# New insights into the neurobiology of language from functional brain imaging

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## Introduction

Undoubtedly, language is among the most celebrated hallmarks of human cognition. Even though we perceive, produce, and comprehend language, and do so seemingly effortlessly every day of our lives, the underlying neural mechanisms for language remain far from understood. With the cognitive revolution of the last century, it became a common viewpoint that language is a modular system segregated from other functional systems in the nervous system. This notion combined with the findings from neuropsychological "lesion analysis" studies from earlier research led to the notion that these modules are instantiated in localized brain regions of the left inferior frontal, temporal and inferior parietal regions of the human brain. The most commonly cited characterization of this system, sometimes referred to as the Broca-Wernicke-Geschwind model, is represented by the iconic diagram of a white matter pathway (the arcuate fasciclus; AF) connecting the posterior superior temporal region ("Wernicke's area") involved in receptive language to the posterior part of the inferior frontal gyrus ("Broca's area") involved in expressive language (Fig. 1A). The 19th century studies of patients presenting language difficulties following brain injury have had a tremendous influence in the field of language neurobiology. For instance, the classic description of two severely dysfluent patients (Leborgne and Lelong) by the French neurologist Paul Broca in 1861 led to the longstanding belief that the posterior two thirds of the inferior frontal gyrus ("Broca's Area") is the motor center for language. The lesion method, however, is not without faults. For example, recent MRIs of Leborgne's and Lelong's brain revealed extensive lesions also involving the insula and associated perisylvian white matter [16, 25]. This indicates that the patients' syndrome did not necessarily result from injury to Broca's area. While studies of brain lesions and concomitant behavioral syndromes have had, and continue to have, a tremendous influence in the field of language neurobiology, interpretation of lesion data are complicated by the size of the lesions (which are often extensive) and compensatory mechanisms of plasticity that occur in the brain following injury. In the past fifteen years, the use of state-of-the-art neuroimaging, neurophysiological, and brain stimulation methods has enhanced the precision with which we can investigate language in the brain, and has contributed to rapid progress in the understanding of the neural basis of language. In fact, the consensus of how the brain processes language has shifted in three fundamental ways: (1) there is an increasing consensus that the brain is not organized into dissociable regions for production and comprehension, but rather that language functions are distributed

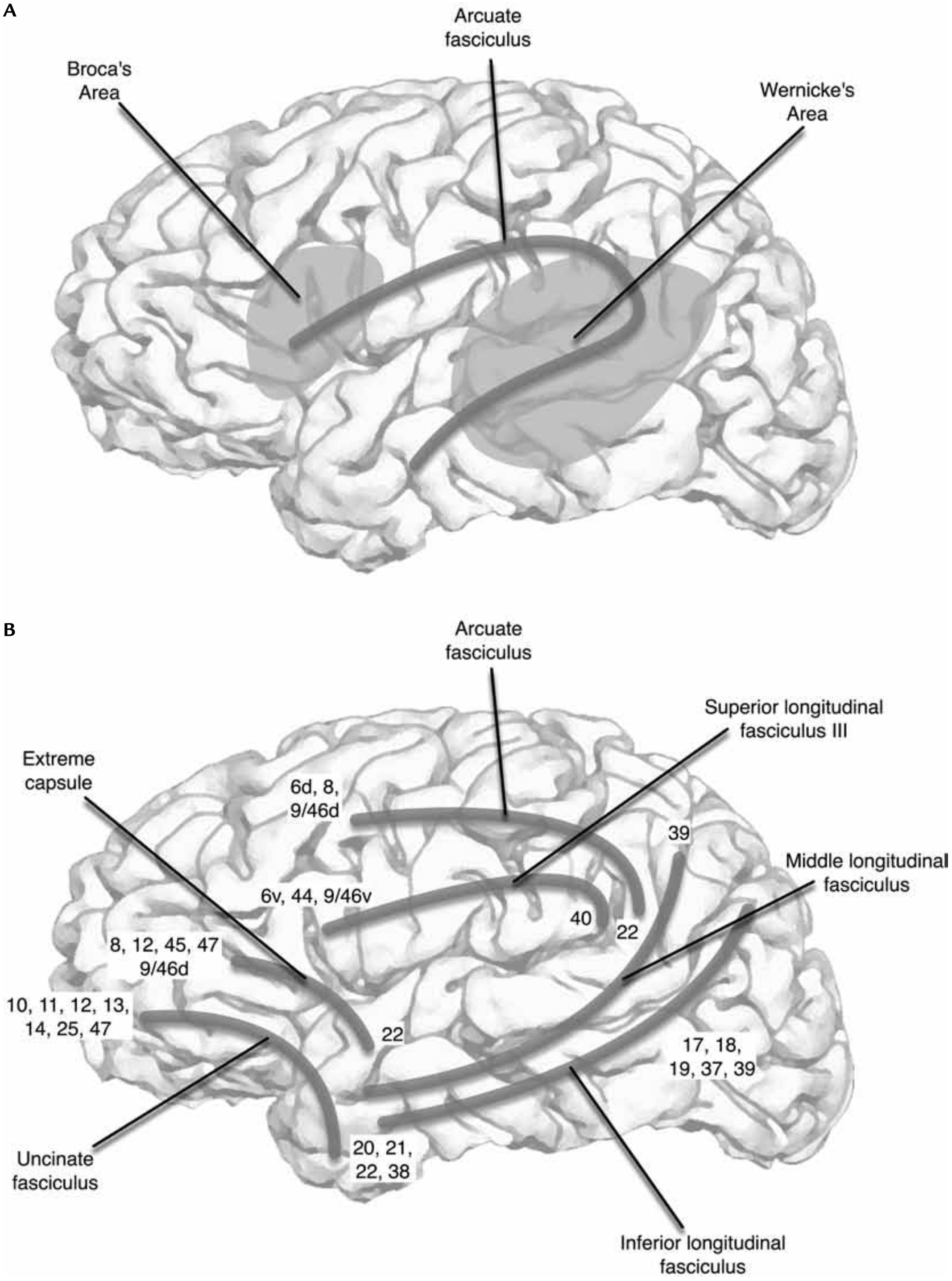

**Fig. 1. (A)** The classical Wernicke-Lichtheim-Geschwind model of language. Broca's area is seen as a primary center for speech production, and Wernicke's area is the primary center for comprehension. These two regions are connected by the arcuate fasciculus. **(B)** An updated view, informed by investigative methods in both the human and monkey, suggests that as many as six dissociable fiber pathways may contribute to language processing in the brain. Numbers indicate Brodmann Areas and potential regions of origin and termination

into large-scale cortical and subcortical networks; (2) there is an increasing focus on hodology [34], or how brain regions within this distributed network are connected by particular fiber pathways; (3) there an increasing acceptance that cortical and subcortical regions involved in processing language are also involved in other cognitive and sensory-motor domains traditionally considered to be nonlinguistic. In this chapter we review the organization and anatomy of language, focusing on the crosstalk among language components (speech production, speech perception, speech comprehension) and among functional systems.

## Language networks: above and beyond compartmentalization

The identification of the brain regions and fiber pathways involved in the production, perception, and comprehension of language is a fundamental problem in neuroscience. As discussed, historically the focus has been on two functional "centers" for language in the brain: Broca's area for production and Wernicke's area for comprehension, with the arcuate fasciculus fiber pathway connecting the two regions. The compartmentalization of language into independent "modules" is unfortunate, as it gives the inaccurate impression that the different processes leading to language occur serially, or at least without much interaction. In this section, we review the neural organization of speech production, and of speech perception culminating with language understanding. Special emphasis is placed on the overlap of the brain mechanisms that implement these various levels of language processing.

### *The production of speech*

Speech production is an exquisitely complex and multistage process. It begins with a (prelexical) intention to communicate, continues to the translation of this message into lexical units (words) which in turn need to be temporally ordered (sequenced) and encoded phonologically [56a]. These processes together conclude with the production of words. This final output stage is inherently quite complex in its own right, as it demands the close coordination of multiple sensory and motor components, including the respiratory system (which generates the power source necessary to produce speech), the laryngeal system (which converts the airflow into a sound by setting the vocal folds in vibration (i.e., *phonation*), and the articulatory system (which changes the configuration of the vocal tract to convert the laryngeal output into sequences of vowels and consonants). Hence, the neural architecture for speech production is extraordinarily complex, including multiple cortical and subcortical control centers, six cranial nerve fibers and their associated nuclei (facial, hypoglossal, trigeminal, glossopharyngeal, vagus, and accessory), a substantial number of muscles covering the abdomen, neck, face, mouth and larynx, and an even larger set of sensory receptors in joints, tendons and muscles. And yet, despite this complexity, the chain of events that leads to the production of speech occurs within several hundreds of milliseconds. Indeed, mature speakers may produce as many as 14 phonemes per second, i.e., between six and nine syllables per second [53].

Some of the neural mechanisms for speech production have been elucidated, but a number remain poorly understood. One of the reasons for this is that imaging the brain during speech production comes with a number of challenges that are not present for studies of receptive language. This is particularly true for electroencephalography (EEG) and functional magnetic resonance imaging (fMRI), which are susceptible to movement correlated signal, or (in the case of fMRI) magnetic field variations resulting from motion [10]. Structural MRI looking at brain lesions and their impact on behavior does not present these problems, and data collected using this methodology have led to reevaluation of long accepted beliefs about how the brain coordinates speech production. For example, in 1996, Dronkers and colleagues [24] showed that, in a group of 25 patients with articulatory planning deficits (i.e., apraxia of speech), all patients had a lesion in the insular cortex, but not all had a lesion in Broca's area. This finding demonstrated that Broca's area is not the only cortical center important for speech production.

Recent solutions to the problem of movement for fMRI, including sparse-sampling imaging protocols (e.g. [42]), have provided data that are consistent with Dronkers and colleagues. These studies also suggest a prominent role for the insula in speech production [66, 72, 11, 71]; for a review, see [2]). Additional brain regions are also implicated for single word repetition and more complex word generation tasks. These include the primary sensory and motor areas of the precentral and postcentral gyri and sulci, the inferior frontal gyrus, the ventral premotor cortex, the medial motor areas (cingulate motor area, supplementary and pre-supplementary motor areas), the insula, basal ganglia and the cerebellum (e.g. [66, 97, 37, 1, 88, 89, 3]). The idea that the machinery for speech production is "special", i.e., that it is specialized for the specific task of producing syllables and words, has been advocated for at least a generation [57, 99]. However, recent evidence supports the opposite view, namely that a general sensory-motor system is involved in multiple tasks, including speaking, swallowing and other oro-facial movements [75, 12, 89].

With new data come new theoretical models, and a growing number of models of language production are now taking into account the neural complexity inherent to speech production. For example, Riecker et al [72] have proposed a dual system for speech production, with a *preparatory* loop including the supplementary motor area, insula, superior cerebellum, and dorsolateral frontal cortex, and an *executive* loop including the primary motor cortex, thalamus, basal ganglia and inferior cerebellum. Guenther and colleagues [43, 44] have proposed a detailed model of speech production (DIVA) that focuses on the role of sensory feedback (auditory, somatosensory) in speech acquisition and production. The model links superior temporal areas to inferior parietal and inferior frontal areas, and includes a contribution of the cerebellum to feed-forward modeling for speech production. As the authors acknowledge, at the neurobiological level, DIVA is incomplete and requires additional data. Despite it shortcomings, however, DIVA and other models are trying to account for an astounding complexity of neural processes that implement the production of speech, and the full model will need to take into account all aspects of language, including detailed speech planning and production mechanisms as well as comprehension mechanisms.

In sum, it is clear that the neural architecture of speech production reflects the inherent complexity of this process, and goes far beyond the so-called Broca's area, involving multiple cortical and sub-cortical domain-general control centers.

## *The perception and comprehension of speech: from acoustic waves to meaning*

Although speech perception is often described as the processing of the sub-lexical units that form the speech stream (i.e., syllables, phonemes), the ultimate goal of speech perception is to comprehend language and to communicate. In this section, we review what is known about the neurobiology of both perception and comprehension.

The first neural signals relevant for speech originate in the inner ear and proceed via the vestibulo-cochlear nerve (auditory nerve; eighth cranial nerve) to the brainstem, then to the inferior colliculus of the midbrain, to the medial geniculate nucleus of the thalamus, and, finally, to the primary auditory cortex located within the transverse temporal gyrus of Heschl. Despite numerous sub-cortical relays, electrophysiological recordings demonstrate that the first cortical manifestations of sounds are promptly observed, approximately 50–200ms after stimulus onset. The primary auditory cortex (A1) receives tonotopically-organized projections from the thalamus (see, for example Hackett, [45], for a review) and is, in turn, also organized tonotopically, with higher frequencies located more medially. The tonotopy of A1, however, is more diffuse than that of the inner ear, suggesting that frequency analysis is completed in the lower levels of the auditory pathway. Moreover, brain imaging studies have shown that the primary auditory cortex responds to the presentation of speech sounds, but no more so than to the presentation noise bursts with similar acoustic properties, suggesting that A1 is not specialized for the processing of speech [98].

From the primary auditory area, the auditory signal is sent to auditory association areas. There are currently two main accounts of how the sounds travel from A1 to be further processed. Rauschecker and colleagues have proposed that there exist a ventral route and a dorsal routes for sound processing. According to this view, a ventral auditory route is involved in auditory object identification and in speech perception [69] leading to the term auditory "what"-stream [70]. The ventral route includes A1 as well as anterior superior temporal gyrus (aSTG), a region that has been shown to be sensitive to "voice" [8, 9] and to vowels [64], and a portion of the inferior frontal gyrus (pars opercularis and triangularis) [69]. This account also postulates a dorsal stream, involved in spatial processing of sounds, in both monkeys and humans, which has been referred to as an auditory "where"-stream [70]. This route includes A1, the planum temporale (PT), which lies immediately posterior to the transverse temporal sulcus on the superior temporal plane, the posterior parietal areas, and ends in the premotor and prefrontal cortex (corresponding to Brodmann's areas 6 and 8) [68]. Within this route, the inferior parietal lobule and superior frontal sulcus are most responsive to spatial information, while PT responds to spatial information just as much as it responds to non-spatial information, providing partial support for the existence of a auditory "where"-stream [4].

Hickok and Poeppel [48, 50, 51] have also proposed a dual route system for language. According to this view, all sounds first undergo spectral and phonological analyses in the dorsal STG and posterior STS. From there, the processing of sounds diverges into a dorsal route for auditory-motor transformation, and a ventral route for auditory language comprehension. The dorsal route is involved in auditory-motor transformations, articulation, and speech perception. This route includes connections from PT to the PMv, pIFG and insula. According to Hickok and Poeppel, PT, rather than being involved in spatial processing as suggested by Rauschecker et al [70], is a key component of the auditory-motor transformation process. A body of evidence originating mainly from brain imaging experiments supports this hypothesis. For instance, brain imaging studies have shown that PT is active during overt speech production [95, 97, 87, 11, 71], but also during silent speech production or speech rehearsal, which does not involve self-generated auditory feedback [14, 97, 49, 17]. Furthermore, it has been shown that the caudal part of PT is more strongly active for sub-vocal rehearsal of auditory stimuli than for the perception of auditory stimuli (e.g., [14, 49]), suggestive of a role in auditory-motor transformation. Thus, whereas the ventral-dorsal model of Rauschecker and colleagues focuses on localizing and identifying sounds in general, the ventral-dorsal model of Hickok and Poeppel proposes a dorsal route for speech perception, and a ventral route for semantic processing and speech comprehension.

Investigations of processing routes for language have revealed an extensive overlap in the neural basis of speech production and speech comprehension. For example, it has been shown that passive listening to syllables and phonemes activates frontal motor regions within and around the ventral precentral sulcus, in the region controlling mouth movements [94, 68, 93]. Passive watching of videos of a speaker telling a story also activates the ventral premotor cortex (PMv), more so than listening to the same stories without seeing the talker, suggesting a role for the premotor cortex in recognizing the talker's articulatory gestures [81]. TMS studies have revealed that stimulation of the left primary motor cortex in the region controlling the face during both passive speech listening and viewing results in the enhancement of motor-evoked potentials (MEP) recorded from the lips or tongues [33, 82, 90, 91]. Furthermore, when applied to the PMv, TMS interferes with the discrimination of speech sounds presented in noise [61]. In sum, brain imaging and TMS findings indicate a role for the PMv and adjacent pIFG—typically implicated in speech production—in speech perception. The current debate centers around whether these motor speech mechanisms are essential for, or simply supportive of, speech perception. More recent data suggests recruitment of motor cortex during perception when speech is difficult to understand, but not when it is easy to understand. For example, repetitive TMS to PMv has no effect on participants' ability to perceive/categorize speech sounds in the absence of ambient noise [82, 76], suggesting that involvement of PMv may not be critical for speech perception under many natural circumstances, but that it may have a contribution under difficult situations, for instance, in a noisy environment, or while performing a difficult phonological task.

The sounds of speech form words, which in turn form sentences, which in turn lead to comprehension of the message of a speaker. Although this process seems straightforward, in reality it is difficult to clearly determine where speech perception ends and language comprehension begins. Nevertheless, a general organizational principle appears to be that more posterior temporal regions are involved in sound processing while anterior and inferior temporal regions are involved in semantics and language comprehension processes. For instance, according to the dual route model of language proposed by Hickok and Poeppel [48, 50, 51], all sounds undergo spectral and phonological analyses in the dorsal and mid posterior superior temporal sulcus (STS). These analyses are followed by access to semantic representations through a lexical interface involving the posterior part of the middle temporal gyrus (pMTG) and inferior temporal sulcus (pITS). Higher aspects of syntactic and compositional semantics (for instance, sentence level semantics) involve the anterior MTG and aSTG. In addition to temporal sites, there is also evidence from brain imaging and brain stimulation studies that the anterior inferior frontal gyrus (aIFG) may also be involved in semantic processing. Petersen and colleagues [65] were among the first to show, using positron emission tomography (PET), that word generation activates the aIFG more strongly than less semantically taxing tasks such as word repetition, suggesting a role in semantic processing for this region. A number of fMRI studies show that when response selection during language tasks relies on semantic processing, the aIFG is activated [52, 3, 88, 89]. Moreover, Devlin et al [22] demonstrated using transcranial magnetic stimulation (TMS) that stimulation of the aIFG results in delayed performance on a semantic decision task, but not on a perceptual decision task. Similarly, Gough et al [41] showed that TMS to the aIFG leads to delayed behavioral performance during a synonym judgment task, but not during a homophone judgment task. Taken together, these studies suggest that the aIFG is involved semantic analysis.

Adding to the complexity of semantic processing in the brain, according to advocates of "embodied semantics," is the observation that understanding the meaning of action words and sentences also recruits motor circuits required to produce that action. By analogy with the macaque, this process is thought to involve mechanisms analogous to those involving mirror neurons. Mirror neurons are individual neurons that respond to both action execution and action observation [23, 38, 73]. In the macaque, neurons with this dual property have been found in the ventral premotor cortex (area F5) and in the inferior parietal lobe. Several brain-imaging studies have shown activation in primary motor and premotor cortex during passive language tasks (e.g., [46, 85, 6]). Brain stimulation experiments have also shown somatotopic modulation of the motor cortex during the processing of sentences [15], and words [67].

Taken together, these results suggest that the motor system may contribute to language comprehension, although it is possible that activation in motor areas during language tasks is not critical for semantic analysis of linguistic stimuli, but instead represents an associational discharge that is not causal to comprehension [58].

As we have seen in this section, the neural basis of speech perception and auditory language comprehension involve a number of components spanning most of the neocortex. We have shown that while speech production, perception and comprehension are associated with some distinct regions, they also exhibit a large degree of overlap.

## *Fiber pathways important for language*

The previous section demonstrates that a large number of brain regions are active during speech production, speech perception and language comprehension, thereby revealing the remarkable complexity of the neural architecture of language. But with the growing consensus that language is distributed into large-scale cortical and subcortical networks [62], there has also been an increasing focus on hodology [34], or how brain regions within this distributed network are connected by particular fiber pathways. That is, there is a renewed acknowledgement that connectivity provides critical insights into function. This focus has been driven by investigations using diffusion tensor imaging (DTI) and intraoperative electrical stimulation in humans, and anterograde tract tracing in the rhesus monkey. These three methods provide both conflicting and complementary information about the fiber pathways important for language. Studies using these methodologies have suggested six fiber pathways that are potentially important for language (Fig. 1B). These are (1) the third subcomponent of the superior longitudinal fasciculus (SLFIII); (2) the arcuate fasciculus (AF); (3) the middle longitudinal fasciculus (MdLF); (4) the inferior longitudinal fasciculus (ILF); (5) the uncinate fasciculus (UF); and (6) extreme capsule (EF).

### *Fiber tract identification in the human: diffusion tensor imaging (DTI) and intraoperative electrical stimulation*

Historically, the examination of fiber pathways in the human has been accomplished with gross dissection methods in the postmortem brain [21, 19]. More recent methods allow examination of the living brain, and considerable effort has been expended to map the cerebral fiber pathways *in vivo* using diffusion tensor imaging (DTI; [63]). The DTI method takes advantage of the anisotropic (directional) nature of diffusion of water molecules in neural fibers, which can be measured with a specific MRI pulse sequence. Because water molecules flow along the direction of the fiber paths, the measure of fractional anisotropy (a measure of diffusion anisotropy) is higher in white matter than in gray matter. Further, the direction of fractional anisotropy can be traced across voxels to map fiber pathways, a procedure known as tractography [7]. This procedure has been used to map long association fiber pathways thought to be involved in language.

Several pathways for language that have been identified in the historical literature (e.g., SLF, AF) have been investigated using DTI [18, 40], and additional pathways have been defined. For example, Makris and colleagues [59] recognized three components of the SLF, which they also distinguished from the AF. They argued that the third SLF subcomponent, SLFIII, which may connect the posterior inferior frontal gyrus with the supramarginal gyrus of the inferior parietal lobe, is involved in the articulatory component of language. This function is typically associated with the AF, classically thought to connect Broca's and Wernicke's areas [29]. Instead, Makris et al argued that the AF connects the posterior temporal cortex with more dorsal frontal cortex, and might be involved in localizing the source of auditory information in space. Thus, it is not, strictly speaking, a language pathway. This dissociation of the AF and SLF fibers is also supported by more recent DTI studies [35, 74, 77].

Additional language pathways identified by DTI include the extreme capsule, middle longitudinal fasciculus (MdLF), and inferior longitudinal fasciculus (ILF; [35, 77]). For example, in their fMRI/DTI study, Saur and colleagues [77] provided evidence that repetition of pseudowords was associated with SLFIII and AF pathways, in conjunction with the MdLF (coursing the length of the superior and middle temporal lobe). This comprised a "dorsal route" involved in auditory-motor representation of speech sounds. Mapping sounds to meaning, indexed by sentence comprehension, was associated with the MdLF, the extreme capsule (connecting the anterior inferior frontal cortex with the anterior superior temporal cortex) and the ILF (coursing the length of the inferior temporal lobe). This comprised a "ventral route" of semantic processing. These findings provide evidence for the relevant fiber pathways that connect the brain regions comprising the "dorsal" and "ventral" language routes discussed earlier (cf. [48, 50, 51]).

Despite these advances in understanding fiber pathways in the human brain, DTI tractography has some serious shortcomings that are often minimized or ignored in the literature [5, 86]. First, in order to perform tractography, a seed region of interest (ROI) must be selected. Thus, DTI begins with anatomical knowledge derived from postmortem studies, and requires *a priori* hypotheses about the course of the fiber tract. Such hypotheses are based on potentially erroneous conclusions of earlier histological and dissection preparations, leading to the perpetuation of such errors into the DTI literature [78]. DTI also assumes that a single diffusion tensor defines each voxel, but this assumption is invalid where grey/white matter or white matter/cerebrospinal fluid overlap (i.e., partial volume averaging) and in cases where there are crossing fiber tracts. Pixels with partial volumes or crossing fibers will appear hypointense, and such errors accumulate along the length of the trajectory path [55, 84]. These issues can lead to several problems, including the premature termination of a fiber, the identification of nonexistent fiber tracts, or the misidentification of two or more fiber tracts as one tract [5]. Methods are being developed to deal with some of these issues (e.g., diffusion spectrum imaging to deal with crossing fibers; [80, 92]), but it remains important to consider the conclusions of DTI studies in light of those reached using other methodologies.

In addition to DTI, extensive studies of the fiber pathways connecting brain regions involved in language have been conducted using intraoperative electrical stimulation [28, 29, 30, 31, 32, 47, 60]. This technique, used during surgery of awake patients, involves stimulating, with an electrode, certain areas of exposed white matter during performance of a task ([83] for a review of the method). If the electrical stimulation results in disruption of a particular task (e.g., picture naming, counting), the pathway is determined to be involved in that task. Thus, electrical stimulation provides information about the function of the pathway, which is information that DTI by itself cannot provide.

These studies have generally supported the DTI findings, suggesting that the more dorsal pathways (i.e., SLF and AF) are involved in phonological and articulatory processes, and the more ventral pathways are involved in semantics (i.e., fiber pathways of the inferior temporal lobe). For example, electrical stimulation of the white matter under the inferior frontal, inferior parietal, and posterior superior temporal cortex results in phonemic paraphasias (i.e., mispronunciation; [28]) and also speech arrest [28, 29]. With respect to semantic processing, electrical stimulation of white matter coursing the inferior temporal cortex induces semantic paraphasias in response to a picture naming task (i.e., instead of labeling the target picture, the patient responds to the picture with words that are either in the same category as the target picture, that are antonyms of the target, or that have associative or functional proximity to the target). The induction of semantic paraphasia occurs across the extent of the pathway (beneath occipito-temporal, insular, and frontal cortex; [31, 60]). Stimulation of a third pathway connecting the anterior temporal lobe with the orbitofrontal cortex, the UF, did not result in any deficit in semantic processing [32]. Interpretation of this null finding, though, should proceed with caution. Due to its connectivity with the anterior temporal lobe, it is possible that the UF is involved in other linguistic functions, and that the semantic task used in this study (i.e., picture naming) has insufficient sensitivity to detect the function of this pathway. Therefore, the status of the UF as a language pathway remains an open empirical question.

Notably, although Duffau and colleagues [30] proposed a distinction between the ILF and a putative inferior occipital-frontal fasciculus (IOFF) connecting the occipital cortex to the frontal cortex, the existence of such an uninterrupted occipital-frontal pathway is disputed by recent investigations using anterograde tract tracing in the rhesus monkey [78], which we discuss in the next section.

Intraoperative electrical stimulation has both advantages and disadvantages for identifying fiber pathways involved in language. A major advantage is the precision of the method, in both spatial and functional terms—i.e., the method can identify, *in vivo*, areas of white matter that are necessary to accomplish certain linguistic tasks to a degree that surpasses what can be learned from more gross lesions of the same pathways. But a major limitation is that there is no way to determine, with certainty, the origin and termination sites of the fiber pathways. Tract tracing methodologies using radioactive tracers are the only available methods for reliably identifying the origin and termination sites of fiber pathways, but their use is limited to animal studies.

## Fiber tract identification in the rhesus monkey: anterograde tract tracing

The anterograde tract tracing method takes advantage of the orthograde transport (transport away from the cell body) of radioactively labeled substances along the axon. Injection of radioactive compound in an animal brain is followed by histological analysis of the tissue, revealing both the labeled fibers and their terminations [54]. Recently, Schmahmann and Pandya [78] conducted a comprehensive study of fiber pathways of the rhesus monkey brain. Based on the proposed correspondence of homologous regions of the monkey and human brain, these authors identified the SLF III, the extreme capsule, and the MdLF as important fiber pathways for language. Notably, two prominent fiber pathways that have been identified using other methods are missing from this list. The first is the IOFF, and its very existence as a distinct fiber path is disputed by the rhesus data. Schmahmann and Pandya instead argue that the rostral extension of the ILF is in reality the UF and the extreme capsule fiber pathways, and that these three fiber pathways comprise what is thought to be the IOFF. More pertinent to both historical [21, 39] and contemporary [26, 27, 32, 36, 40] investigations of language, though, is the proposal that the AF is not a language pathway. The rhesus data instead suggest that the AF links caudal temporal cortex with dorsal and lateral prefrontal regions that are more distal to the classic perisylvian language cortex of the frontal lobe. These findings complement some of the human DTI work (e.g., [35, 59, 74, 77]), but are in conflict with findings from the postmortem dissection and electrical stimulation studies. Given the prominence of the AF for language, these discrepant findings suggest interesting avenues for future research.

Although anterograde tract tracing has the advantages over the other methods in that (1) it can reliably identify origin and termination sites for distant fiber pathways, and (2) it allows a precision that is not approached by other methods, the major disadvantage is its restriction to use in animals, which limits its utility for studying language. That said, much can be gained from considering the three methods in complement.

## Summary of fiber pathways for language

In summary, the available evidence seems to be converging on the involvement of several fiber pathways for language (Fig. 1B). The pathways we have discussed exclude those additional cortico-striatal, cortico-thalamic, and cortico-pontocerebellar pathways likely involved in the execution of speech (reviewed elsewhere in [30, 79]). However, for speech perception and comprehension the core pathways connect the inferior frontal, inferior parietal, and superior and middle temporal cortices. These include the SLF, MdLF, extreme capsule, and the ILF. Whether the SLF pathway can be identified as two pathways—an SLFIII and AF pathway—and whether both the SLFIII and AF participate in language, is a matter of debate. The status of the UF as a language pathway also awaits additional investigation. Further debate centers on the status of an uninterrupted pathway through the ventral temporal cortex connecting occipital, temporal, and frontal regions, potentially involved in semantic processing (i.e., the IOFF). The relevant monkey data suggest that this pathway may in fact be comprised of the dissociable ILF, UF, and extreme capsule fiber paths.

## Conclusion

To summarize, in this brief survey of current thinking on the neurobiological basis of language, we suggest that language, which is one of the most celebrated higher functions of the human brain, is deeply rooted in distributed networks that work in synchrony to perceive, produce and comprehend language. We summarize literature that demonstrates that many of the regions involved in any of these levels of organization (i.e. perception, production and comprehension) are typically also involved in the other levels, and that with modern tools and analytical methods, it is no longer necessary to investigate individual levels in isolation from the others.

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