from single experimental tests, and, additionally, it will complement the traditional experimental neuroscientific approach, allow the refinement of linguistic theory, and produce a neural theory of language. Finally, this method of investigating the neural correlates of language also has the advantage of incorporating the theory of performance level: i.e., the pragmatic elements of meaning that are not noticeable in the words or syntactic structures and that are dependent on the contextually communicative use of language (see Bambini, 2010; Bara & Tirassa, 2000; Pulvermüller, 2012; Tesink et al., 2009).
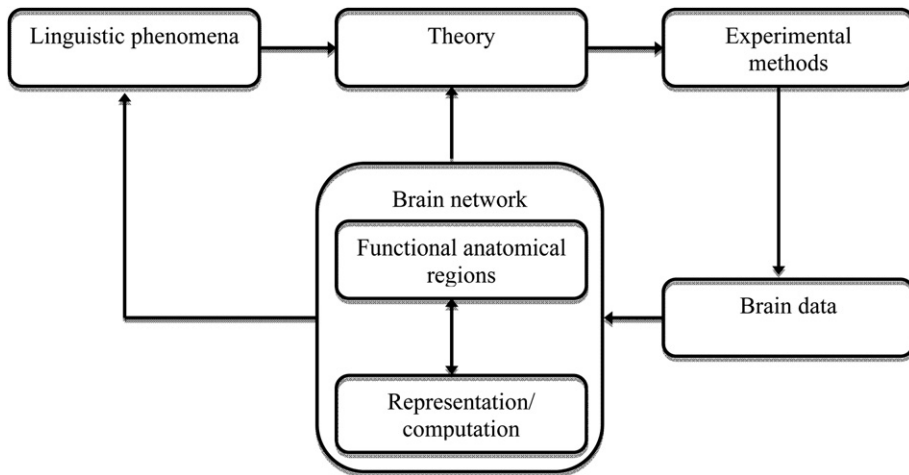
Fig. 2. An integrated model to study the functional-anatomic organization of language in the brain. Starting from observable linguistic phenomena, a theory of language should be verified through a set of differentiated experimental methods to obtain brain data useful for verifying the theory and linking the discrete representations that form the basis of linguistic computations within the functional-anatomic brain network.

Because human beings are the only species endowed with language and speech behaviors, by extracting the computational operations uniformly correlated to specific cognitive processes, we can attain a more granular knowledge of the biological basis of language, i.e., we can make predictions on the cortical and subcortical brain areas specialized to perform particular kinds of computation.

Obviously, this method of investigation represents only the first stage of a possible cross-fertilization process. Additionally, we cannot exclude that more as well as deeper and finer knowledge in the fields of genetics (Wolfgang et al., 2009) and neuropsychopharmacology (Hughes, Jacobs, & Heilman, 2000) will help CNL in reaching its objective. In the future, this perspective could lead the development of a unified theory of language, which is neurally motivated and computationally explicit, that is able to make predictions on the biological nature of language.

7. Conclusions

In this article, I proposed a possible way to integrate linguistics and cognitive neuroscience, arguing that both disciplines have a great deal to offer to each other. Despite extensive knowledge acquired regarding the physical structures of the brain in relation to language, this knowledge by itself has so far not been able to provide a comprehensive picture of how brain functioning performs the mental processes we use in producing and in understanding language and speech (instead, it has just begun to reveal some specific elements of the functional interaction between the brain and language).

To understand the functional anatomy of language processing, it will be necessary to move from the brain-mapping strategies toward a search for selective associations of dynamical linguistic neuro-cognitive structures. This means that the current intrinsic limitations of neuroscientific techniques (see Section 4.1) may strongly benefit by a formal apparatus verifiable through neural data in order to elaborate a unified ontology. In his turn linguistics can converge toward neuroscientific testability recalibrating its assumptions and notions in order to encapsulate real-time neural constraints and make predictions. This view implies that an approach to grammar cannot simply be reduced to a set of abstract mathematical rules; rather, it involves an unavoidable explanation of neural control pathways that form the basis of computation and representation processing, from the beginning of an utterance to the successful production or comprehension of that utterance. Grammars such as these measure the build-up and flow of information from the initial to the final state of an utterance. As suggested by Pulvermüller (2002, p. 272), "Availability of a brain-language interface of this type, a neuronal language

theory, may be a necessary condition for deciding between alternative approaches to grammar as it could be a tool for exploring neuron circuits specific to the human brain. A language theory at neuronal level is required in cognitive neuroscience."

To such a theory, cognitive neuroscience offers differentiated means of empirical testing, enabling us to ground the theory in the real (physical) world, at the very least. Crucially, this new course does not have to change the fundamental goals of linguistics theory but can instead advance them. Instead of advocating a reduction of linguistics to cognitive neuroscience, I suggest a model that fruitfully integrates the two fields of study. In this model, linguistic assumptions and notions that are already theoretically verified play an important role in functionally correlating neural data related to complex cognitive representations and computations. A theory that makes explicit predictions about the regions that are involved across levels of language and that can be tested against empirical findings across a battery of neuroanatomical and electrophysiological measures will be crucial in resolving the issues raised here. In this way, in the future, we can achieve two objectives: (i) to reduce the conceptual granularity mismatch and (ii) to elaborate a commensurable ontology between the categorical concepts of linguistics and those used in cognitive neuroscience (Poeppel & Embick, 2005).

Building a neural theory of language is certainly not an easy task, but it is clear that this enterprise should be placed on interdisciplinary foundations, incorporating theoretical and methodological approaches both across and within disciplines. In turn, interdisciplinary research presupposes a strong tension among scholars that have different programs, divergent research tools, and most of all, different models of analysis. Clearly, this is a demanding task, and, as pointed out by Jackendoff (2007a, p. 5), many prominent linguists do not want to be bothered about the psychological, neural, and biological ramifications of language, and many others only give it a cursory overview, passing these attitudes on to their students. To address this challenge, I feel, it is necessary to begin to provide a real interdisciplinary academic background for students intending to explore this field of study. If future scholars will be able to coherently manipulate different linguistic, psychological, neurophysiological and methodological tools, the asymmetries displayed between linguistics and cognitive neuroscience can hopefully be reduced. The success of this enterprise relies only on a common effort to render these asymmetries compatible.

Acknowledgments

References

Aaltonen, O., Hellström, Å., Peltola, M. S., Savela, J., Tamminen, H., & Lehtola, H. (2008). Brain responses reveal hardwired detection of native-language rule violations. *Neuroscience Letters, 444*, 56–59.

Adger, D. (2003). *Core syntax: A minimalist approach.* Oxford: Oxford University Press.

Anderson, J. M., Gilmore, R., Roper, S., Crosson, B., Bauer, R. M., Nadeau, S., et al. (1999). Conduction aphasia and the arcuate fasciculus: a reexamination of the Wernicke–Geschwind model. *Brain & Language, 70*, 1–12.

Arbib, M. A. (2005). From monkey-like action recognition to human language: an evolutionary framework for neurolinguistics. *Behavioral and Brain Sciences, 28*, 105–167.

Arbib, M. A. (2008). From grasp to language: embodied concepts and the challenge of abstraction. *Journal of Physiology – Paris, 10*, 4–20.

Bader, M., & Häussler, J. (2010). Toward a model of grammaticality judgments. *Journal of Linguistics, 46*, 273–330.

Badre, D., Kayser, A. S., & D'Esposito, M. (2010). Frontal cortex and the discovery of abstract action rules. *Neuron, 66*, 315–326.

Bahlmann, J., Schubotz, R. I., Mueller, J. L., Koester, D., & Friederici, A. D. (2009). Neural circuits of hierarchical visuo-spatial sequence processing. *Brain Research, 1298*, 161–170.

Bambini, V. (2010). Neuropragmatics: a foreword. *Italian Journal of Linguistics, 22*(1), 1–20.

Bara, B. G., & Tirassa, M. (2000). Neuropragmatics: brain and communication. *Brain & Language, 71*(1), 10–14.

Bates, E., & Goodman, J. C. (1997). On the inseparability of grammar and the lexicon: evidence from acquisition, aphasia, and real-time processing. *Language and Cognitive Processes, 12*(5/6), 507–584.

Baudouin de Courtenay, J. N. (1895). *Versuch einer Theorie phonetischer Alternationen. Ein Kapitel aus der Psychophonetik*. Strassburg: Trübner.

Bechtel, W., & Graham, G. (1998). *A companion to cognitive science*. Oxford: Blackwell.

Ben Shalom, D., & Poeppel, D. (2008). Functional anatomic model of language: assembling the pieces. *The Neuroscientist, 1*, 119–127.

Bever, T. G., & Poeppel, D. (2010). Analysis by synthesis: a (re-)emerging program of research for language and vision. *Biolinguistics, 4*(2–3), 174–200.

Blumstein, S. E., Myers, E. B., & Rissman, J. (2005). The perception of voice onset time: an fMRI investigation of phonetic category structure. *Journal of Cognitive Neuroscience, 17*, 1353–1366.

Bookheimer, S. (2002). Functional MRI of language: new approaches to understanding the cortical organization of semantic processing. *Annual Review Neuroscience, 25*, 151–188.

Bressler, S. L., & Kelso, J. A. S. (2001). Cortical coordination dynamic and cognition. *Trends in Cognitive Sciences, 5*(1), 26–36.

Bromberger, S., & Halle, M. (2000). The ontology of phonology (revised). In N. Burton-Roberts, P. Carr, & G. Docherty (Eds.), *Phonological knowledge. Conceptual and empirical issues* (pp. 19–37). Oxford: Oxford University Press.

Burton, M. W. (2001). The role of inferior frontal cortex in phonological processing. *Cognitive Science, 25*, 695–709.

Calabrese, A. (2005). *Markedness and economy in a derivational model of phonology*. Berlin: Mouton-De Gruyter.

Calabrese, A. (2012). Auditory representations and phonological illusions: A linguist's perspective on the neuropsychological bases of speech perception. *Journal of Neurolinguistics, 25*(5), 304–327.

Chang, E. F., Rieger, J. W., Johnson, K., Berger, M. S., Barbaro, N. M., & Knight, R. T. (2010). Categorical speech representation in human superior temporal gyrus. *Nature Neuroscience, 13*(11), 1428–1432.

Chomsky, N. (1959). Review of skinner's verbal behavior. *Language, 35*, 26–58.

Chomsky, N. (1965). *Aspects of the theory of syntax*. Cambridge, MA: MIT Press.

Chomsky, N. (1986). *Knowledge of language. Its nature, origin and use*. New York: Praeger Publisher.

Chomsky, N. (1988). *Language and problems of knowledge*. The Managua lecture. Cambridge, Mass.: The MIT Press.

Chomsky, N. (1995). *The minimalist program*. Cambridge, MA: The MIT Press.

Chomsky, N. (2000a). *New horizons in the study of language and mind*. Cambridge, MA: Cambridge University Press.

Chomsky, N. (2000b). Linguistics and brain science. In A. Marantz, Y. Miyashita, & W. O'Neil (Eds.), *Image, language, brain* (pp. 13–27). Cambridge, MA: The MIT Press.

Chomsky, N. (2005). Three factors in language design. *Linguistic Inquiry, 36*(1), 1–22.

Chomsky, N. (2006). *Language and mind*. Cambridge, MA: Cambridge University Press.

Cornell, S. A., Lahiri, A., & Eulitz, C. (2011). What you encode is not necessarily what you store: evidence for sparse feature representations from mismatch negativity. *Brain Research, 1394*, 79–89.

Damasio, A. R., & Damasio, H. (1994). Cortical systems for retrieval of concrete knowledge: the convergence zone network. In C. Koch, & J. Davis (Eds.), *Large scale neural theories of the brain* (pp. 61–74). Cambridge, MA: Cambridge University Press.

Damasio, H., Tranel, D., Grabowski, T., Adolphs, R., & Damasio, A. (2004). Neural systems behind word and concept retrieval. *Cognition, 92*(1/2), 179–229.

Darden, L., & Maull, N. (1977). Interfield theories. *Philosophy of Science, 43*, 44–64.

D'Ausilio, A., Pulvermüller, F., Salmas, P., Bufalari, I., Begliomini, C., & Fadiga, L. (2009). The motor somatotopy of speech perception. *Current Biology, 19*, 381–385.

D'Ausilio, A., Craighero, L., & Fadiga, L. (2012). The contribution of the frontal lobe to the perception of speech. *Journal of Neurolinguistics, 25*(5), 328–335.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Source of mathematical thinking: behavioral and brain-imaging evidence. *Science, 284*(5416), 970–979.

Dehaene-Lambertz, G. (1997). Electrophysiological correlates of categorical phoneme perception in adults. *Neuroreport, 8*, 919–924.

Desai, R., Liebenthal, E., Possing, E. T., Waldron, E., & Binder, J. R. (2005). Volumetric vs. surface-based alignment for localization of auditory cortex activation. *NeuroImage, 26*, 1019–1029.

Desai, R., Liebenthal, E., Waldron, E., & Binder, J. R. (2008). Left posterior temporal regions are sensitive to auditory categorization. *Journal of Cognitive Neuroscience, 20*, 1174–1188.

de Saussure, F. (1986). *Course in general linguistics*. Illinois: Open Court. [de Saussure, F. (1916). *Course de linguistique generale*. Paris: Payot].

Edelman, G. M. (1989). *The remembered present. A biological theory of consciousness*. New York: Basic Books.

Edelman, G. M. (1992). *Bright air, brilliant fire. On the matter of mind*. London: Penguin Group.

Embick, D., & Poeppel, D. (2006). Mapping syntax using imaging: problems and prospects for the study of neurolinguistic computation. In K. Brown (Ed.), *Encyclopedia of language and linguistics* (pp. 484–486). New York: Elsevier.

Eulitz, C. (2007). Representation of phonological features in the brain: evidence from mismatch negativity. In *ICPhS*, Saarbrücken, 6–10 August 2007 (pp. 113–116).

Eulitz, C., & Lahiri, A. (2004). Neurobiological evidence for abstract phonological representations in the mental lexicon during speech recognition. *Journal of Cognitive Neuroscience, 16*, 577–583.

Featherston, S. (2009). Relax, lean back, and be a linguist. *Zeitschrift für Sprachwissenschaft, 28*, 127–132.

Fedorenko, E., & Kanwisher, N. (2009). Neuroimaging of language: why hasn't a clearer picture emerged? *Language and Linguistics Compass, 3*(4), 839–865.

Ferreira, F. (2005). Psycholinguistics, formal grammars, and cognitive science. *The Linguistic Review, 22*, 365–380.

Feyman, R. (1994). *The character of physical law* (pp. 118–120). New York: Modern Library.

Flinker, A., Chang, E. F., Barbaro, N. M., Berger, M. S., & Knight, R. T. (2011). Sub-centimeter language organization in the human temporal lobe. *Brain & Language, 117*(3), 103–109.

Fodor, J. A., Bever, T. G., & Garrett, M. F. (1974). *The psychology of language: An introduction to psycholinguistics and generative grammar*. New York: McGraw-Hill.

Foss, D. J., & Hakes, D. T. (1978). *Psycholinguistics: An introduction to the psychology of language*. Englewood Cliffs, N.J.: Prentice-Hall.

Friederici, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Science, 6*, 78–84.

Friederici, A. D. (2004). The neural basis of syntactic processes. In M. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 789–801). Cambridge, Mass.: The MIT Press.

Friederici, A. D. (2009). Pathways to language: fiber tracts in the human brain. *Trends in Cognitive Sciences, 13*(4), 175–181.

Friederici, A. D., Bahlmann, J., Friedrich, R., & Makuuchi, M. (2011). The neural basis of recursion and complex syntactic hierarchy. *Biolinguistics, 5*(1/2), 87–104.

Friederici, A. D., Kotz, S. A., Scott, S. K., & Obleser, J. (2010). Disentangling syntax and intelligibility in auditory language comprehension. *Human Brain Mapping, 31*, 448–457.

Friedrich, C. K., Lahiri, A., & Eulitz, C. (2008). Neurophysiological evidence for underspecified lexical representations: asymmetries with word initial variations. *Journal of Experimental Psychology, Human Perception and Performance, 34*, 1545–1559.

Fuster, J. M. (2003). *Cortex and mind – Unifying cognition*. Oxford, UK: Oxford University Press.

Gallese, V. (2003). A neuroscientific grasp of concepts: from control to representation. *Philosophical Transaction of the Royal Society, Biological Sciences, 358*, 1231–1240.

Gelman, R., & Butterworth, B. (2005). Number and language: how are they related? *Trends in Cognitive Sciences, 9*(1), 6–10.

Geschwind, N. (1967). The varieties of naming errors. *Cortex, 3*, 97–112.

Gibson, E., & Fedorenko, E. The need for quantitative methods in syntax and semantics research. *Language and Cognitive Processes, 26*, 8, in press.

Gouvea, A. C., Phillips, C., Kazanina, N., & Poeppel, D. (2010). The linguistics processes underlying P600. *Language and Cognitive Processes, 25*(2), 149–188.

Griffiths, T. D., & Warren, J. D. (2003). The planum temporale as a computational hub. *Trends in Neurosciences, 25*(7), 348–353.

Grodzinsky, Y. (2003). Imaging the grammatical brain. In M. A. Arbib (Ed.), *The handbook of brain theory and neural networks* (pp. 551–556). Cambridge, Mass.: The MIT Press.

Grodzinsky, Y., & Amunts, K. (2006). *Broca's region: Mysteries, facts, ideas, and history*. New York: Oxford University Press.

Guenther, F. H. (2006). Cortical interactions underlying the production of speech sounds. *Journal of Communication Disorders, 39*, 350–365.

Hagoort, P. (2005a). Broca's complex as the unification space for language. In A. Cutler (Ed.), *Twenty-first century psycholinguistics: Four cornerstones* (pp. 157–172). New Jersey: Lawrence Erlbaum.

Hagoort, P. (2005b). On Broca, brain, and binding: a new framework. *Trends in Cognitive Sciences, 9*(9), 416–423.

Halle, M. (2002). *From memory to speech and back: Papers on phonetics and phonology 1954–2002*. Berlin: Mouton de Gruyter.

Hartwigsen, G., Baumgaertner, A., Price, C. J., Koehnke, M., Ulmer, S., & Siebner, H. R. (2010). Phonological decisions require both the left and right supramarginal gyri. *Proceedings of the National Academy of Sciences of the United States of America, 107*(38), 16494–16499.

Hauser, M. D., Chomsky, N., & Fitch, T. (2002). The faculty of language: what is it? Who has it? And how did it evolve? *Science, 298*, 1569–1579.

Hickok, G. (2009a). The functional neuroanatomy of language. *Physics of Life Reviews, 6*, 121–143.

Hickok, G. (2009b). Eight problems for the mirror neuron theory of action understanding in monkeys and humans. *Journal of Cognitive Neuroscience, 21*, 1229–1243.

Hickok, G., Buchsbaum, B., Humphries, C., & Muftuler, T. (2003). Auditory-motor interaction revealed by fMRI: speech, music, and working memory in area Spt. *Journal of Cognitive Neuroscience, 15*, 673–682.

Hickok, G., Holt, L. L., & Lotto, A. J. (2009). Response to Wilson: what does motor cortex contribute to speech perception? *Trends in Cognitive Sciences, 13*, 330–331.

Hickok, G., & Poeppel, D. (2000). Towards a functional neuroanatomy of speech perception. *Trends in Cognitive Sciences*, (4), 131–138.

Hickok, G., & Poeppel, D. (2004). Dorsal and ventral streams: a framework for understanding aspects of the functional anatomy of language. *Cognition, 92*, 67–99.

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Review Neuroscience, 8*, 393–402.

Hickok, G., & Rogalsky, C. (2011). What does Broca's area activation to sentences reflect? *Journal of Cognitive Neuroscience, 23*(10), 2329–2331.

Hughes, J. D., Jacobs, D. H., & Heilman, K. M. (2000). Neuropharmacology and linguistic neuroplasticity. *Brain & Language, 71*(1), 96–101.

Idsardi, W. J. (2007). Some MEG correlates for distinctive features. In *ICPhS*, Saarbrücken, 6–10 August 2007 (pp. 107–112).

Indefrey, P., & Levelt, W. J. (2004). The spatial and temporal signatures of word production components. *Cognition, 92*, 101–144.

Jackendoff, R. (1988). Why are they saying these things about us? (topic-comment column). *Natural Language and Linguistic Theory, 6*, 435–442.

Jackendoff, R. (1994). *Patterns in the mind*. New York: Basic Books.

Jackendoff, R. (2002). *Foundations of language: Brain, meaning, grammar, evolution*. Oxford: Oxford University Press.

Jackendoff, R. (2007a). Linguistics in cognitive science: the state of the art. *The Linguistic Review, 24*, 347–401.

Jackendoff, R. (2007b). A parallel architecture perspective on language processing. *Brain Research, 1146*, 2–26.

Jakobson, R. (1941). *Kindersprache, aphasie und allgemeine. Lautgesaetze*. Uppsala: Almqvist u. Wilsells. [Reprinted as *Child language, aphasia, and phonological universals*, 1968. The Hague: Mouton].

Jakobson, R. (1956). Two aspects of language and two types of aphasic disturbances. In R. Jakobson, & M. Halle (Eds.), *Fundamentals of language* (pp. 115–133). The Hague: Mouton.

Jakobson, R. (1964). Towards a linguistic typology of aphasic impairments. In A. V. S. deReuck, & M. O'Connor (Eds.), *Disorders of language* (pp. 21–41). Boston: Little, Brown.

Jakobson, R. (1970). Toward a linguistic classification of aphasic impairments. In R. Jakobson (Ed.), *Selected writings II*. The Hague: Mouton.

Jakobson, R., & Waugh, E. (1979). *The sound shape of language* (11th ed.). Brighton Sussex: Harvester Press.

Kazanina, N., Phillips, C., & Idsardi, W. (2006). The influence of meaning on the perception of speech sounds. *Proceedings of the National Academy of Sciences of the United States of America, 103*(30), 11381–11386.

Koechlin, E., & Summerfield, C. (2007). An information theoretical approach to prefrontal executive function. *Trends in Cognitive Sciences, 11*, 229–235.

Kotz, S. A., D'Ausilio, A., Raettig, T., Begliomini, C., Craighero, L., Fabbri-Destro, M., et al. (2010). Lexicality drives audio-motor transformations in Broca's area. *Brain & Language, 112*(1), 3–11.

Lahiri, A., & Reetz, H. (2002). Underspecified recognition. In C. Gussenhoven, & N. Warner (Eds.), *Laboratory phonology 7* (pp. 637–685). Berlin & New York: Mouton de Gruyter.

Lahiri, A., & Reetz, H. (2010). Distinctive features: phonological underspecification in representation and processing. *Journal of Phonetics, 38*(1), 44–59.

Lancker Sidtis, D. V. (2006). Does functional neuroimaging solve the questions of neurolinguistics? *Brain & Language, 98*, 276–290.

Lau, E. F., Phillips, C., & Poeppel, D. (2008). A cortical network for semantics: (de)constructing the N400. *Nature Reviews, 9*, 920–933.

Leaver, A. M., & Rauschecker, J. P. (2010). Cortical representation of natural complex sounds: effects of acoustic features and auditory object category. *Journal of Neuroscience, 30*, 7604–7612.

Leff, A. P., Iverson, P., Schofield, T. M., Kilner, J. M., Crinion, J. T., Friston, K. J., et al. (2009). Vowel-specific mismatch responses in the anterior superior temporal gyrus: an fMRI study. *Cortex, 45*, 517–526.

Levelt, W. J. M. (1999). Producing spoken language: a blueprint of a speaker. In C. Brown, & P. Hagoort (Eds.), *The neurocognition of language* (pp. 83–122). Oxford: Oxford University Press.

Liberman, A. M., & Whalen, D. H. (2000). On the relation of speech to language. *Trends in Cognitive Sciences, 4*(5), 187–196.

Lipski, S. C., Lahiri, A., & Eulitz, C. (2007). Differential height specification in front vowels for German speakers and Turkish–German bilinguals: an electroencephalographic study. In *ICPhS*, Saarbrücken, 6–10 August 2007 (pp. 809–812).

Logothetis, N. K. (2008). What we can do and what we cannot do with fMRI. *Nature, 453*(12), 869–878.

Luria, A. (1966). *The higher cortical function in man*. New York: Basic Books.

MacDonald, M. C. (1993). The interaction of lexical and syntactic ambiguity. *Journal of Memory and Language, 32*, 692–715.

Manzini, M. R., & Savoia, L. M. (2007). *A unification of morphology and syntax. Investigations into Romance and Albanian dialects*. London/New York: Routledge.

Marangolo, P., Piras, F., Galati, G., & Burani, C. (2006). Functional anatomy of derivational morphology. *Cortex, 42*, 1093–1106.

Marantz, A. (2005). Generative linguistics within cognitive neuroscience of language. *The Linguistic Review, 22*, 429–445.

Marr, D. (1982). *Vision*. San Francisco, CA: Freeman.

Moro, A., Tettamanti, M., Perani, D., Donati, C., Cappa, S. F., & Fazio, F. (2001). Syntax and the brain: disentangling grammar by selective anomalies. *NeuroImage, 13*, 110–118.

Musso, M., Moro, A., Glauche, V., Rijntjes, M., Reichenbach, J., Buchel, C., et al. (2003). Broca's area and the language instinct. *Nature Neuroscience, 6*, 774–781.

Näätänen, R., Kujala, T., & Winkler, I. (2011). Auditory processing that leads to conscious perception: a unique window to central auditory processing opened by the mismatch negativity and related response. *Psychophysiology, 48*, 4–22.

Näätänen, R., Lehtokoski, A., Lennes, M., Cheour, M., Huotilainen, M., Livonen, A., et al. (1997). Language-specific phoneme representations revealed by electric and magnetic brain responses. *Nature, 30*(385), 432–434.

Näätänen, R., Paavilainen, P., Rinne, T., & Alho, K. (2007). The mismatch negativity (MMN) in basic research of central auditory processing: a review. *Clinical Neurophysiology, 118*, 2544–2590.

Newman, S. D., Ikuta, T., & Burns, T., Jr. (2010). The effect of semantic relatedness on syntactic analysis: an fMRI study. *Brain & Language, 113*, 51–58.

Obleser, J., Boecker, H., Drzezga, A., Haslinger, B., Hennenlotter, A., Roettinger, M., et al. (2006). Vowel sound extraction in anterior superior temporal cortex. *Human Brain Mapping, 27*, 562–571.

Obleser, J., Lahiri, A., & Eulitz, C. (2004). Magnetic brain response mirrors extraction of phonological features from spoken vowels. *Journal of Cognitive Neuroscience, 16*, 31–39.

Obleser, J., Zimmermann, J., Van Meter, J., & Rauschecker, J. P. (2007). Multiple stages of auditory speech perception reflected in event-related fMRI. *Cerebral Cortex, 17*, 2251–2257.

Osnes, B., Hugdahl, K., Hjelmervik, H., & Specht, K. (2011). Increased activation in superior temporal gyri as a function of increment in phonetic features. *Brain & Language, 116*, 97–101.

Pallier, C., Devauchelle, A. D., & Dehaene, S. (2011). Cortical representation of the constituent structure of sentences. *Proceedings of the National Academy of Sciences of the United States of America, 108*, 2522–2527.

Papoutsi, M., Stamatakis, E. A., Griffiths, J., Marslen-Wilson, W. D., & Tyler, L. K. (2011). Is left fronto-temporal connectivity essential for syntax? Effective connectivity, tractography and performance in left-hemisphere damaged patients. *NeuroImage, 58*, 656–664.

Patel, A. D. (2003). Language, syntax, music and the brain. *Nature Neuroscience, 6*(7), 674–681.

Philips, C. (2001). Levels of representation in the electrophysiology of speech perception. *Cognitive Science, 25*, 711–731.

Phillips, C. (2003). Linear order and constituency. *Linguistic Inquiry, 34*, 37–90.

Phillips, C. (2009). Should we impeach armchair linguists? In S. Iwasaki, H. Hoji, P. Clancy, & S. O. Sohn (Eds.), *Japanese/Korean linguistics 17* (pp. 49–72) Stanford, CA: CSLI Publications.

Phillips, C. (2011). Some arguments and non-arguments for reductionist accounts of syntactic phenomena. *Language and Cognitive Processes, 26*(8), 1–32.

Phillips, C., & Lau, E. (2004). Foundational issues (review article on Jackendoff 2002a). *Journal of Linguistics, 40*, 1–21.

Phillips, C., Pellathy, T., Marantz, A., Yellin, E., Wexler, K., Poeppel, D., et al. (2000). Auditory cortex accesses phonological categories: an MEG mismatch study. *Journal of Cognitive Neuroscience, 12*, 1038–1045.

Phillips, C., & Wagers, M. (2007). Relating structure and time in linguistics and psycholinguistics. In G. Gaskell (Ed.), *Oxford handbook of psycholinguistics* (pp. 739–756). Oxford: Oxford University Press.

Pinker, S., & Jackendoff, R. (2005). The faculty of language: what's special about it? *Cognition, 95*, 201–236.

Poeppel, D. (1996a). A critical review of PET studies of phonological processing. *Brain & Language, 55*, 317–351.

Poeppel, D. (1996b). Some remaining questions about studying phonological processing with PET: response to Demonet, Fiez, Paulesu, Petersen, and Zatorre. *Brain & Language, 55*, 380–385.

Poeppel, D. (2008). The cartographic imperative: confusing localization and explanation in human brain mapping. In H. Bredekamp, G. Werner. M. Bruhn (Eds.), Bildwelten des Wissens. "Ikonographie des Gehirns". Bildwelten,6(1), 19–29.

Poeppel, D., & Embick, D. (2005). The relation between linguistics and neuroscience. In A. Cutler (Ed.), *Twenty-first century psycholinguistics: Four cornerstones* (pp. 1–16). New Jersey: Lawrence Erlbaum.

Poeppel, D., & Hickok, G. (2004). Towards a new functional anatomy of language. *Cognition, 92*, 1–12.

Poeppel, D., Idsardi, W. J., & van Wassenhove, V. (2008). Speech perception at the interface of neurobiology and linguistics. *Philosophical Transactions of the Royal Society, Biological Sciences, 363*, 1071–1086.

Poeppel, D., & Marantz, A. (2000). Cognitive neuroscience of speech processing. In A. Marantz, Y. Miyashita, & W. O'Neil (Eds.), *Image, language, brain* (pp. 29–50). Cambridge, MA: The MIT Press.

Poeppel, D., & Monahan, P. J. (2011). Feedforward and feedback in speech perception: revisiting analysis by synthesis. *Language and Cognitive Processes, 26*(8), 935–951.

Poldrack, R. A. (2006). Can cognitive processes be inferred from neuroimaging data? *Trends in Cognitive Sciences, 10*, 59–63.

Poldrack, R. A. (2010). Mapping mental function to brain structure: how can cognitive neuroimaging succeed? *Perspectives on Psychological Science, 5*(6), 753–761.

Price, C. J. (2000). Functional imaging studies of aphasia. In J. C. Mazziotta, A. W. Toga, & R. S. J. Frackowiak (Eds.), *Brain mapping: The disorders* (pp. 181–200). San Diego: Academic Press.

Price, C. J. (2010). The anatomy of language: a review of 100 fMRI studies published in 2009. *Annals of the New York Academy of Sciences, 1191*, 62–88.

Price, C. J., Moore, C. J., Humphreys, G. W., & Wise, R. J. S. (1997). Segregating semantic from phonological processes during reading. *Journal of Cognitive Neuroscience, 9*, 727–733.

Pulvermüller, F. (2002). *The neuroscience of language*. Cambridge, MA: Cambridge University Press.

Pulvermüller, F. (2010). Brain-language research: where is the progress? *Biolinguistics, 4*(2–3), 255–288.

Pulvermüller, F. (2012). Meaning and the brain: The neurosemantics of referential, interactive, and combinatorial knowledge. *Journal of Neurolinguistics, 25*(25), 423–459.

Pulvermüller, F., & Fadiga, L. (2010). Active perception: sensorimotor circuits as a cortical basis for language. *Nature Reviews Neuroscience, 11*, 351–360.

Pulvermüller, F., Huss, M., Kherif, F., Moscoso del Prado Martin, F., Hauk, O., & Shtyrov, Y. (2006). Motor cortex maps articulatory features of speech sounds. *Proceedings of the National Academy of Sciences of the United States of America, 103*(20), 7865–7870.

Pulvermüller, F., & Shtyrov, Y. (2006). Language outside the focus of attention: the mismatch negativity as a tool for studying higher cognitive processes. *Progress in Neurobiology, 79*, 49–71.

Pulvermüller, F., Shtyrov, Y., & Hauk, O. (2009). Understanding in an instant: neurophysiological evidence for mechanistic language circuits in the brain. *Brain & Language, 110*, 81–94.

Pylkkänen, L., Brennan, J., & Bemis, D. (2011). Grounding the cognitive neuroscience of semantics in linguistic theory. *Language and Cognitive Processes, 26*(9), 1317–1337.

Pylkkänen, L., Feintuch, S., Hopkins, E., & Marantz, A. (2004). Neural correlates of the effects of morphological family frequency and family size: an MEG study. *Cognition, 91*(3), 35–45.

Pylkkänen, L., & Marantz, A. (2003). Tracking the time course of word recognition with MEG. *Trends in Cognitive Sciences, 7*, 187–189.

Rauschecker, J. P., & Scott, S. K. (2009). Maps and streams in the auditory cortex: nonhuman primates illuminate human speech processing. *Nature Neuroscience, 12*, 718–724.

Rimol, L. M., Specht, K., Weis, S., Savoy, R., & Hugdahl, K. (2005). Processing of sub-syllabic speech units in the posterior temporal lobe: an fMRI study. *NeuroImage, 26*, 1059–1067.

Rizzi, L. (2004). *The structure of CP and IP. The cartography of syntactic structures*. Oxford: Oxford University Press.

Rizzi, L. (2012). Core linguistics computations: How are they expressed in the brain? *Journal of Neurolinguistics, 25*(5), 489–499.

Rogalsky, C., & Hickok, G. (2009). Selective attention to semantic and syntactic features modulates sentence processing networks in anterior temporal cortex. *Cerebral Cortex, 19*, 786–796.

Rogalsky, C., & Hickok, G. (2011). The role of Broca's area in sentence comprehension. *Journal of Cognitive Neuroscience, 23*(7), 1664–1680.

Rogalsky, C., Love, T., Driscoll, D., Anderson, S. W., & Hickok, G. (2011). Are mirror neurons the basis of the speech perception? Evidence from five cases with damage to the purported human mirror system. *Neurocase, 17*(2), 178–187.

Rogalsky, C., Matchin, W., & Hickok, G. (2008). Broca's area, sentence comprehension, and working memory: an fMRI study. *Frontiers in Human Neuroscience, 2*(14).

Sabri, M., Binder, J. R., Desai, R., Medler, D. A., Leitl, M. D., & Liebenthal, E. (2008). Attentional and linguistic interactions in speech perception. *NeuroImage, 39*, 1444–1456.

Sahin, N. T., Pinker, S., Cash, S. S., Schomer, D., & Halgren, E. (2009). Sequential processing of lexical, grammatical, and phonological information within Broca's area. *Science, 36*, 445–449.

Santi, A., & Grodzinsky, Y. (2007). Working memory and syntax interact in Broca's area. *NeuroImage, 37*, 8–17.

Santi, A., & Grodzinsky, Y. (2010). fMRI adaptation dissociates syntactic complexity dimensions. *NeuroImage, 51*, 1285–1293.

Schnelle, H. (2010). *Language in the brain*. Cambridge, MA: Cambridge University Press.

Schwartz, J. L., Basirat, A., Ménard, L., & Sato, M. (2012). The Perception for Action Control Theory (PACT): a perceptuo-motor theory of speech perception. *Journal of Neurolinguistics, 25*(5), 336–354.

Schütze, C. (1996). *The empirical base of linguistics: Grammaticality judgments and linguistic methodology*. Chicago: The University of Chicago Press.

Scott, S. K. (2005). The neurobiology of speech perception. In A. Cutler (Ed.), *Twenty-first century psycholinguistics: Four cornerstones* (pp. 141–156). New Jersey: Lawrence Erlbaum.

Scott, S. K., McGettigan, C., & Eisner, F. (2009). A little more conversation, a little less action – candidate roles for the motor cortex in speech perception. *Nature Review Neuroscience, 10*, 295–302.

Shapleske, J., Rossell, S. L., Woodruff, P. W. R., & David, A. S. (1999). The planum temporale: a systematic, quantitative review of its structural, functional and clinical significance. *Brain Research Reviews, 29*, 26–49.

Simonyan, K., & Horwitz, B. (2011). Laryngeal motor cortex and control of speech in humans. *Neuroscientist, 17*(2), 197–208.

Skipper, J. I., Goldin-Meadow, S., Nusbaum, H. C., & Small, S. L. (2007). Speech-associated gestures, Broca's area, and the human mirror system. *Brain & Language, 101*, 260–277.

Snijders, T. M., Vosse, T., Jos, G. K., van Berkum, J. A., Petersson, K. M., & Hagoort, P. (2009). Retrieval and unification of syntactic structure in sentence comprehension: an fMRI study using word category ambiguity. *Cerebral Cortex, 19*, 1493–1503.

Sörös, P., Guttman Sokoloff, L., Bose, A., McIntosh, A. R., Graham, S. J., & Stussf, D. T. (2006). Clustered functional MRI of overt speech production. *NeuroImage, 32*, 376–387.

Sprouse, J. (2007). Continuous acceptability, categorical grammaticality, and experimental syntax. *Biolinguistics, 1*, 118–129.

Sprouse, J. (2011). A test of the cognitive assumptions of magnitude estimation: commutativity does not hold for acceptability judgments. *Language, 87*(2), 274–288.

Sprouse, J., & Almeida, D. Power in acceptability judgment experiments and the reliability of data in syntax, submitted for publication.

Stevens, K. N. (2002). Toward a model for lexical access based on acoustic landmarks and distinctive features. *Journal of the Acoustical Society of America, 111*, 1872–1891.

Tesink, C. M. J. Y., Buitelaar, J. K., Petersson, K. M., van der Gaag, J., Kan, C. C., Tendolkar, I., et al. (2009). Neural correlates of pragmatic language comprehension in autism spectrum disorders. *Brain a Journal of Neurology, 132*(7), 1941–1952.

Tettamanti, M., Alkadhi, H., Moro, A., Perani, D., Kollias, S., & Weniger, D. (2002). Neural correlates for the acquisition of natural language syntax. *NeuroImage, 17*, 700–709.

Tettamanti, M., Moro, A., Messa, C., Moresco, R. M., Rizzo, G., Carpinelli, A., et al. (2005). Basal ganglia and language: phonology modulates dopaminergic release. *Neuroreport, 16*(4), 397–401.

Tettamanti, M., Rotondi, I., Perani, D., Scotti, G., Fazio, F., Cappa, S. F., et al. (2009). Syntax without language: neurobiological evidence for cross-domain syntactic computations. *Cortex, 45*, 825–838.

Thompson-Schill, S. L. (2005). Dissecting the language organ: a new look at the role of Broca's area in language processing. In A. Cutler (Ed.), *Twenty-first century psycholinguistics: Four cornerstones* (pp. 173–189). Mahwah, New Jersey: Lawrence Erlbaum.

Tian, X., & Poeppel, D. (2010). Mental imagery of speech and movement implicates the dynamics of internal forward models. *Frontiers in Psychology, 1*(166).

Turkeltaub, P. E., & Coslett, H. B. (2010). Localization of sublexical speech perception components. *Brain & Language, 114*, 1–15.

van Wassenhove, V., Grant, K. W., & Poeppel, D. (2005). Visual speech speeds up the neural processing of auditory speech. *Proceedings of the National Academy of Sciences of the United States of America, 102*, 1181–1186.

Walenski, M., & Ullman, M. T. (2005). The science of language. *The Linguistic Review, 22*, 327–346.

Weisberg, D. S., Keil, F. C., Goodstein, J., Rawson, E., & Gray, J. R. (2008). The seductive allure of neuroscience explanations. *Journal of Cognitive Neuroscience, 20*(3), 470–477.

Winkler, I. (2007). Interpreting the mismatch negativity. *Journal of Psychophysiology, 21*, 147–163.

Wolfgang, E., Gehre, S., Hammerschmidt, K., Hölter, S. M., Blass, T., Somel, M., et al. (2009). A humanized version of Foxp2 affects cortico-basal ganglia circuits in mice. *Cell, 137*, 961–971.

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *Nature Neuroscience Review, 3*, 1212–1217.

Woods, D. L., Herron, T. J., Cate, A. D., Kang, X., & Yund, E. W. (2011). Phonological processing in human auditory cortical fields. *Frontiers in Human Neuroscience, 5*(45), 1–15.

Woods, D. L., Herron, T. J., Cate, A. D., Yund, E. W., Stecker, G. C., Rinne, T., et al. (2010). Functional properties of human auditory cortical fields. *Frontiers in Neuroscience, 4*, 155.

Xiang, H. D., Fonteijn, H. M., Norris, D. G., & Hagoort, P. (2010). Topographical functional connectivity pattern in the perisylvian language networks. *Cerebral Cortex, 20*(3), 549–560.

Yarkoni, T., Poldrack, R. A., Van Essen, D. C., & Wager, T. D. (2010). Cognitive neuroscience 2.0: building a cumulative science of human brain function. *Trends in Cognitive Sciences, 14*(11), 489–496.

Zatorre, R. J., Belin, P., & Penhune, V. B. (2002). Structure and function of auditory cortex: music and speech. *Trends in Cognitive Sciences, 6*(1), 37–46.

Zheng, Z. Z., Munhall, K. G., & Johnsrude, I. S. (2010). Functional overlap between regions involved in speech perception and in monitoring one's own voice during speech production. *Journal of Cognitive Neuroscience, 22*, 1770–1781.