

PART III

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ARTICULATION AND
PRODUCTION
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CHAPTER 15

NEUROMOTOR ORGANIZATION OF SPEECH PRODUCTION

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INTRODUCTION

THE act of speaking is a complex and integrative behavior, which associates high-level cognitive and linguistic processes with fine motor-control mechanisms. Speaking begins with an intention to communicate, continues to the translation of the message into lexical units (words), which in turn need to be broken down into sequences of temporally ordered syllables and adjusted to the context in terms of rhythm, loudness, and prosody. The final stage requires the coordination of multiple sensorimotor systems, including the respiratory system, which provides the airflow necessary to set the vocal folds into vibrations, the intrinsic and extrinsic laryngeal muscles that convert this airflow into phonation, and, finally, the supralaryngeal muscles that modulate the configuration of the vocal tract to convert the laryngeal output into vowels and consonants (articulation). Speaking also requires the interaction of sensorimotor mechanisms with linguistic processes including grammatical, syntactic, and semantic processes, as well as cognitive/executive processes such as verbal memory and audiovisual attention. In spite of this remarkable complexity, adult speakers are able to produce as many as six to nine syllables per second (Kent, 2000). Perhaps given this extraordinary speed and complexity, the manner in which this process is accomplished at the neural level has not been fully elucidated. Historical models of spoken language production have focused on a single region for speech production (“Broca’s area”) and a single region for comprehension (“Wernicke’s area”), and a single white matter pathway connecting these regions (the arcuate fasciculus). The complexity of the sensorimotor processes supporting

articulation has thus been minimized, and is often represented as a “final-output stage” black box within serial and compartmentalized models of language (for a discussion of this topic, see Tremblay & Dick, 2016). More recently, advances in brain imaging and brain stimulation techniques have contributed tremendously to uncovering the sophisticated neural system that underlies the production of speech. The seminal meta-analysis conducted by Indefrey and Levelt (2004) was among the first to highlight the complexity of the cortical network underlying word production. More recent analyses of functional connectivity support the notion of a highly distributed network (Simonyan, Ackermann, Chang, & Greenlee, 2016; Simonyan & Fuertinger, 2015). Here we propose, in Figure 15.1, an overview of the cortico-subcortical network that underlies speech production from phonological planning to articulation. In this chapter, we review and discuss the most up-to-date knowledge on speech production, from phonological planning to motor execution, with an emphasis on functional neuroanatomy and anatomical connectivity.

PHONOLOGICAL PLANNING FOR SPEECH PRODUCTION

Phonological planning refers to the specification of the abstract phonological representations that are used during speech production. It is preceded by conceptual, lexical, semantic, and syntactic processes, and followed by motor planning, thereby representing an interface between the cognitive and the motor dimensions of speech production. The mechanisms underlying phonological planning have been studied intensively (Cholin, Levelt, & Schiller, 2006; Costa & Caramazza, 2002; Damian & Dumay, 2007; Dell & Reich, 1981; Jescheniak, Schriefers, Garrett, & Friederici, 2002; Meyer, 1990, 1991; Roelofs, 1999; Schiller, Bles, & Jansma, 2003; Schnur, Costa, & Caramazza, 2006; Shattuck-Hufnagel & Klatt, 1979; Treiman, 1985; Wheeldon & Lahiri, 1997). According to several prominent models, the phoneme and the syllable are the basic phonological units necessary to produce fluent speech (Bohland, Bullock, & Guenther, 2010; Dell, 1986; Indefrey & Levelt, 2004; Levelt, 1992, 1999; Levelt & Wheeldon, 1994; MacNeilage, 1998; Roelofs, 1997; Tourville & Guenther, 2010). During phonological planning, phonological encoding processes are called upon to build a word’s phonemic and syllabic codes from abstract linguistic representations containing conceptual, semantic, and syntactic information.

Most models of speech production assume that phonological planning involves the serial retrieval of phonemic- and syllabic-level information for items that are to be produced (e.g., Bohland et al., 2010; Hickok, 2014; Indefrey & Levelt, 2004; Van der Merwe, 2009). Indefrey and Levelt (2004) propose that the phonological word forms are built online through a segment-by-segment internal syllabification process, a process associated with the left inferior frontal gyrus (IFG). According to the GODIVA model

AQ: “According to the GODIVA model (Bohland et al., 2010)—an extension of the well-known DIVA model . . .” If an acronym, please provide full form (also for DIVA).

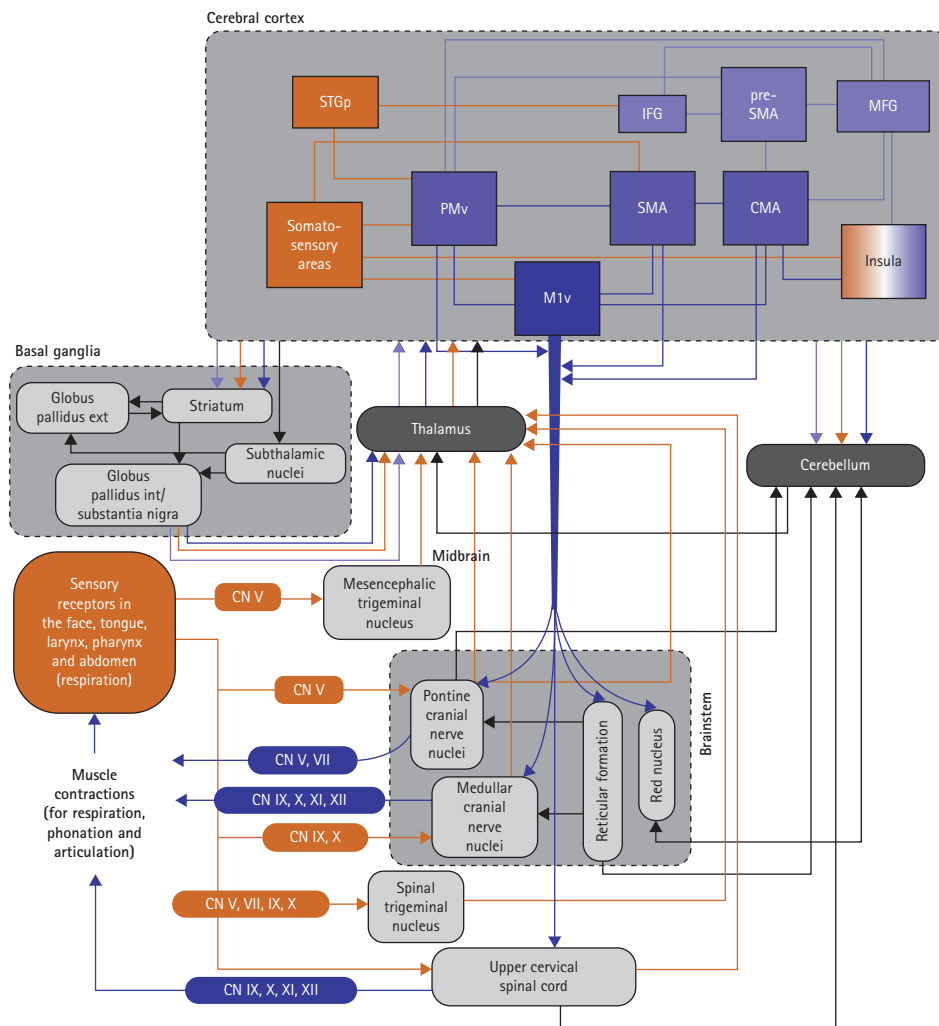


FIGURE 15.1. Schematic representation of the neurocognitive organization of speech production. Blue lines denote connections predominantly conveying motor information. Orange lines denote connections predominantly conveying sensory information. Purple denotes connections predominantly conveying cognitive/linguistic (higher-order) information. For simplicity, the thalamus, cerebellum, and striatum were not subdivided into their subcomponents, and connections between specific cortical areas and these structures are also not included. Lines with arrows indicate the direction of the information flow. Lines without arrows indicate bidirectional connections.

Abbreviations: Globus pallidus ext: external globus pallidus; Globus pallidus int: internal globus pallidus; STGp: posterior superior temporal gyrus; PMv: ventral premotor cortex; CN: cranial nerve; IFG: inferior frontal gyrus; SMA: supplementary motor area; CMA: cingulate motor area; MFG: middle frontal gyrus.

(Bohland et al., 2010)—an extension of the well-known DIVA model—phonemic codes and syllabic position specification are computed within the left inferior frontal sulcus, whereas syllabic frame specifications (i.e., abstract structure above the phonemic level) are associated with the pre-supplementary motor area (Bohland et al., 2010; Guenther, 1995, 2006; Guenther, Ghosh, & Tourville, 2006b; Tourville & Guenther, 2011). The notion that phonological planning is accomplished in a two-step fashion (operating serially or in parallel, depending on the speech production model) is supported by a few functional neuroimaging studies that have focused either on specific phonological representations or on the mechanisms involved in building a word's phonological form. For instance, in a recent functional magnetic resonance imaging (fMRI) experiment, Markiewicz and Bohland (2016) investigated, using multi-voxel pattern analysis (MVPA), whether the response patterns (i.e., hemodynamic response) of specific cortical areas predicted the linguistic class (i.e., phonemes and syllables) of the stimuli during the production of Consonant-Vowel-Consonant (CVC) syllables. The authors identified numerous regions spanning across both the left and right hemispheres in which predictive phoneme and/or syllable information was found. Of particular interest is the finding that the left inferior frontal sulcus was among the regions whose activation pattern was predictive of phoneme level information, consistent with the GODIVA model of speech production (Bohland et al., 2010). Syllable-level predictive information was found in numerous regions, including the left ventral premotor cortex (PMv) and motor cortex, as well as the left posterior superior temporal gyrus (STGp), and the right posterior superior temporal sulcus. Similarly, Peeva and colleagues (2010), using an fMRI repetition-suppression paradigm (Grill-Spector, Henson, & Martin, 2006; Grill-Spector & Malach, 2001), also identified the left PMv as a region that responds to syllabic complexity during speech-production, suggesting a role for this region in the encoding of entire syllables, perhaps through speech sound maps that represent syllabic motor programs, as proposed in the DIVA model (Guenther, Ghosh, & Tourville, 2006a). The authors also identified regions that specifically responded to phonemic complexity (the left supplementary motor area, the left globus pallidus, the left posterior superior temporal gyrus, and the left superior posterior lateral cerebellum).

Other functional neuroimaging studies have manipulated psycholinguistic variables during speech production (i.e., picture naming, reading, and spoken word/nonrepetition) to target phonological encoding mechanisms, including phonological neighborhood density, and syllable and word frequency (Acheson, Hamidi, Binder, & Postle, 2011; de Zubicaray, McMahan, Eastburn, & Wilson 2002; Indefrey & Levelt, 2000; Papoutsis et al., 2009; Peramunage, Blumstein, Myers, Goldrick, & Baese-Ber, 2011; Vihla, Laine, Matti, & Salmelin, 2006). These studies have found that one region—the posterior superior temporal cortex (including the posterior segment of both the superior and middle temporal gyri)—is sensitive to these manipulations, suggesting a role for this region in phonological planning (i.e., mechanisms involved in encoding a word's phonological form).

In sum, neuroimaging experiments suggest that both the syllable and the phoneme are used during phonological planning for speech production. While many issues remain

regarding the networks involved with the implementation of syllabic- and phonemic-level processes during phonological planning in speech production, empirical evidence suggests that regions distributed across the frontal and temporal lobes are involved in phonological planning. Recent promising developments of neurocomputational models of speech production (e.g., Bohland et al., 2010; Hickok, 2012) will allow researchers to test specific predictions regarding the implementation of phonological planning mechanisms.

MOTOR PLANNING/PROGRAMMING FOR SPEECH PRODUCTION

Speech motor planning builds upon phonological planning and possibly proceeds simultaneously. There is general agreement that the output of phonological encoding is a phonological word, in which metrical, syllabic, and segmental properties are specified. However, models of speech production differ in terms of the output of phonological planning, with some positing that the phonological form is pre-syllabified, and others postulating that syllabification occurs within the sensorimotor system. In either case, motor preparation for speech ~~actions precedes the action itself and~~ involves several steps, including response selection, motor timing, and sequencing processes. This speech motor preparation process, often globally referred to as “supra-motor” or “motor cognition” (Freund, Jeannerod, Hallett, & Leiguarda, 2005), may not be speech specific and may have evolved from more general motor functions. Thus, the system “[. . .] gets what service it can out of organs and functions, nervous and muscular, that have come into being and are maintained for very different ends than its own” (Sapir, 1921, p. 8). Several steps in this motor-planning process are specified in specific neural systems, which are reviewed in the following. There is a growing consensus in the field of speech motor control that speech motor programs for well-practiced sounds are stored within the left PMv, as proposed in the DIVA model ~~of speech production~~ (Guenther, 2006). Consistent with this idea, it was recently shown, using fMRI, that the process of learning new speech sequences is associated with a decline in activation in the left PMv, suggesting that individual motor programs become merged into one, thus requiring the activation of only one motor program (Segawa, Tourville, Beal, & Guenther, 2015). Similarly, a recent electrocorticographic study conducted in awake patients showed that tissue adjacent to the PMv in the left IFG is active early on during auditory repetition, possibly reflecting the activation of speech motor plans (Flinker et al., 2015). It was found that activity was stronger for pseudo-words, which are not associated with motor programs, ~~compared~~ to real words, ~~which are~~. The contribution of the PMv and IFG to speech production has been notoriously difficult to untangle. In the Flinker study, activity in the precentral sulcus containing the PMv was not reported, leaving the question unanswered.

Motor Response Selection

The neural mechanism by which a phonological form is transformed into stored motor routines is often referred to as *response selection*, or sometimes, *action selection*. Though it is still not included in most neurobiological models of spoken-language production, motor response selection is a well-documented mechanism in the non-speech motor-control literature. Several neuroimaging studies have examined the process of selecting non-speech motor responses, including finger and hand movements. These studies have shown activation in the pre-supplementary motor area (pre-SMA) (Brodmann's medial area 6) that varied as a function of response selection modality (voluntary selection vs. forced selection) (Deiber, Ibanez, Sadato, & Hallett, 1996; Lau, Rogers, & Passingham, 2006; Weeks, Honda, Catalan, & Hallett, 2001). The pre-SMA is a region located in the medial aspect of the superior frontal gyrus, immediately anterior to the SMA and corresponding to the anterior part of Brodmann's medial area 6. The pre-SMA is densely connected to the prefrontal cortex, particularly the dorsolateral prefrontal cortex in the middle frontal gyrus (MFG) (Lu, Preston, & Strick, 1994; Luppino, Matelli, Camarda, & Rizzolatti, 1993), and to several non-primary motor areas, such as the SMA-proper and the PMv (Luppino & Rizzolatti, 2000), for controlling motor output. Recent data suggest that the pre-SMA is also connected to the posterior part of the inferior frontal gyrus through the frontal aslant tract (FAT) (Catani et al., 2012a; Ford, McGregor, Case, Crosson, & White, 2012). Thus, the pre-SMA has a connectivity pattern that is ideal for linking higher-level cognitive functions (including linguistic processes) and motor processes, which is critical to implementing response selection. In agreement with the literature on motor cognition, a number of fMRI studies have shown that manipulating response selection during word production modulates the pre-SMA, the neighboring cingulate motor area (CMA), and the PMv (Alario, Chainay, Lehericy, & Cohen, 2006; Crosson et al., 2001; Tremblay & Gracco, 2006; Tremblay & Small, 2011). This was also found during the selection of non-speech orofacial movements (Braun, Guillemin, Hosey, & Varga, 2001; Tremblay & Gracco, 2010). There is also evidence from neurostimulation studies that noninvasive transcranial magnetic stimulation (TMS; see Schuhmann, Chapter 5 in this volume) to the pre-SMA impairs the voluntary selection of words and non-speech orofacial movements (Tremblay & Gracco, 2009). Taken together, these results suggest that the pre-SMA plays a central role in selecting motor responses for speech production and, more generally, for all voluntary actions.

In addition to a key role for the pre-SMA in response selection, recent fMRI evidence suggests a role for the striatum, and more specifically the caudate nucleus, in response selection during speech production (Argyropoulos, Tremblay, & Small, 2013). Consistent with this observation, it has been suggested that the caudate is involved in speech planning, and more specifically sequencing speech motor responses, receiving input from both the inferior frontal sulcus and the pre-SMA (Bohland et al., 2010). The caudate also has been found to be activated in memory-driven manual sequencing tasks (Menon, Anagnoson, Glover, & Pfefferbaum, 2000), and during sequence

learning (Bischoff-Grethe, Goedert, Willingham, & Grafton, 2004), ~~suggesting of a~~ role in higher-order cognitive/executive aspects of movement preparation. The caudate has a connectivity pattern consistent with a role in motor planning rather than execution, ~~being~~ connected to prefrontal structures and not to the primary motor area (Alexander, DeLong, & Strick, 1986; Hoover & Strick, 1999; Postuma & Dagher, 2006); ~~which suggests a role in higher-order aspects of speech motor planning such as response selection.~~

Speech Motor Sequencing

One of the most distinctive features of spoken-language production is its serial ordering, that is, the organization of speech movements into precise, smooth, and coordinated temporal sequences of movements of the lips, tongue, and jaw (Lashley, 1951). Indeed, normal communicative speech consists of a continuous, connected stream of sounds. Motor sequencing is the planning of the specific sequences of movements required to produce smooth and co-articulated temporal sequences of movements of the lips, tongue, and jaw. Sequencing mechanisms are closely related to motor-timing mechanisms (see earlier discussion), which involve initiating movement sequences and timing each movement within a sequence. The production of streams of speech sounds thus requires the close coordination of sequencing and timing mechanisms. Neuroimaging and neuromodulation evidence shows that, for manual movements, motor sequencing is implemented in a complex and distributed neural network involving cortical premotor areas (SMA-proper, PMv), the cerebellum, and the striatum (caudate and putamen) (Bengtsson, Ehrsson, Forssberg, & Ullen, 2005; Gerloff, Corwell, Chen, Hallett, & Cohen, 1997; Macar et al., 2002); for example, repetitive TMS of the SMA-proper results in sequential timing disruptions in a complex finger-movement task (Gerloff et al., 1997). SMA-proper activation also occurs in tasks requiring the processing of temporal patterns (Macar et al., 2002). Consistent with the idea of a role for the striatum and other basal ganglia structures in motor sequencing, it has been shown that patients with basal ganglia disorders, such as Parkinson's disease (PD), a neurodegenerative disorder characterized by progressive loss of dopaminergic neurons in the substantia nigra, have difficulty with switching rapidly from one movement to another, reflecting a deficit in the initiation and termination of sequential movements (e.g., Agostino, Berardelli, Formica, Accornero, & Manfredi, 1992; Benecke, Rothwell, Dick, Day, & Marsden, 1987). It is also suspected that FOXP2, the transcription factor associated with impairments in articulation (Fisher & Scharff, 2009; Vargha-Khadem, Gadian, Copp, & Mishkin, 2005), affects these cortico-basal ganglia circuits (Reimers-Kipping, Hevers, Pääbo, & Enard, 2011).

For speech sequencing more specifically, a broad network appears to be involved in the process of producing sequential speech (Bohland & Guenther, 2006; Shuster & Lemieux, 2005). For example, using fMRI, Bohland and Guenther (2006) showed that several cortical regions, including the PMv, the inferior parietal lobule (IPL), the

inferior frontal sulcus, the SMA, and the pre-SMA, are sensitive to serial complexity in speech-sequence production. Peeva et al. (2010) further demonstrated a contribution of the right superior lateral cerebellum to syllable sequencing.

Other studies have shown that the anterior insula, which is functionally connected to the striatum (Postuma & Dagher, 2006), is also involved in motor timing/sequencing during finger-tapping tasks (Bengtsson, Ehrsson, Forssberg, & Ullen, 2004; Lewis & Miall, 2002). Consistent with these findings, Dronkers and colleagues (Dronkers, 1996; Ogar et al., 2006) have shown, using voxel-based morphometry, that lesions to the anterior insula are related to speech apraxia, a disorder of speech planning that affects speech sequencing. Though it is unlikely that the anterior insula is involved in either speech-specific or motor-specific processes, it is a region that is active during demanding speech tasks (e.g., Ackermann & Riecker, 2004; Bilodeau-Mercure, Lortie, Sato, Guitton, & Tremblay, 2015; Bohland & Guenther, 2006; Peeva et al., 2010). It has been suggested that the anterior insula contributes to the attention-orientation system (Corbetta, Patel, & Shulman, 2008), as well as to general executive processes involved during goal-oriented tasks (Nelson et al., 2010). It is therefore possible that the insula provides the attentional control necessary to produce precisely ordered and timed sequences, which is cognitively demanding.

In sum, while there remain several questions regarding the implementation of selection and sequencing mechanisms for speech, the available empirical evidence, though limited, suggests that sequencing for speech production relies largely upon common action-control mechanisms involving the pre-SMA, SMA, PMv, insula, cerebellum, and striatum.

Speech Motor Timing

Motor timing refers to the ability to initiate movement sequences and to time each sub-movement within a sequence. It occurs at the interface of sequencing mechanisms and motor execution. For speech, initiation corresponds to the moment at which air is expelled from the lungs; it is followed by phonation, articulation, and resonance (opening or closing of the nasal cavity by the soft palate to produce nasal and oral sounds, respectively). Several regions appear to participate in motor timing, including the SMA-proper, the pre-SMA, the basal ganglia, and the prefrontal cortex. Unfortunately, though, there is little neuroimaging data focusing specifically on the neural basis of speech motor timing. An important distinction for both the neural control systems and for assessing speech motor disorders is the manner in which movements are initiated, whether externally by sensory events, or by internal events. Motor responses initiated by external stimuli are associated with activity in the SMA-proper (Lee, Chang, & Roh, 1999; Thickbroom et al., 2000; Wiese et al., 2004), as well as in the left dorsal PM (PMd) (Krams, Rushworth, Deiber, Frackowiak, & Passingham, 1998; Lepage et al., 1999; Weeks et al., 2001). In humans, inhibition of the left PMd results in a response delay in an externally triggered choice reaction-time task, which suggests a role in the initiation of movements (Schluter, Rushworth, Passingham, & Mills, 1998). The direct

comparison of self-initiated and externally triggered finger movements reveals activation in the pre-SMA (Deiber, Ibanez, Sadato, & Hallett, 1996; Jenkins, Jahanshahi, Jueptner, Passingham, & Brooks, 2000; Tsujimoto, Ogawa, Tsukada, Kakiuchi, & Sasaki, 1998), which suggests that the pre-SMA may be generating internal triggers to produce actions. Using both fMRI and electroencephalography (EEG), it has been shown that the pre-SMA/SMA-proper is involved in preparing sequences of finger movements with high demands on ordering (sequencing), while the dorsolateral prefrontal cortex is involved in preparing sequences with high demands on temporal precision and timing, suggesting distinct roles for these regions in movement preparation (Bortoletto & Cunnington, 2010). Comparing self-initiated sequences to sequences in which the internal order of the sub-movements was varied also points to a role for the dorsolateral prefrontal cortex in initiation and the SMA for sub-movement timing (Bortoletto, Cook, & Cunnington, 2011). These findings are supported by TMS evidence suggesting a role for the right dorsolateral prefrontal cortex in temporal preparation for finger movements (Vallesi, Shallice, & Walsh, 2007). The right dorsolateral prefrontal cortex in the middle frontal gyrus is also thought to be part of the speech preparation network (Brendel et al., 2010; Garnier et al., 2013; Riecker et al., 2005). Consistent with evidence from finger sequence paradigms, fMRI research on speech motor preparation, though limited, suggests that several regions are involved, including the pre-SMA and SMA-proper, the bilateral putamen, the bilateral thalamus, the bilateral anterior insula, and the right dorsolateral prefrontal cortex (Brendel et al., 2010). In a recent study by Long and colleagues (Long et al., 2016), a promising cortical cooling approach was used to study speech production in awake participants awaiting brain surgery. The results show that cooling of the left IFG leads to slower speech, while cooling of the primary motor cortex (M1v) leads to articulation errors. Based on these results, the authors suggested a role for the left IFG in the control of speech timing. A role for the left IFG in the planning of speech more generally was also suggested by recent electrocorticographic recordings, which demonstrated early activity in this region during an auditory word-repetition task, which was followed by activity in M1v (Flinker et al., 2015).

There is also converging clinical and imaging data for a role for the basal ganglia in motor timing, particularly movement initiation. In patients with Parkinson's disease, there is a decline in the ability to initiate movements at will. However, externally triggered actions are preserved (Cunnington, Ianssek, & Bradshaw, 1999; Freeman, Cody, & Schady, 1993; Praamstra, Stegeman, Cools, Meyer, & Horstink, 1998), which suggests a role in movement initiation for the basal ganglia, directly or through its connections with prefrontal and premotor areas. This notion is supported by fMRI studies comparing self-initiated to externally paced finger-movement sequences, which show activity in the left anterior putamen for self-initiated, but not externally paced, movements (Boecker, Jankowski, Ditter, & Scheef, 2008). For speech, Brendel et al. (2010) have shown activation of the bilateral anterior putamen during speech preparation. There is also evidence that basal ganglia dysfunction (including Parkinson and Huntington diseases) is associated with abnormal speech movement timing, including impaired movement duration (Ludlow, Connor, & Bassich, 1987), rate (Skodda, 2011; Skodda & Schlegel, 2008;

Volkman, Hefter, Lange, & Freund, 1992), and pace stability (Schmitz-Hubsch, Eckert, Schlegel, Klockgether, & Skodda, 2012; Skodda, 2011; Skodda, Flasskamp, & Schlegel, 2010, 2011; Skodda & Schlegel, 2008). The available literature therefore suggests a role for medial premotor areas (both pre-SMA and SMA-proper), prefrontal cortex, and the basal ganglia in the timing of speech actions.

Speech Motor Programming

Once selected, ordered, and precisely timed, speech movements need to be fine-tuned, which includes adjustments of velocity, muscle tone, movement range, and direction, all accomplished within specific phonetic, environmental, emotional, and social contexts. The sensory systems provide information about the initial conditions such that the motor commands for a desired outcome can be successfully achieved given the state of the vocal tract. In each language, a closed set of syllables and phonemes is available. These syllables and phonemes are stored as a set of sensorimotor routines with invariant goals and include information about the proprioceptive, tactile, and auditory feedback associated with movements. Nevertheless, adjustments to these routines are always necessary because phonemes, syllables, and words are never produced in an identical manner. Indeed, one important notion for speech production is that of *motor equivalency*, which is the capacity to achieve a movement goal in various ways, from different starting points and under different conditions. A related notion is that of *co-articulation*, which is the temporal-spatial overlap of movements associated with the production of more than one sound occurring at a single point in time (Liberman, Harris, Hoffman, & Griffith, 1957; MacNeilage & DeClerk, 1969). In every language, phonemes in the speech stream have a strong effect on the phonemes that are produced close to them (both before or after) leading to anticipatory and carryover co-articulation effects. This suggests either that motor commands for adjacent vowels and consonants are processed simultaneously, or that plans for moving the articulators (tongue, lips, soft palate, mandible) from one position to the other are established in advance. Because of the speed at which speech is produced, and the difficulty in dissociating motor programming from motor planning steps with current neuroimaging and neuromodulation techniques, little is known about the neural basis of co-articulation processes. According to the model developed by Van Der Merwe (2009), brain regions involved in speech motor programming would include the cerebellum, SMA-proper, M1, and the basal ganglia (especially the putamen), but empirical evidence still awaits, and research is ongoing to provide additional information about the neural underpinning of these important processes.

SPEECH MOVEMENT EXECUTION

Once motor planning and programming is terminated and a trigger for initiation has been generated, the execution of speech movements begins. Understanding the neural

basis of speech movement production—including both phonation and articulation—requires an understanding of the central and peripheral nervous system because both are essential to producing speech. Indeed, in addition to the complex organization in the central nervous system (CNS) that we have touched upon in the previous sections, the production of speech sounds requires the orchestration of ~100 striated and visceral muscles located in the abdomen, neck, larynx, pharynx, and oral cavity, which are innervated through six pairs of cranial nerves.

Motor commands for speech are sent to the ventral part of M1v, sometimes referred to as the final common pathway, which contains (most of) the neurons controlling the vocal apparatus (Penfield & Boldrey, 1937). From M1v, the motor commands are sent toward the relevant muscles through the pyramidal system. The pyramidal system is one of the most important efferent pathways for the control of voluntary movements, including speech. It includes two major divisions: the corticospinal and corticobulbar tracts. For speech, the primary division is the corticobulbar one, but both divisions play a part. While the corticospinal tract innervates motor nuclei located in the spinal cord, the corticobulbar tract innervates motor nuclei located in the brainstem. Motor nuclei are collections of neuron bodies in the brainstem and spinal cord that are associated with one or more cranial or spinal nerve nerves, respectively. The pyramidal system serves to connect neurons in the cortex, called the upper motor neurons (UMNs), to neurons located in the brainstem (corticobulbar) and spinal cord (corticospinal), which are called lower motor neurons (LMNs). That is, UMNs in the cortex do not directly connect to the periphery. It is the LMNs that innervate the muscle fibers located in the face, neck, and abdomen.

M1 is the cortical area that contains the largest number of pyramidal neurons (Kuypers, 1973; Murray & Coulter, 1981; Ralston & Ralston, 1985), in particular, the giant Betz cells located in cortical layer V. However, it is not the only cortical area that projects to LMNs. Indeed, anatomical studies have shown that other cortical areas contain a high density of neurons directly projecting to LMNs (for a review of the connectivity of non-primary motor areas, see Picard & Strick, 1996, 2001). These are the same regions that are directly connected to M1 through long and short association fibers: the SMA (Dum & Strick, 1991, 1996; Muakkassa & Strick, 1979), the CMA located just beneath the SMA on the dorsal and ventral banks of the cingulate sulcus (Dum & Strick, 1991; Muakkassa & Strick, 1979), the PMd and the PMv (Barbas & Pandya, 1987; He, Dum, & Strick, 1993). For example, electrical stimulation of the SMA (Fried et al., 1991; Penfield & Welch, 1951; Talairach & Bancaud, 1966) and CMA (von Cramon & Jurgens, 1983) induces vocalization and speech arrest in humans, suggesting a role in the control of phonation and articulation for these regions. This means that premotor areas have some level of direct control over the generation and control of movement, independently of M1v (Dum & Strick, 1991). Axons originating from M1v, SMA, CMA, and PMv are arranged in a fan-shaped collection of axons that is directed downward toward the brainstem. At the level of the thalamus and basal ganglia, the axons are compacted into a dense band of axons, which is known as the *internal capsule* and within which axons originating from different locations are segregated (Beever & Horsley, 1890; Dejerine, 1901). Most corticobulbar axons are located in the genu of the internal capsule, while corticospinal

axons are located in the posterior limb of the internal capsule. Because all the projections to and from the cortex go through the internal capsule, even small lesions can produce widespread motor deficits, including speech deficits, particularly if the lesion occurs in the genu of the internal capsule. Most pyramidal axons cross from one hemisphere to the other before entering the spinal cord at the level of the medulla oblongata (i.e., the pyramidal decussation). Corticobulbar axons also cross at the level of the brainstem, though there is substantial bilateral innervation of the cranial nerve (CN) motor nuclei, making the speech system fairly resistant to unilateral UMN damages. The exceptions include contralateral innervation of ventral cell groups of the motor nucleus of the facial nerve (CN VII), and the hypoglossal nucleus (CN XII).

The production of speech and voice depends upon the integrity of both the corticospinal tract, which innervates the muscles of respiration located in the abdomen, neck, and shoulder, and the corticobulbar tract, for the innervation of laryngeal and supra-laryngeal muscles (for reviews, see Jurgens, 2002, 2009). Six pairs of cranial nerves are involved: (1) the trigeminal nerve (CN V), which controls the muscles of mastication (jaw) (important for articulation) and carries general sensory information from the pharynx and anterior two-third of the tongue; (2) the facial nerve (CN VII), which controls muscles of facial expression (e.g., those controlling the lips) and eye movements; (3) the glossopharyngeal nerve (CN IX), which controls the stylopharyngeus muscle (which elevates the pharynx during speech and swallowing) and carries general sensory information from the face and posterior one-third of the tongue; (4) the vagus nerve (CN X), which controls muscles of the larynx and pharynx and carries general sensory information from the larynx; (5) the accessory nerve (CN XI), which controls the sternomastoid (head rotation and chin elevation) and trapezius muscle; and, finally, (6) the hypoglossal nerve (CN XII), which controls intrinsic and extrinsic tongue muscles (except the palatoglossus).

Another peculiarity of the speech system is that some of its components are under dual control (voluntary and autonomous). The autonomous pathway involves the anterior cingulate cortex (ACC), the periaqueductal gray matter (PAG), and the reticular formation (Jurgens, 2002, 2009; von Cramon & Jurgens, 1983). This pathway is important for the innate control of nonverbal and emotional vocalizations (e.g., crying, laughing, and moaning) (Scheiner, Hammerschmidt, Jurgens, & Zwirner, 2004). Vocalizations can also occur without a cortical intervention through the reticular formation's connection to brainstem motoneurons. Interestingly, unlike humans, other mammals lack a direct control of M1 on laryngeal motoneurons. In mammals, M1 connects to the laryngeal motoneurons indirectly through the reticular formation (Jurgens, 2009; Simonyan & Jurgens, 2003). In addition to these two pathways, it is worth mentioning that there are other connections, often called *extrapyramidal* or *indirect*, between the cortex, the reticular formation, and laryngeal motoneurons in the brainstem (see Figure 15.1 for an overview of these connections). These extrapyramidal pathways link the cortex, including M1v, premotor, and sensory areas, with brainstem nuclei, in particular the reticular formation (through the corticoreticular tract), which in turn modulate laryngeal motoneurons in the brainstem. Though the roles of these pathways have not

been completely elucidated, they would be involved in controlling posture and muscle tone, thus providing a framework upon which voluntary speech movements can take place. They may also play a role in coordinating reflect activities within different cranial nerves.

SENSORIMOTOR INTEGRATION

Sensory and motor systems for speech are constantly interacting, and sensorimotor integration is key to successful and efficient speech production. There is strong empirical evidence that the unanticipated alteration of auditory and somatosensory feedback during speech production can lead to compensatory movement adjustments, which show the importance of sensory feedback for speech motor control. Indeed, compensatory movements have been shown following unanticipated alteration of auditory feedback for pitch (Burnett, Freedland, Larson, & Hain, 1998; Jones & Munhall, 2000), and vowel formants (Purcell & Munhall, 2006a, 2006b), as well as for unexpected perturbation of lip or jaw movements (Abbs, Gracco, & Cole, 1984; Ito, Kimura, & Gomi, 2005; Tremblay et al., 2003).

Though sensory feedback is important for speech motor control, if all movement adjustments depended solely on afferent sensory (external) feedback, speech motor control would be inefficient because of the delay involved in receiving and processing this information. The speech production system therefore also relies upon predictive feed-forward processes for movement control. When a speech act is ready to be produced, a copy of the prepared motor commands, the *efference copy*, or *corollary discharge* (Sperry, 1950; Von Holst & Mittelstaedt, 1973), is sent to an internal model of the vocal tract to predict movement sensory consequences, while in parallel a copy is sent through the descending pathway to the muscles involved. The efference copy signal inhibits activation of the STGp, which results in a phenomenon referred to as *speech-induced suppression* in which the auditory cortex responds less to speaking than to hearing a recording of a similar utterance (Christoffels, van de Ven, Waldorp, Formisano, & Schiller, 2011; Eliades & Wang, 2003; Houde, Nagarajan, Sekihara, & Merzenich, 2002; Meekings et al., 2016). The internal model is useful for online movement control because the sensory consequences of a movement command can be evaluated and corrected even before external feedback has reached the central nervous system. When a mismatch is detected between expected and planned sensory consequences, an error signal is generated. fMRI studies of altered auditory feedback have shown an increased activation in the superior temporal cortex in the presence of altered feedback compared to unaltered feedback (Christoffels et al., 2011; Meekings et al., 2016; Tourville, Reilly, & Guenther, 2008), suggesting that the error signal is generated in the superior temporal cortex. Similar mechanisms would exist for the somatosensory modality as well. According to Houde and Nagarajan (2011), the signal to correct the motor commands is sent from the temporal cortex to M1v through PMv, which is connected to both somatosensory areas,

including area SII (Matelli, Camarda., Glickstein, & Rizzolatti, 1986) and the STGp (Chavis & Pandya, 1976; Schmahmann et al., 2007).

Most models of speech production acknowledge a role for both external and internal feedback in speech motor control. External feedback is **important for learning** the relationship between motor commands and their sensory consequences (the internal model), to continuously update the internal model and to detect and correct for sudden perturbations (Hickok, 2014), while internal feedback is critical for fast online adjustments.

WHITE MATTER CORTICAL AND SUBCORTICAL TRACKS AND ARTICULATION

Given the complexity of the speech production system, vast networks of fiber pathways are required to support speech processes, which can be together considered as part of three speech streams: (1) a *dorsal speech stream* also involved in speech perception and sensorimotor integration (Hickok & Poeppel, 2007; see Hickok, Chapter 20 in this volume); (2) a *ventral stream* also involved in semantic processing (Hickok & Poeppel, 2007); and (3) a *motor-speech stream* involved in the implementation of phonation, articulation, and resonance (Dick, Bernal, & Tremblay, 2014). These fiber pathways (see Figure 15.2 for an overview) include (1) long-association cortical fiber pathways, comprising the superior longitudinal/arcuate fasciculus (SLF/AF), the frontal aslant tract (FAT), and cortico-striatal fibers (including the external capsule, and fronto-striatal tract or subcallosal fasciculus of Muratoff [i.e., the Muratoff bundle]); (2) the descending motor tracts, especially the corticobulbar pathway; and (3) the cortico-ponto-cerebellar system.

Long Association Cortical Pathways for Speech Production

Superior Longitudinal/Arcuate Fasciculus

The SLF/AF is the most prominent fiber pathway associated with speech and language. Historically, the SLA/AF was proposed to connect the posterior IFG with the inferior parietal lobule (including the supramarginal gyrus) and posterior superior middle temporal gyrus/sulcus (MTG/MTS) (von Monakow, 1897; Wernicke, 1874). However, the anatomical connectivity of this pathway has been re-evaluated in recent years, and it is now thought that the SLF/AF can be differentiated into several subcomponents. For example, research in macaque suggests that the SLF/AF can be differentiated into four subcomponents (SLF I, II, III, and AF) (Schmahmann & Pandya, 2006; Yeterian,

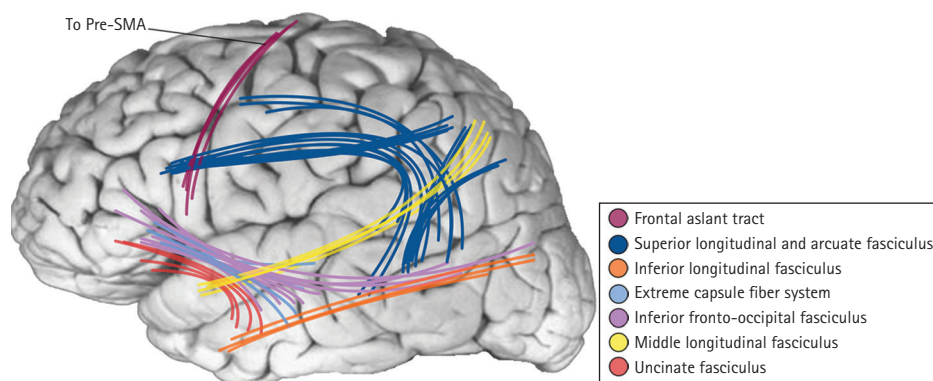


FIGURE 15.2. Long association fiber pathways of the perisylvian cortex. The superior longitudinal and arcuate fasciculus are the major fibers of the dorsal stream, while the inferior longitudinal fasciculus, extreme capsule fiber system, inferior fronto-occipital fasciculus, middle longitudinal fasciculus, and uncinate fasciculus comprise the ventral stream. The frontal aslant tract connects the pre-SMA with the pars opercularis of the IFG.

Pandya, Tomaiuolo, & Petrides, 2011). Within this parcellation, the SLF III and AF components are the components most likely involved in articulation. In the macaque, the SLF III is a parieto-frontal pathway connecting the anterior inferior parietal lobule with the PMv and posterior IFG. In contrast, the AF component is a temporo-premotor pathway thought to connect the STGp with more dorsal premotor and lateral prefrontal cortex (areas 9/46d, 8Ad, and 6d), though not to the IFG (Schmahmann & Pandya, 2006), as previously believed.

In contrast to the macaque data, however, other models based on diffusion-weighted imaging of the human brain do support direct temporo-inferior frontal connectivity in humans (Bernal & Altman, 2010; Brauer, Anwender, Perani, & Friederici, 2013; Brown et al., 2013; Catani et al., 2005; Glasser & Rilling, 2008; Makris et al., 2005; Patterson, Van Petten, Beeson, Rapcsak, & Plante, 2014; Perani et al., 2011; Thiebaut de Schotten, Dell'Acqua, Valabregue, & Catani, 2012). Given the inability of nonhuman primates to speak naturally, it is possible that the connectivity of this pathway may differ between species. In Catani's influential model, the "long (direct) segment" of the SLF connects the posterior superior temporal, middle, and inferior temporal gyrus with the IFG (*pars triangularis* and *pars opercularis*) and PMv (see Catani & Forkel, Chapter 9 in this volume). This is closer to the classical definition of the SLF/AF. Two "indirect" segments are also identified in this model: anterior and posterior. The anterior part is a fronto-inferior parietal-posterior temporal segment, and can be considered to constitute the SLF III. A posterior part constitutes a posterior temporal-inferior parietal segment (Catani et al., 2005; Martino et al., 2013).

Because of the connectivity between posterior IFG and supramarginal gyrus, the anterior component may be an important component of the articulatory loop. Electrostimulation of the white matter underneath the IFG and IPL/pSTG results in

speech arrest/articulation disturbance (Duffau et al., 2002; Duffau, Gatignol, Denvil, Lopes, & Capelle, 2003; Maldonado et al., 2011), and damage to the pathway is associated with transient dysarthria (Duffau et al., 2003; see, in this volume, Duffau, Chapter 8, and Ziegler, Schölderle, Aichert, & Staiger, Chapter 18). A number of studies have suggested that the white matter of the long segment and the anterior segment is related to speech articulation/speech fluency. For example, measures of fluency (Marchina et al., 2011; Tanabe et al., 1987) and verbal repetition (Breier, Hasan, Zhang, Men, & Papanicolaou, 2008; Fridriksson et al., 2010) in people with left hemisphere stroke are associated with white matter damage to these pathways.

The involvement of the ventral stream in speech production is less well established, but if it is involved in speech production it is likely to support semantic processing. According to a recent computational model (called Lichtheim 2; Ueno, Saito, Rogers, & Lambon Ralph, 2011), this is the presumed pathway, via the left uncinate fasciculus (UF) and left extreme capsule fiber system (EmC-fs), by which meaning is mapped to articulation. Damage to this pathway is mainly associated with deficits in naming famous faces (Papagno et al., 2011), which fits with the model's predictions. However, this proposal is disputed by another model, the Weaver++/ARC model (Roelofs, 2014). These authors suggest that the dorsal stream involvement is the primary pathway in speech production. Roelofs points to data showing that production impairments are more associated with damage to the left AF than to damage to the ventral pathways (namely, UF; Marchina et al., 2011; Wang, Marchina, Norton, Wan, & Schlaug, 2013). Another pathway that may play a role in semantic memory and semantic processing during speech production is the inferior fronto-occipital fasciculus (IFOF; de Zubicaray, Rose, & McMahon, 2011; Duffau et al., 2005; Mandonnet, Nouet, Gatignol, Capelle, & Duffau, 2007). The IFOF originates in the inferior and medial occipital lobe (and possibly the medial parietal lobe), sends projections to the ventral temporal lobe, travels through the temporal stem dorsal to the UF, and projects to the IFG, the medial and orbital frontal cortex, and the frontal pole (Catani et al., 2003). Connectivity of the temporal and frontal lobes, and its importance for speech, remains an area of intense research.

The Frontal Aslant Tract

Although it does not appear in historical atlases of white matter, the frontal aslant tract (FAT) has been recently identified using diffusion weighted imaging in humans (Broce, Bernal, Altman, Tremblay, & Dick, 2015; Catani et al., 2012b; Catani et al., 2013; Ford, McGregor, Case, Crosson, & White, 2010; Henry, Berman, Nagarajan, Mukherjee, & Berger, 2004; Kinoshita et al., 2014; Klein et al., 2007; Lawes et al., 2008; Oishi et al., 2008; Vergani et al., 2014). As shown in Figure 15.3, the FAT runs obliquely (aslant) from lateral to medial cortex, and is proposed to connect the posterior IFG, *pars opercularis*, to the pre-SMA and (to a lesser degree) the SMA-proper. This connectivity profile is consistent with a number of emerging studies of the functional association between the FAT and speech. For example, Catani and colleagues (2013) reported that reduced integrity of the FAT is associated with decreased verbal fluency in people with primary progressive aphasia (PPA). In a case study using both electrostimulation and diffusion tensor

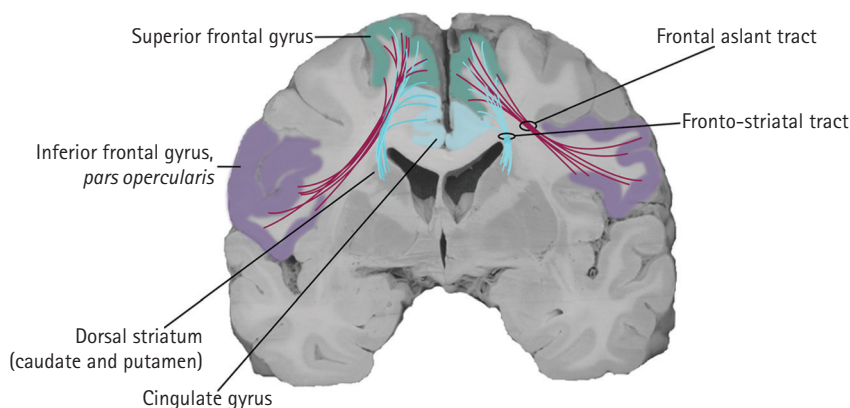


FIGURE 15.3. Connectivity of the frontal aslant and fronto-striatal tracts. The frontal aslant tract connects pre-supplementary motor area (pre-SMA) with the IFG, *pars opercularis*. The dorsal striatum (caudate and putamen) has dense connectivity with the SMA and CMA, in addition to other frontal (dorsolateral and orbitofrontal) projections not shown. Cortico-striatal connectivity is also supported by fibers of the external capsule (not shown).

imaging (DTI), Vassal and colleagues (Vassal, Boutet, Lemaire, & Nuti, 2014) showed that stimulation of the left FAT induced speech arrest, with normalization of speech occurring when stimulation stopped. Kinoshita and colleagues (2014) also used both electrostimulation and DTI in 19 participants, and showed that electrostimulation of the left, but not the right, FAT induced speech arrest. Finally, emerging evidence suggests that this tract is associated with stuttering (Kemerdere et al., 2016; Kronfeld-Duenias, Amir, Ezrati-Vinacour, Civier, & Ben-Shachar, 2016; see Ziegler, Schölderle, Aichert, & Staiger, Chapter 18 in this volume). The evidence thus suggests that the FAT is a tract that can be reliably identified, and that it has a functional relevance to the production of speech.

Fronto-Striatal Pathways: External Capsule and Subcallosal Fasciculus of Muratoff (Muratoff Bundle, or Fronto-Striatal Tract)

The medial frontal cortex makes connections with the dorsal striatum, and planning and execution of fluent speech relies on the integrity of these cortico-striatal pathways (Civier, Bullock, Max, & Guenther, 2013). There are at least two fiber bundles important for these cortico-striatal connections. Primary and non-primary motor areas connect to the posterior third of the striatum (particularly the posterior putamen), and travel mainly in the external capsule (Schmahmann & Pandya, 2006). After targeting the putamen and caudate nuclei, connections are established with the external and internal pallidum, subthalamic nucleus, and ventrolateral thalamic nuclei. The ventrolateral thalamic nuclei project back to primary and nonprimary cortical motor areas, forming the motor component (“motor loop”) of the cortico-striatal circuit. The pre-SMA, in contrast, along with prefrontal cortex, connects to more anterior parts of the striatum, also via the external capsule. From there, these regions target the internal pallidum, and

the ventral anterior thalamic nuclei, which in turn projects back to these same cortical areas, forming a cortico-striatal loop. In addition to the external capsule, the fronto-striatal tract (FST; Kinoshita et al., 2014; Lehericy et al., 2004a; Lehericy et al., 2004b), essentially the frontal component of the subcallosal fasciculus of Muratoff (Muratoff bundle), has received more recent interest. It is more easily detected in the macaque, and can be differentiated reliably from the fronto-occipital-fasciculus (Schmahmann & Pandya, 2006). Yet, Kinoshita and colleagues (2014) reported successful tractography in patients undergoing awake surgery for tumor resection, and also showed that stimulation of the pathway (namely caudate-pre-SMA connections) evokes motor initiation impairment and speech disturbances. Thus, fibers traveling in this pathway may be important for speech.

Cortico-Cerebello-Cortico Loops

The majority of the afferent connections to the cerebellum are conveyed through the middle and inferior cerebellar peduncles, while the majority of the efferent fibers travel via the superior cerebellar peduncle. Major inputs from the cortex travel via various pontine nuclei, where almost all the cortico-ponto-cerebellar fibers cross the midline in the basal pons to terminate in the contralateral half of the cerebellar cortex. The cerebellum itself projects to primary and nonprimary motor areas and to the prefrontal cortex (including the pre-SMA) through projections from the cerebellar dentate nucleus via the ventrolateral nucleus of the thalamus, which projects to the contralateral primary and nonprimary motor areas and prefrontal cortex (Salmi et al., 2010). These connections form a cortico-cerebello-cortical loop involved in the control of actions in general, including speech. Empirical studies indicate that cerebellar lesions impact speech and language function (Fiez, Petersen, Cheney, & Raichle, 1992). Fluency deficits in both semantic (category) and letter fluency tasks are observed in adult patients with focal and degenerative cerebellar pathologies (Akshoomoff, Courchesne, Press, & Iragui, 1992; Appollonio, Grafman, Schwartz, Massaquoi, & Hallett, 1993; Leggio, Silveri, Petrosini, & Molinari, 2000; Neau, Arroyo-Anllo, Bonnaud, Ingrand, & Gil, 2000; Richter et al., 2007; Schweizer et al., 2010).

Summary

Many fiber pathways support the production of speech, integrating information from large segments of the cortex, basal ganglia, thalamus, and cerebellum. The importance of the basal ganglia and cerebellum to speech production has been known for some time (Robin & Schienberg, 1990; see, in this volume, Ziegler, Schölderle, Aichert, & Staiger, Chapter 18, and Copland & Angwin, Chapter 33), but the study of the particular fiber pathways supporting the communication among these regions, using newly established methodologies such as diffusion-weighted imaging or connectivity modeling, is a more

recent phenomenon (Manes et al., 2014). What this brief review has hopefully accomplished is to reinforce that these fiber pathways should be understood as part of a distributed network supporting speech production, and attempts should be made to study them as such.

CONCLUSIONS

In this chapter, we have reviewed the neural systems that controls speech production at all levels of the nervous system, from a complex web of cortical regions such as M1v, PMv, SMA, pre-SMA, CMA, and the insula, interconnected through both short- and long-association pathways, all the way down to the cranial nerve nuclei in the brainstem through the corticobulbar tract. We have seen that loops of internal control involving the basal ganglia, thalamus, and cerebellum are also involved in speech movement preparation, including sequencing and motor timing. Though several aspects of speech motor-control processes remain to be clarified, such as motor programming and co-articulation, it is clear that the advent of multimodal imaging and brain stimulation techniques have allowed us to make major strides toward understanding the neural basis of human communication, one of the most distinctive features of our species.

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