The modern study of language is guided by four principal questions. First, what is it that you know when you know a language? Language is a system of knowledge, and characterizing that system of knowledge in the mature adult speaker is the domain of linguistics. Second, how is that knowledge acquired? Language acquisition research and psycholinguistics concern themselves with the range of questions surrounding how the initial state is transformed into the final state in the adult speaker, given the primary linguistic data that the learner is confronted with. Third, how is this knowledge of language deployed in comprehension and production? Psycholinguistics and neurolinguistics concern themselves with these issues. Four, how does the brain form the basis for acquiring and processing language? What neural mechanisms instantiate knowledge of language? These issues lie in the domain of neurolinguistics, cognitive neuroscience of language, and computational neuroscience.

This particular way of investigating language -- viewing it as a part of the biological world and investigating it using the conceptual and methodological approaches of the natural sciences -- is largely due to the work of Noam Chomsky (Chomsky 1957, 1965, 1981, 1995, 2000). Chomsky has forcefully articulated the view on which knowledge of language and its use should be investigated as a part of the natural world. That being said, the contributions to our understanding of language deriving from the humanities and social sciences, while important and worthwhile, simply deal with very different types of questions and do not (at least directly) contribute to our understanding of which properties of the human brain make it possible to have and use the language system. For example, the significant concerns of sociolinguistics (see, say, the influential work of Labov, e.g. 1972) or the philosophy of language (see, say, Kripke 1972) interact only very indirectly with the concerns of the neural basis of language. Crucially, an intellectual agenda such as the one captured by the phrase ‘cognitive neuroscience of language’ would not have arisen without the naturalistic perspective developed in last 50 years of research.
It is also worth bearing in mind that the approach to speech perception and language processing that builds on this tradition and that I sketch out below connects to cognitive science questions as they have been engaged by researchers such as Jerry Fodor (philosophy, foundations of cognitive science, psycholinguistics), Randy Gallistel (learning theory, foundations of cognitive science, numerical cognition), Steven Pinker (psycholinguistics, foundations of cognitive science), and others. It is a view of the cognitive sciences deeply influenced by rationalist philosophy as well as the computational perspective well articulated by David Marr in his seminal book *Vision* (1982).

In what follows, I highlight what I take to be some of the central questions that one has to engage with in studying the brain basis of speech and language. As indicated in the title, this is a necessarily short and heavily biased piece, emphasizing the research and perspective that my colleagues and I have been advocating in our own laboratories. There is a large literature that approaches the problem from a different perspective, and although many of the readings arguably overlap, the philosophical stance in motivating the research is quite different. The difference in these approaches derives, by and large, from philosophically held beliefs about the nature of mental representation. On one view, the mind is a highly structured device, in which part of the structure is innately determined. On the other view, the mind/brain has more general-purpose characteristics, and its principal feature is the remarkable ability to associate information with other information. This latter, empiricist stance, is often associated with connectionist modeling in cognition and neuroscience. To get a feeling for the literature through this different perspective, the reader might consults reviews by researchers such as Jay McClelland or Joseph Devlin. [[To get a flavor of the conceptual foundations, students should read, minimally, the first chapter of Marr’s book, something (easy) by Chomsky, and perhaps something of a general nature, say from Pinker.]]

**Conceptual challenges**

The first question one might ask oneself (and students) is deceptively straightforward: does research linking brain and language actually work? Or, more pointedly, is such research worth pursuing? The easy answer is, of course, yes. But it does require/merit some reflection … Yes, I think we should do research on the brain mechanisms that form the basis for language processing. But why is that true? Executing such studies implies that one expects either to learn something about language or to learn something about the brain. It is, however, not straightforward to identify studies using brain-based methodologies that provide a clear-cut insight into how the brain works or how language works. Why are these studies such a challenge?

Consider a very basic question. [[This is a useful point to discuss with students, making the argument explicit on the board.]] Suppose one is asked to generate a list of the “atoms” of language. What are the elementary units that make up language, the so-called “primitives”? Although there might be some disagreement, by and large language researchers will converge on such units as *feature*, *syllable*, *morpheme*, *clause*, *noun phrase*, etc. Similarly, if one asks neurobiologists to list the atoms of their research, the list will contain concepts such as *dendrite*, *neuron*, *cortical column*, *synapse*, etc. But now, how are these concepts linked? There is no doubt that neuroscientists are deeply committed to the “reality” of what they take to be the physical infrastructure. And linguists and psychologists are equally committed to the relevance
and “reality” of their psychological primitives. What is missing – and what is at the center of much current research and debate – are the linking hypotheses that provide principled ways to connect what we know about the brain to what we know about language.

There exists, of course, much interesting research that uses sophisticated technologies (see below) to test which brain areas appear to be responsible for what kinds of language function. That research, however, while fascinating and important, remains correlative. We have been learning quite a bit about the cartography of the brain and where in the head things seem to be located. We have not, however, learned how these brain areas compute. That is to say, we do not have explanatory models. In the next 10-20 years, we hope to be able to construct models that link in a convincing, mechanistic, computationally explicit way neuronal circuitry and linguistic computation. But to achieve that we need to learn much more about the nature of the neuronal circuitry and more about how to decompose language functions into the elementary computations that could be executed by such circuits.

Recently, some researchers have reviewed these old issues, examining how cognitive neuroscience of language has proceeded and might proceed in the future. These (straightforward and easily readable) perspective pieces provide some important intellectual context for this area of research (Marantz 2005; Poeppel & Embick 2005; Hagoort 2008).

**Methodological challenges**

Given the conceptual complexity of the scientific issue, what methods should one use to address brain and language? The technical approach, of course, depends precisely on the nature of the question. To visualize something very small, one utilizes a microscope. To measure the temperature of something, one employs a thermometer. This might sound banal or pedantic, but one is consistently surprised by how a single method is occasionally employed to address questions simply not suited to the measurement provided. As a reader of this literature, one must be very aware of the methodology in order to be able to assess whether the experiments appropriately address the putative questions.

In the cognitive neurosciences, there now exists an array of methods, most of them new and all of them exciting -- but each of them differentially suited to address different types of questions. Historically, this type of research started with looking at data from patients. Brain injury -- either resulting from trauma or resulting from stroke – is unfortunately quite common, and in the middle of the 19th century these types of data began to be systematically studied. Indeed, the very origin of brain and language research -- and to some extent the origin of modern neuroscience and segregation of function in the brain-- lies in the findings of the French neurologist Broca (1861), who first correlated a dramatic impairment in spoken language with damage to the particular part of the left frontal lobe, the third frontal convolution of the inferior frontal gyrus (now known as Broca’s area). This method, deficit–lesion correlation, was the dominant approach for at least 100 years. By carefully examining what kind of brain injury leads to what kind of language deficits, we have made enormous progress in identifying the “parts lists” of language processing and its brain basis.

[[There are excellent patient videos that depict how a local brain lesion can generate a surprisingly specific language deficit. Many of these videos are linked to the websites that go]
Despite the historical success, and despite the fact that the dominant model of brain and language derives from such data, the model is seriously underspecified. The Broca-Wernicke-Geschwind classical model of brain and language (e.g. Geschwind 1985) is too primitive from a neurobiological perspective and significantly too naive from the linguistic and psychological perspectives. This model, incorporating the left anterior Broca’s area in the frontal lobe and the left posterior Wernicke’s area and the temporal lobe has been a resilient, long-lasting, and partially successful clinical model, but it is now widely agreed to be insufficient (for extended discussion, see Poeppel & Hickok 2004; Hickok & Poeppel 2004). That being said, the method of deficits – lesion correlation remains one of the most useful ways to collect data about which brain areas are implicated in which language function.

At the moment, the dominant methods are the noninvasive brain recording techniques. These techniques – widely reviewed in the technical literature and described in numerous websites – come in two flavors. One set of approaches are called hemodynamic, meaning that the basis of the measurements and the images collected is the relationship between neuronal brain activity and blood – blood flow, blood volume, or blood oxygenation. The most widely used of these approaches is functional magnetic resonance imaging, fMRI, an imaging approach that generates pictures with a remarkable spatial resolution, on the order of 1 mm. This represents a remarkable achievement of physics, engineering, and signal processing. To develop a camera that can, from the outside, take a picture of the inside of the brain at 1 mm resolution is a terrific accomplishment. fMRI – along with the older technique PET scanning and the still quite new Near Infrared Spectroscopy, NIRS -- provides a unique window into the spatial organization of the awake, functioning brain.

Hemodynamic imaging using fMRI has compelling properties for the study of the brain basis of language, but also some principled limitations. Some of these limitations derive from the nature of the signal and the physiological basis of fMRI (see, for example, Logothetis 2008), other limitations derive from the type of experimental design that is required. Although the spatial resolution of these approaches is now better than 1 mm in-plane resolution, the temporal resolution will remain on the order of hundreds of milliseconds, at best. This limitation suggests that one might use other approaches to investigate the online time course of language processing.

Measuring language processing with high temporal resolution is best accomplished using electromagnetic techniques. Here, the older electroencephalography, EEG, and the newer magnetoencephalography, MEG, standout. These recording approaches capture brain activity with a millisecond resolution, commensurate with online brain activity. The disadvantage of these techniques is that it is challenging to calculate the source of the brain activity: the spatial resolution is on the order of 5-10 mm. This brief discussion illustrates that one cannot have one’s cake and eat it too. To describe with great spatial detail which areas are activated requires FMRI; to investigate with appropriate temporal resolution the time course of processing requires an electromagnetic technique. A given experiment must specify quite clearly whether the answer to the question will more likely lie in the spatial domain – in which case a hemodynamic technique
is likely more suited – or in the temporal domain – in which case an electromagnetic technique is the right one.

There is no question that hemodynamic imaging using fMRI has captured both the scientific and popular imaginations. The colorful images of slices of brain with localized “hot spots” suggests that we are getting ever closer to a map of the brain that specifies which chunk of tissue executes which chunk of psychological function. However, while it is true that we are developing increasingly granular maps of localized function, it is essential to remember that localization is not an end goal for this type of research. In particular, localization is not equivalent to explanation. To have a model of brain and language that is linguistically sophisticated, biologically realistic, and computationally transparent and explicit – in other words an explanatory model – requires much more work than localizing where some activity might be occurring. It requires understanding how a local neuronal circuitry executes computations of a specific type. This is a research challenge and it is not obvious which techniques are optimally suited for addressing it. It is very likely that cognitive neuroscience at this sophisticated level of granularity will closely interact with computational theories. [[For extended discussion of these issues, see, for example, Poeppel (2008) and Poeppel & Embick (2005). These are suited for upper level students.]]

We now turn briefly to three areas of research in which substantive progress has been made, (i) speech perception and spoken language recognition, (ii) the representation and processing of words, and (iii) sentence processing. There are many other areas in the cognitive neuroscience of language area that have yielded important and exciting new insights; the brevity of this review demands that we stick to a few key studies to illustrate the type of research that is being executed.

**Sounds**

One of the remarkable things about the language system is that it can use different sensory modalities to be processed. The most frequent and most typical way to process language is via an *auditory* channel, speech perception (and of course speech production). But the language system can also be engaged or triggered by *visual* information, obviously. At this moment you are reading text, specifically some sentences that I have written. If you are competent at using a sign language, you’re also using the visual channel. Finally, the *tactile* system can be used to interface with the language system: Braille reading uses the mapping from touch to linguistic representation. Evidently, the language system can use input/output interfaces of rather different types. Language comprehension must therefore be a set of operations that are at least to some extent independent of the input/output interfaces. It is, in this context, helpful to remind oneself that *speech perception* refers to operations that take auditory information and connect that to linguistic information; *language comprehension* is a set of operations that acts on more abstract internal representations. Terminological confusion on this can lead to all kinds of confusions and misunderstandings.

Comprehending language via the auditory channel is the most biologically engrained system. Reading and writing are extremely useful – but these are, biologically speaking, very recent cultural inventions, so in order to understand the neurobiology of language processing it is important to specify what exactly is at stake. Barring some pathology, and given typical input
(primary linguistic data), all children learn to parse the speech signal and ultimately to output intelligible speech. Thus, speech perception seems to be the basic input channel for the language system.

Perceiving, analyzing, and understanding this continuously varying signal is a major challenge for the perceptual and cognitive systems. The mapping from “vibrations in the ear” (sounds) to “abstractions in the head” (words) turns out to be particularly complex, involving many stages in the auditory pathway from the cochlea to the cortex. Cognitive neuroscience studies have tried to tackle many of these steps. In order to illustrate the complexity of the problem, it is worth showing visually what a speech signal looks like. The signal associated with a speaker saying some sentence is a continuously varying waveform that carries information on different time scales and different frequency scales. How those squiggles map to information that is stored in a listener’s long-term memory, broken up into individual stored representations (roughly, words), is a profound challenge. How, for example, is the continuously varying waveform broken up? How and where does segmentation occur? Some innovative EEG studies (for example by Helen Neville and her students) have addressed this fundamental question, showing that very early responses in auditory cortex provide at least some physiological index of when information is broken up in time. But, to be honest, we know very little about this critical yet poorly understood requirement of how speech perception works. Words and sentences are analyzed as sequential discrete chunks of information – but the input signal is a seemingly unstructured, continuous waveform. This problem alone illustrates a deep challenge that any perceptual system faces, namely how to map from the signal to the internal representation.

Let me highlight, very briefly, two areas of inquiry in which cognitive neuroscience has made some progress. One concerns the so-called functional anatomy of speech perception. Speech perception is not an unstructured, monolithic cognitive function. Mapping from sounds to words involves many steps, and depending on what one is expected to do as a listener – remain silent, repeat the input, write it down, etc. – the different tasks will also play a critical role in the speech perceptual process. Accordingly, it is now well established that there is no single brain area that is responsible for speech perception. Rather, a set of several brain regions in different parts of the cerebral cortex interact in systematic ways in speech perception. This has been established by detailed consideration of brain injury data as well as functional imaging data. For example, several areas of the temporal lobe, some parietal areas, and some frontal areas conspire to form the network for speech recognition. This distributed functional anatomy contrasts with other systems; for example, in the study of face recognition, one particular brain area plays a disproportionately large role (the fusiform face area). Interestingly the functional anatomic models that have been developed for speech recognition have striking parallels to the organization of the visual system. A dorsal stream is principally responsible for mapping from sounds to motor representations (for output); and a ventral stream is involved in mapping from sounds to meanings (words), more or less. Notice that this is much like the parallel pathways in the visual system, where we contrast a where/how (dorsal) and a what (ventral) system. Discussing these parallels is enlightening both from the perspective of anatomy as well as from the perspective of the functional organization of cognition, more generally. In addition, a discussion of the functional anatomy of speech perception illustrates what a distributed functional anatomy actually looks like. [[The functional anatomy of spoken language processing
Our understanding of the functional anatomy comes primarily from deficit-lesion data (neuropsychology) and from imaging data (PET, fMRI). Which areas of speech sound processing have benefited from electrophysiological techniques? One of the most fascinating questions associated with speech processing concerns how speakers of different languages must have a different inventory of sounds in their brains. Speakers of different languages do not just sound different because they pronounce sounds differently, they in fact have different inventories. In a series of remarkable electrophysiological studies, researchers have been able to document responses that indicate in which way speakers’ phonemic inventories differ. Most of the time, these studies are done using a so-called mismatch design. Listeners hear a sequence of sounds in which a standard sound is repeated often (say /ba/), interrupted occasionally by a deviant sound (say /da/). A deviant sound elicits a specific mismatch brain response that peaks approximately 150 ms after the sound onset. This response can be measured effectively with EEG or MEG. Some very clever experimental designs contrasting languages that are very close in terms of their inventories for certain sounds have documented how the auditory system reflects distinct phonemic inventories. For example, Näätänen et al. (1997) used both EEG and MEG to demonstrate that speakers of Finnish and Estonian have precisely differing responses from auditory cortex, conditioned by the speech sounds these languages contain. Importantly, these two languages are extraordinarily similar in terms of their speech sound inventory, yet they differ in a highly specific pattern -- electrophysiological data are able to distinguish between the response profile, indicating the absence or presence of a particular sound in that speaker’s language. Dehaene-Lambertz et al. (2000) were able to use a related design, contrasting speakers of Japanese and French, to document how the syllable structure of a language leads to the perceptual presence or absence of vowels, so-called epenthetic vowels. Finally, Kazanina et al. (2006) used a mismatch design and MEG to investigate the phenomenon of allophony. They studied speakers of Russian and Korean and showed how sounds that are acoustically different are or are not treated as the same category depending on the native language of the speaker. In short – and not doing justice to the subtlety of the studies – there are subtle electrophysiological designs that can be used to probe how early in the auditory stream there exists an interaction between the abstract information of the knowledge of language that a speaker has and the input signal coming from the speech sounds. The cognitive neuroscience data argue for a highly integrative model in which the bottom up signal elicits a very rich contribution from the top-down knowledge. A discussion of the mismatch design and its contribution to speech perception is quite rewarding; it is informative about experimental design the nature of phonology, as well as how brain responses are recorded.

**Words**

The main goal of speech perception is, of course, to identify words in the context of spoken language. To understand how words – and their (theoretically more well supported) parts, morphemes -- are accessed during perception, produced, and represented in the human brain constitutes one of the central questions in cognitive neuroscience of language. Every conceivable methodological approach has been harnessed to investigate how knowledge of words is implemented. Remarkably, we still understand very little about the nature of lexical representation and processing.
Words are a fascinating type of mental “stuff”. They are the linking points of, on the one hand, *meaning*, on the other, *sound*. The English word *chair* and the German word *Stuhl* have very different types of sounds (phonology) but the same meaning (lexical semantics). Speakers typically have a memorized mental dictionary that contains somewhere between 10,000 and 100,000 entries of that type, that is arbitrary sound–meaning pairings. Now, this many entries in a mental dictionary may not strike you as that huge a number. Consider, though, that each entry is constructed from a rather small inventory of primitives or atoms. English, for example, has somewhere in the vicinity of 40 phonemes, which are then combined to yield the rather large mental dictionary of native speakers. This means that the way words are stored in the mind/brain must permit the speaker and listener to extract rapidly and accurately the stored information from a “hard disk” that stores very similar looking information. Even acoustically very similar sounding words must be retrieved immediately and effortlessly, for example *sad* versus *sat*, or *ban* versus *pan*. The brain’s storage device for every speaker’s lexical information is extremely sensitive to differences that are subtle (in terms of sound distinctions) but categorical (in terms of meaning).

An additional challenge derives from the fact that words are not ‘monolithic’. Often words have internal structure (morphological structure). This is quite transparently observed in languages other than English, where word structure is extremely obvious. But even in English there is much evidence for the parts that make up words. For example, pluralization of nouns -- adding an /s/ in English – makes words sound like and look like they have structure, say *cat* versus *cats*, or *aardvark* versus *aardvarks*. Or consider a verb such as *running*. The *run* part and the *ing* part are clearly distinct and suggestive of some internal structure. Finally, take noun-noun compounds such as *flagship* or *teapot* or *bellhop*. It seems intuitively obvious that such words have internal parts. Note that these issues elicit vigorous debate and brain-based studies that differ in their motivation and interpretation (see, say, Devlin et al. 2004, Tyler et al. 2005).

Given these types of observations about the nature of words or their parts, research in the cognitive neurosciences has focused on (i) how and where words are stored, (ii) how they are accessed in perception and production, and (iii) whether they in fact have internal morphological structure and whether that structure plays a role in processing. The first, anatomic question concerning where in the brain words are stored is itself quite complex. If, as we discussed above, words have many parts and different attributes (sound, meaning), then identifying a single brain area as the “storage area” for words might be too optimistic or too naive. Perhaps, just as was the case for a speech sound processing, different aspects of words might be stored in different areas. As it turns out, there is no clear-cut answer to this issue. The conceptual information associated with words (the basis of meaning) seems quite clearly to be distributed across many brain areas. On the other hand, this conceptual information seems to map to lexical–phonological information in a more circumscribed part of the brain, the middle part of the temporal lobe (middle temporal gyrus). In other words, the information contributing to word meaning may be rather more distributed whereas the information contributing to word form -- and the insertion of words into further linguistic processes -- may be more localized. There are as yet no widely accepted answers to this issue, but the data from patients, from brain imaging, and from electrophysiology all point to the middle temporal gyrus as a critical brain area for lexical processing, whereas conceptual information appears to be distributed across numerous different
brain areas. Unsurprisingly, how words are stored is an even more difficult question. Specifying the format of their representation is of course a challenge for all aspects of the cognitive sciences. In the present context, we would like to know the code for word storage, whether that code is (the brain version of) C++ or Matlab or Microsoft Brain or whatever. Alas, we know virtually nothing about the actual encoding of information in nervous tissue.

These caveats notwithstanding, experimental research has made good progress. For example, the various brain areas associated with the production of words have been characterized by looking across the numerous studies that have employed the relevant word production tasks. In a tour de force review, Indefrey & Levelt (2004) provide an overview of the data in the context of a particular word production model. Interestingly, the functional anatomic model they describe for speech production (in particular the production of single words in response to pictures) converges very well with the functional anatomic model outlined by Hickok & Poeppel (2007) for speech perception. Cortical areas in the frontal lobe, parietal lobe, and temporal lobe form a network that is the basis of speech production. Once again, the didactic message is that, just as speech production is a process with many subroutines, the functional anatomy underlying production suggests a group of areas acting in concert to facilitate this cognitive faculty. There is no single brain area that is the “cortical basis of the production of words”. Rather, the careful decomposition of cognitive tasks into hypothesized subroutines shows that there are many different implicated brain areas for every cognitive task that is executed.]]

Electrophysiological studies employing both EEG and MEG have begun to document the time course of lexical access in perception and production. For example, van Turennout et al. (1998) used an ingenious EEG design, the lateralized readiness potential (LRP), to investigate how quickly phonological information becomes available in the production of words in a sentential context. They demonstrate how rapidly (in the range of 10s of milliseconds) the different “mental codes” are available in the processing of language (syntax, phonology, etc.). Turning to the recognition of words, here the results are quite mixed. Some investigators argue that lexical information is available – and visible in the brain using electrophysiology – as early as 100-200 ms after the onset of a word (F. Pulvermüller is the main proponent of this view). Others suggest that lexical access occurs somewhat later, perhaps between 250-350 ms. Still other researchers maintain that the recognition of words does not occur at a single point, but is rather a temporally extended process in which there are (either continuous or discrete) mappings from input waveform to potential lexical representation (M. Tanenhaus is a prominent advocate of such a position). It is also worth noting that these experiments are typically designed bearing in mind specific models of lexical access and lexical processing. For example, the TRACE model of speech perception (McClelland & Elman 1986) and the cohort model of lexical access (W. Marslen-Wilson, in various publications) have played a key role in motivating many studies. The two key points to remember are (i) that we are once again confronted with a distributed functional anatomy and (ii) that the time course of lexical processing is not yet well established, although we can specify that the access to words in the mental dictionary as implemented in the brain must occur sometime between 150 and 300 ms after the onset of a word.

The third question mentioned above, whether words have internal structure, has received a large amount of attention in the cognitive neuroscience of language literature. To the non-specialist, the question may seem surprising. When hearing or reading the word teacup, most people
intuitively judge this to be formed from tea and cup. Accordingly one might imagine that the stored form includes both tea and cup, i.e. a structured representation. Alternatively, perhaps the entire form is simply stored, and there is no internal structure to the word teacup. Analogously, some researchers argue that an inflected verb such as the past tense walked is stored as walk+ed, others suggests that walked is stored as a simplex form. What is at stake is the nature of representation in the mind/brain: are words stored as structured and abstract representations, or are they stored as holistic, simplex entries? Cognitive neuroscience data have been used to adjudicate between these alternatives. Theoretical linguistic research suggests that there is a strong role for morphology and abstraction. Certain strands of computational modeling, on the other hand, point out that storage is cheap, and that it is easy to simply store similar forms ‘near’ each other, without the requirement for decomposition and abstract structure. Both brain imaging and patient data (Marslen-Wilson & Tyler 2007) as well as electrophysiological data (Fiorentino & Poeppel 2007) have been used to argue the case. In my view, unsurprisingly, the studies support a structured, morphologically motivated perspective. Words, insofar as they have parts, are stored with reference to the parts, as structured representations. For example, MEG data show that by 300 ms after the beginning of a word, the internal parts of words “reveal themselves”, whether one is looking at lexical decision designs or priming designs. This is often called evidence for decomposition in lexical processing. Finally, insofar as one is focusing on the meaning of words, the data suggest a rather more distributed cortical representation – but the discussion of this goes too far for the present piece.

Sentences
Words are nice – but collections of word, sentences, are nicer. The defining feature of human language is that we (can) use sentences, mental representations that by necessity have a particular kind of structure, including structure over long distances. This syntactic structure – only loosely correlated with the boring sentence diagramming one has to do in school -- has specific and precise consequences for the computation of meaning, semantics. (Note that lexical semantics refers to word meaning, compositional semantics refers to the meaning of sentences.) To illustrate with a banal example, Dog bites man is a boring headline, but Man bites dog is unusual. The same words arranged in a different order mean decidedly different things, the hallmark of syntactic organization.

There is a long and respectable history of research on sentence representation and processing, both in linguistics and in psychology. In the context of cognitive neuroscience research, one issue stands out as receiving a lot of attention. Specifically, is there a brain basis of syntax that is separable from the brain basis of semantics? Behavioral research has documented that syntax and semantics can be discussed (somewhat) separately. Chomsky’s famous sentence, Colorless green ideas sleep furiously, is an example that illustrates that a sequence of words that makes no sense can nevertheless be interpreted as syntactically correct. [[Construct examples of this at will – it is very illuminating.]] The intuition that sentence processing and the computation of sentence meaning can be separated has led to two strands of research in the cognitive neurosciences. In one set of studies, researchers use hemodynamic imaging, principally fMRI, to test whether ‘syntax tasks’ versus ‘semantics tasks’ activate different brain areas. Notice that to do such an experiment presupposes that there is such an object as “syntax” and “semantics”. From the mid-1990s on, numerous studies have sought to identify the brain basis of syntax and semantics, but there has been only partial progress. Syntactic experiments have shown that frontal areas, in
particular in the inferior frontal gyrus, parietal areas, and temporal areas are all implicated in sentence processing tasks. Ironically, semantic experiments have shown the same type of distribution – although the specific areas implicated are not the identical ones that show up in syntactic tasks. A recent review of these patterns can be found in Ben Shalom & Poeppel 2007. Notice that, if one assumes that syntax and semantics are complex sets of operations with many different ‘moving parts’, it is unwise to expect single, strongly localized brain activations. Since syntax is a collection of many different computational subroutines, it is not surprising that many different brain areas are implicated in the processing of sentence structure. The same goes for compositional semantics. There exist sophisticated models of the functional anatomy of sentence processing (see, e.g., Friederici 2002), and it is now uncontroversial that there is no single brain area for “syntax”. The real research on functional anatomy of sentence processing concerns which brain areas support which computational subroutines.

A different strand of research has focused on error detection studies, primarily using electrophysiological methods. If syntax and semantics are different kinds of cognitive faculties, then sentences with errors that are syntactic versus errors that are semantic should yield different response patterns. Interestingly, semantic versus syntactic errors do in fact generate strikingly different electrophysiological responses. In particular, sentences that contain a semantic anomaly, such as “I enjoyed my coffee with cream and socks” reveal a particular EEG response called the N400: measured from the onset of the anomalous word (here, socks), there is a pronounced negativity that peaks at 400 ms, when compared to a control word (here, sugar). The discovery of this electrophysiological response, by Kutas & Hillyard in 1980, led to a huge number of studies investigating sentential anomalies. Crucially, errors that are not semantic but rather syntactic revealed a different type of response profile. For example, sentences such as “Every Friday he mow the lawn” showed an EEG response after the incorrect verb mow (compared to mows) that was a long lasting positivity between 600 and 900 ms after the onset of the anomalous item. In addition, such grammatical errors show an early negativity that is left lateralized. Now, given that syntactic anomalies yielded one type of brain response, a P600, and that semantic anomalies yielded a different type of data, and N400, it has been widely concluded that syntactic processing and semantic processing are separable on the grounds of brain data.

In my view, these data lead to a conclusion quite similar to the data associated with the processing of sounds and words: there is no single computational entity called syntax; there is no unstructured operation called semantics, just like there is no single brain area for words or sounds. Cognitive science research, in particular linguistic and psycholinguistic research, shows convincingly that these domains of processing are collections of subroutines. Therefore it is not surprising that the functional anatomy is not a one-to-one mapping from putative language operation to piece of brain. In short: there is no straightforward mapping from syntax to brain area X, semantics to brain area Y., phonology to brain areas Z, etc. Just as cognitive science research reveals complexity and structure, so the neurobiological research reveals fractionated and complex and distributed anatomic organization. Moreover this fractionation is not just in space (anatomy) but also in time: different computational subroutines act at different points in the time course of language processing. When processing a spoken sentence, multiple operations occur simultaneously at multiple timescales, and, unsurprisingly, many brain areas are implicated
in supporting these concurrent operations. The brain mechanisms that form the basis for the representation and processing of language are fractionated both in space and in time.

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