NEUROSCIENCE RESEARCH NOTES

OPEN ACCESS | MINI-REVIEW ISSN: 2576-828X

Brain regions involved in speech production, mechanism and development

Mohammad Jahanaray *, Ali Jahanaray and Zahra Zohoorian

Department of English, Mashhad Branch, Islamic Azad University, Mashhad, Iran.
***Correspondence:** Mohammadjahanaray@outlook.com; Tel.: +98-936-467-7428

Received: 29 August 2022; **Accepted:** 18 October 2022; **Published:** 25 November 2022
Edited by: Pike See Cheah (Universiti Putra Malaysia, Malaysia)
Reviewed by: Hui Ying Jong (University Sains Malaysia, Malaysia);
Siti Fadziyah Mohamad Asri (Universiti Putra Malaysia, Malaysia);
Zaitunnatakhin Zamli (International Islamic University Malaysia, Malaysia)
https://doi.org/10.31117/neuroscirn.v5i4.178

Abstract: Speech might be one of the best inventions of human beings due to its critical communicative role in individuals' daily lives. Hence any study about it is valuable. To our knowledge, merely three studies focused on brain regions' associations with speech production were published more than eighteen years ago; furthermore, research on the brain areas associated with speech production is currently insufficient. The present review aims to provide information about all brain areas contributing to speech production to update the knowledge of brain areas related to speech production. The current study confirms earlier claims about activating some brain areas in the process; however, the previous studies were not comprehensive, and not all brain areas were mentioned. Three cerebral lobes are involved in the process, namely, the frontal, parietal and temporal lobes. The regions involved include the left superior parietal lobe, Wernicke's area, Heschl's gyri, primary auditory cortex, left posterior superior temporal gyrus (pSTG), Broca's area, and premotor cortex. In addition, regions of the lateral sulcus (anterior insula and posterior superior temporal sulcus), basal ganglia (putamen), and forebrain (thalamus) showed participation in the process. However, there was a different brain activation of overt and covert or silent speech (Broca's and Wernicke's areas). Moreover, mouth position and breathing style showed a difference in speech mechanism. In terms of speech development, the early postnatal years are important for speech development, as well as identifying three crucial stages of speech development: the pre-verbal stage, transition to active speech, and refinement of speech. In addition, during the early years of speech development, auditory and motor brain regions showed involvement in the process.

Keywords: Superior temporal gyrus; speech production; speech development; speech mechanism

1. INTRODUCTION

Human beings use speech to communicate, which is a natural way of communication (Honda, 2003). In other words, Kurdiukova and Suntsova (2020) believed that speech could be used as an interactive way with others, as an instrument of thinking, as a means to control behaviours and activities, and as a way of volitional regulation.

The crucial role of speech in human beings' lives is an undebatable matter. However, the importance of speech casts doubts on whether its process is well-understood. In addition, all research papers focused on one specific brain area in speech production. To our knowledge, there is merely one review and two research papers on brain areas associated with speech production that was carried out by Wise et al. (1999), Dronkers & Ogar (2004), and Nota (2004) which were published more than eighteen years ago. Therefore, this review aimed to fill this gap by gathering all new findings on brain regions associated with speech production.

The present review paper also addresses the following questions:

- Is a specific brain lobe associated with speech production?
- Which brain regions within the superior temporal gyrus (STG) are responsible for speech production?
- Are STG areas activated in other aspects of speech?
- What regions outside the STG participate in speech production?
- How is speech produced (the mechanism)?
- What are the important stages in the development of speech?
- Which brain regions are activated during speech development?

Speech does not start from the lungs, as many assume. Instead, the brain is where speech begins, a process studied by psycholinguists (Belinchón et al., 1994). Hence, the knowledge about brain regions linked with speech production can be prioritised to fully understand the process of speech production, which can be used as base knowledge in various experiments and studies related to speech production. The current review paper aimed to gather an overview of all available scientific data related to brain regions associated with speech production to assist future researchers in the field of speech production to what brain regions contribute to speech production and their roles. Additionally, speech development and mechanism were also addressed. It needs to be maintained that the focus was mainly on the left pSTG since there has been little research on this region and its relation to speech production. This approach has not been used in any other review paper on speech production. Other scholars either focused on brain activation of one specific brain region or speech mechanism, but having them all reviewed would leave no gaps in understanding speech production.

Humans' auditory responses allow them to continuously monitor and adjust their voices while speaking (Behroozmand et al., 2016). Integration of motor and sensory information in speech is one of the most important abilities in human beings. This vital function has, however, been poorly understood in terms of neural processes (Behroozmand et al., 2016). However, the superior temporal gyrus cortex has long been known to play a role in hearing, speech, and language. Still, the function of the brain while producing speech is just so basically understood, and our understanding of the function is inadequate (Howard et al., 2000). Additionally, the previous studies on brain regions' associations with speech production indicated participation of the anterior insula, Broca's area, the motor cortex, putamen, thalamus, midbrain and cerebellum (Dronkers & Ogar, 2004; Nota, 2004; Wise et al. 1999).

Furthermore, some perspectives from which speech production can be approached, including linguistics, psychology, acoustics, neurophysiology, neurology, electronic engineering, clinical linguistics, and others. So, specialists or experts in these fields might have reasons for conducting research or studying speech production (Tatham & Morton, 2011). According to Palmer et al. (2001), traditionally, the most commonly used tasks in neurology and cognitive psychology study of language have been dependent on verbal responses.

Fortunately, the investigation of brain activities or neural mechanisms of speech motor control, speech motor disorders, and speech motor have become much more straightforward compared to the last century owing to the new neuroimaging methods such as functional magnetic resonance imaging and positron emission tomography (Gracco et al., 2005). Moreover, during tasks requiring a spoken output, research on language processing conducted using fMRI has proven to be so valuable that it can provide high-quality images of brain activities (Palmer et al., 2001).

The speech production process includes compound stages in which the acoustic signals get produced from conceptual ideas that are comprehensible to others (Price et al., 2011). Speech production involves various stages, from the vocal organs' movement to sound production (Honda, 2003). Another essential issue in speech production is its development; according to Kurdiukova and Suntsova (2020), the ability to speak is not something humans are born with. Instead, speech develops and gets formed.

In addition, the inability of researchers to access or observe the spoken responses has made it difficult for them to determine whether subjects are following instructions as expected and, indeed, whether subjects are doing the tasks as expected (Barch et al., 1999). What makes the knowledge of different regions responsible for speech production so advantageous is that this knowledge can be used in various research fields.

2.0 METHODOLOGY

2.1 Methodology approach

A literature review approach was used to achieve our goal. The authors in the current review paper sought advice from over 100 articles and books. The scholarly works included experimental research, systematic and technical reviews, fMRI studies on speech production, and a few books on speech production.

2.2 Search strategy

In this literature review, the following databases were used: primarily Google Scholar, ResearchGate, Science Direct, and Frontiers. We used the following keywords and terms: "Brain regions related to speech production," "Brain regions activity in speech production," "Speech production," "STG," "Left pSTG," "Wernicke area," and "Role of STG in speech production," Broca's area role in speech production," "Anterior insular," "Right pSTS," "Auditory cortex," "Thalamus role in speech," "Putamen role in speech," Partial lobe role in speech," "Heschl's gyri," "Covert speech brain activity," Silent speech," "Speech mechanism," "Speech development."

2.3 Selection criteria

All articles and books used in this review paper were written in English and were published in verified publications. Articles on brain activities from the past decades were not easy to find; hence, the data collected on brain activities are from 2000 to 2022.

2.4 Data collection

All data, including the study aim, methodology, research title, author's names, and major findings of each article, was extracted for data comparison, finding trends, and gathering an overview for each section of this literature review.

3.0 BRAIN REGIONS ASSOCIATED WITH SPEECH PRODUCTION

3.1 Superior temporal gyrus

The STG lies in the temporal lobe, above the lateral sulcus and below the superior temporal sulcus. It starts from the temporal pole and extends posteriorly until it meets the temporoparietal junction, where it blends with the angular gyrus and supramarginal gyrus of the inferior part of the parietal lobe **(Figure 1A)** (Loh and Bell, 2022).

STG is heterogeneous in its functionality. Anterior STG lateral to transverse temporal gyrus (Heschl's gyrus) is categorised as a unisensory auditory association cortex (Rauschecker, 2015). Likewise, based on a suggestion, auditory speech is represented in the anterior STG; visual speech representations reside in extrastriate visual areas (Bernstein and Liebenthal, 2014; Nath and Beauchamp, 2011).

Several studies have shown that the pSTG and STS (superior temporal sulcus) are multisensory regions. These regions respond to auditory and visual stimuli such as faces and voices, letters and voices, and recordings and videos of objects (Atteveldt et al., 2004; Beauchamp et al., 2004; Calvert et al., 2000; Foxe et al., 2002; Miller & D'Esposito, 2005; Reale et al., 2007).

In 2009, Zevin claimed that STG, or superior temporal gyrus is a site of multisensory integration (Zevin, 2009). He also indicated that this region takes part in recognising spoken words. Yamamoto et al. (2019) found that the STG is associated with extracting meaningful linguistic information from the speech input. Moreover, it has been stated that written words can also activate the left posterior temporal gyrus (Zaidel, 2001).

According to Bhaya-Grossman & Chang (2022) STG might have other functions such as forecasting hearing reports. Additionally, activation in different parts of STG revealed that pSTG has a role in error monitoring and feedback control (Meekings & Scott, 2021). However, this review paper only presents functions linked with speech production.

3.1.2 Regions within the superior temporal gyrus

3.1.2.1 The left pSTG role in speech production

Hickok et al. (2000) used the fMRI approach to indicate the left pSTG activation in an object naming task. Participants were asked to name the things sub-vocally during the production task (i.e., without overt articulation) to eliminate the risk that their brain activity is not due to hearing their voices. As a result of their experiment, they observed an activation of the left pSTG in speech production.

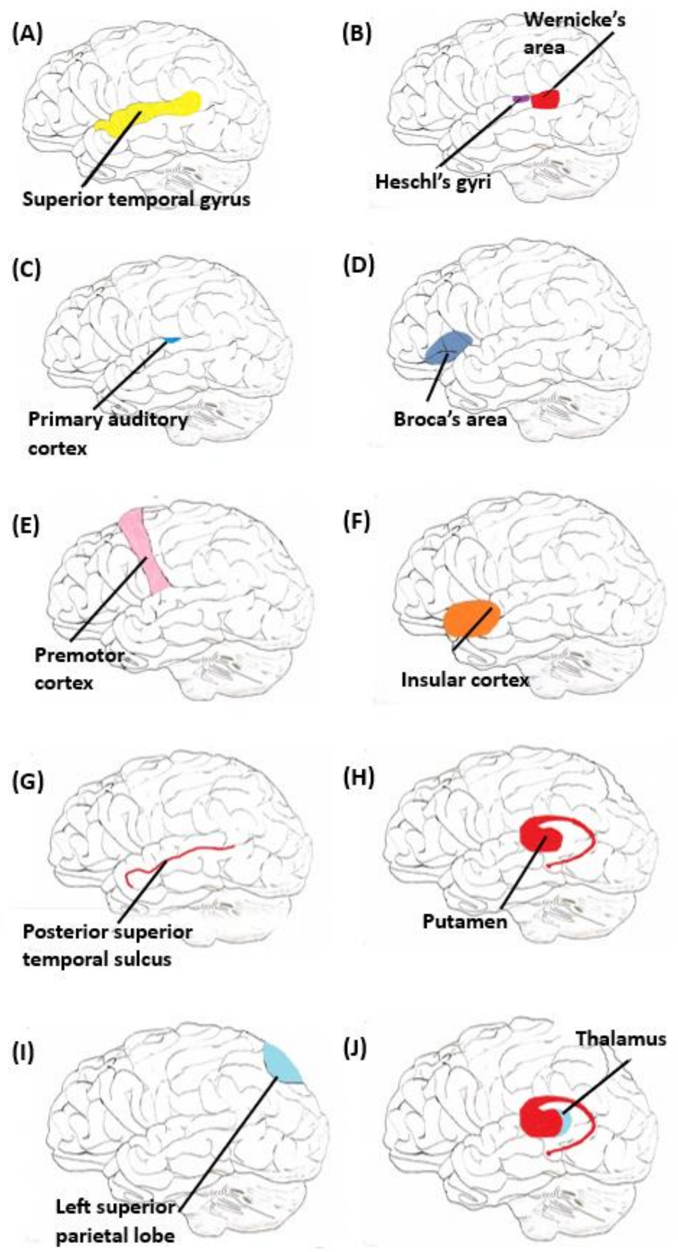

Figure 1. Location of **(A)** superior temporal gyrus, **(B)** Wernicke's area and Heschl's gyri, **(C)** primary auditory cortex, **(D)** Broca's area, **(E)** premotor cortex, **(F)** insular cortex, **(G)** posterior superior temporal sulcus, **(H)** putamen, **(I)** left superior parietal lobe and **(J)** thalamus.

Based on a recent study, left pSTG showed participation in verbal recognition processes and visual word recognition (Rivera-Urbina et al., 2022).

Graves et al. (2011) claimed that the damage to the left pSTG had been linked with impairments in phonological processing, but the degree to which it enables phonological processing, independently from semantic processing, remained uncertain. Hence, using fMRI experiments, the researchers employed repetition priming and suppression of neural repetition to describe phonological access during the lexical (whole-word) onset of lexical (phrase) repetition. Furthermore, they found that the left pSTG changes activity under conditions eliciting phonological processing. These changes seemed governed by similar processes across tasks requiring overt production and differing only in terms of the lexical status and presentation type of the stimuli. In this area, access to lexical phonology is specifically focused on.

Although language perception and speech production seem to be bilaterally mediated by the left pSTG (Buchsbaum et al., 2001), language processing and auditory short-term memory were also associated with the left pSTG (Leff et al., 2009). During speech production, the left pSTG was studied using magnetoencephalography (MEG) (Levet et al., 1998) and showed that it was activated during speech production.

Role of the left pSTG in speech perception

The question is whether the left pSTG activation is specific to speech production or activated during other aspects of speech. Several researches revealed that the left pSTG gets activated during speech production and perception. The relationship between speech perception and production processes, and their neural basis, comes from the hypothesis by Wernicke (1874/1977). Wernicke emphasised the crucial role of the left superior temporal gyrus (left STP) in speech perception and production. He also insisted that similar "auditory word images" are activated during speech production and perception (Buchsbaum et al., 2001). Based on a recent study, the pSTG showed involvement in syntactic processes (Chen et al., 2021)

According to research results, regions in the left pSTG and dorsal areas get activated during speech production tasks where verbal auditory input is absent. As well as observation of the association of the auditory cortex with the pSTG while speech perception increases the possibility that this region takes part in phonemic-level processes during speech perception and production (Buchsbaum et al., 2001; Coleman, 1998; Coleman et al., 2000; Hickok & Poeppel, 2000; Hickok et al., 2000). According to the observations and findings of Buchsbaum et al. (2001), it is proposed that while left pSTG is damaged, the phonemic perception is not entirely stopped. The isolated right hemisphere precisely does the process of phonemic information. The physiological indexes illustrated bilateral and symmetric pSTG activations when a speech is auditorily presented. Accordingly, speech perception does not rely exclusively on the left pSTG for perception.

The neural substrates of audio-visual speech perception were examined by Ozker et al. (2017) using electrocorticography and direct recordings of neural activity. They implanted electrodes on the cortical surface of their experiment's subjects. They also used Bayesian models of multisensory integration to examine and study the computational roles of both regions (anterior and posterior superior temporal gyrus). They assumed that in the speech stimulus, noise might variously impact responses in posterior and anterior electrodes. According to Ozker et al. (2017), pSTG is crucial for integrating multisets of visual and noisy auditory speech. Besides visual and noisy speech, it is clear that the left pSTG has a role in speech perception, as Mesgarani et al. (2014) and Binder et al. (2000) claimed STG is a critical area for speech perception.

However, speech perception and speech production are connected and correlated; according to a recent study by Berti et al. (2021), children with speech sound disorder face perceptual difficulties (phonological contrasts) and experience difficulty in producing those phonological contrasts at the same time.

Phonological systems of speech perception and production

The fact that the left pSTG takes part in speech perception raises the question of whether the phonological systems for perception and production are discrete phonological systems (Dell et al., 1997; Levelt et al., 1999) or whether there is only one system involved, in the phonological process (Allport, 1984; Coleman, 1998; MacKay, 1987). Buchsbaum et al. (2001) aimed to answer this question by investigating the left pSTG function in phonological processing for speech perception and production. They used an event-related fMRI experiment whereby the subjects were requested to listen to and then produce a speech. Buchsbaum et al. (2001) suggested that the activation of the left pSTG during speech production and speech perception depicts the activity of cortical systems during some aspects of the phonological process. Based on the observation, it can be concluded that the phonological input and output systems overlap, which supports psycholinguistic models.

Based on the discussion, it has been made clear that the left pSTG activates speech production and perception (Allport, 1984; Buchsbaum et al., 2001; Coleman, 1998; MacKay, 1987; Ozker et al., 2017). Buchsbaum et al. (2001) highlight that subfields in the left pSTG take part in speech perception and production regarding phonological aspects. Hence, the result illustrates a limited overlap between phonological input and output systems. Hickok and Poeppel (2000) claimed that the difference in dorsal and ventral processing streams in speech and language might be related to the functional distinctions between pSTG regions. Hence, more knowledge about the STG regions can clarify the understanding of brain activations during speech production.

3.1.2.2 Wernicke's area

The first region to focus on is the Wernicke area in the pSTG **(Figure 1B)**. Moini and Piran (2020) claim the same for the location of the Wernicke area. It is through this area that sensory information is received; hence, as a result of the integration of sensory information, it facilitates access to auditory and visual memories. In addition, language comprehension and speech perception are assumed to be impacted by this area (Mesulam et al., 2018).

As mentioned earlier, this region contributes to language comprehension in conventional thinking. However, with the emergence of modern imaging techniques and neuropsychological research, this region has been shown to take a significant part in the production of speech (Binder, 2015). Binder also claimed that this area is involved in phonologic retrieval during speech production, which is activating knowledge of vowels and sounds to prepare words for speech.

However, Mesulam et al. (2018) claimed that this area has an ancillary role rather than a critical role in language comprehension, suggesting that this area is involved in both speech production and speech perception. Recent research revealed that learning words both semantically and lexically could be improved by direct stimulation (Anodal tDCS) of the Wernicke's area (Kurmakaeva et al., 2021).

3.1.2.3 Heschl's gyri (primary auditory cortex)

The transverse temporal gyrus (Heschl's gyrus, HG) refers to the gyrus that runs from the upper surface of the temporal lobe (Hassanzadeh & Gaillard, 2014) **(Figure 1B)**. According to Wong et al. (2007), the HG has a role in auditory learning abilities and pitch processing. In other words, they have concluded that the left HG has a crucial role in pitch information integration that is phonetically/lexically relevant.

According to Schonwiesner et al. (2006), another function that HG has a role in is detecting sound change. Their research about Heschl's gyrus, Posterior superior temporal gyrus, and mid-ventrolateral prefrontal cortex discovered that these areas have distinct parts in detecting acoustic changes. Several modalities have been claimed, such as seeing someone's face moving without producing any auditory speech, activate some lateral aspects of TTG or Heschl's gyri that was recorded from an experiment with subjects having normal hearing abilities (Calvert & Campbell, 2003; Calvert et al., 1997). In addition, according to MacSweeney (2002), this region also activates in deaf individuals in the same circumstances. So, sign language activates this part in both cases (MacSweeney, 2002). Recently, this area showed participation in processing acoustic features (Khalighinejad et al., 2021).

Primary auditory cortex

According to Yang et al. (2020), the primary auditory cortex, referred to as area A1, is situated on the Heschl gyrus **(Figure 1C)**. This area is also connected with Brodmann area 41. There is a general agreement about the location of the auditory cortex, which is situated in the superior temporal gyrus (Campbell, 1905; Galaburda and Sanides, 1980; Kaas & Hackett, 1998; Hopf, 1964; Seldon, 1981). Yang et al. (2021) also claimed that the primary auditory cortex participates in language comprehension functions, such as integrating and processing complex auditory signals.

In other words, the auditory cortex is where many representations of speech characteristics, namely, voice onset time and articulatory features, can be observed (Mesgarani et al. 2008). Based on this claim, it can be postulated that the required mechanism for robust speech encoding is available in the mammalian auditory systems independent of learning (Mesgarani et al., 2014). According to Houde et al. (2002), the auditory cortex has two activities in speech production: reducing its sensitivity and providing acoustic feedback and modulating its activity. In addition, this area also plays a role in stuttering (Max et al., 2004).

By analysing Heschl's gyrus, posterior superior temporal gyrus, and mid-ventrolateral prefrontal cortex, Schonwiesner et al. (2007) investigated their role in detecting acoustic changes. They found out from the study that while the process of acoustic changes, three regions of the cerebral cortex are involved: the primary auditory cortex, the posterior superior temporal gyrus, the planum temporale, and the midventrolateral prefrontal cortex. It has been identified that these three specific regions are involved in detecting acoustic changes, analysing them in-depth, and judging whether they are sufficiently novel for allocating attentional resources.

3.2 Other brain areas associated with speech production

Hence, overall knowledge of the STG parts (Wernicke area, Heschl's gyri, and primary auditory cortex) has been gathered. However, other brain regions not located on the STG, called Broca's area, putamen, left parietal lobule**,** the anterior insula, and the right pSTS showed participation in speech production.

3.2.1 Broca's area

This area lies within the inferior frontal gyrus near the motor cortex **(Figure 1D)**. The motor speech area, also known as Broca's, contributes to speech production. Moreover, this region plays a part in modulating the breathing patterns in speech production (speaking and vocalisations) to make a typical speech. It has been claimed that when Broca's area is damaged, the person suffering from this condition is not capable of forming words. However, individuals can make sounds (Moini and Piran, 2020).

Buchsbaum et al. (2001) found an activation pattern in their experiments in which a high correlation between Broca's area and the pSTG/PO activation time course was uncovered. This pattern postulates that PST regions and Broca's area have a closer functional association than the relation between posterior temporal regions and the premotor cortex.

3.2.1.1 Premotor cortex

According to Sira and Mateer (2014), the anterior to the primary motor cortex is the location of the premotor cortex. Therefore, this area plays a role in planning and organising movements and actions. In addition, the two left frontal regions (Broca's area and a premotor region) regularly showed combined perceptual-motor responses. These two left frontal regions are illustrated to have different activation patterns. However, the premotor region **(Figure 1E)** depicted a slow response during auditory stimulation, while the rehearsal phase showed a more robust response. (Buchsbaum et al., 2001).

The left frontal regions have been known to have a more critical role in speech production than speech perception. For instance, Broca's area has been conventionally assumed to be linked with output processes, and likely this area plays a less critical role in phonemic aspects of speech perception (Hickok & Poeppel, 2000).

By studying Granger's causal interactions between cortical neuronal populations and the evolution of activity, Flinker et al. (2015) sought to understand the development of neural activity in the cortex. They found that Broca's area plays a coordinating role in converting information across large-scale cortical networks involved in speech production. In addition, the motor cortex implements a proper articulatory code formulated by Broca's area.

3.2.2 Anterior insula

The anterior insula is another part of the human brain that is not located in the STG, and it was found to be linked with speech production. The following reviews provide proof of this fact. Augustine (1996) states that the brain's lateral sulcus is the insular cortex's location **(Figure 1F)**. However, Johann Christian Reil, in 1809, discovered the location of this region for the first time (Uddin et al., 2017). Moreover, this area is also referred to as the 'Island of Reil'. In addition, this region is traditionally known as a paralimbic or limbic integration cortex. This cortex takes part in different human functions ranging from sensory and affective processing to high-level cognition (Uddin et al., 2017). Based on the results from studies on lesions (Dronkers, 1996) and functional imaging studies (Wise et al., 1999), the anterior insula is claimed to have a link with the speech production process, and phonological aspects might be involved.

Recently, Tomaiuolo et al. (2021) investigated the brain areas of four patients suffering from speech apraxia. There was neither any damage caused to the Broca's area and STG nor any signs of aphasia. Tomaiuolo et al. (2021) located the brain lesions, and they found lesions at the insular cortex (precentral gyrus of the insula) inferior part of the central sulcus. Furthermore, these areas are involved with sequential articulatory movements for speech production (Tomaiuolo et al., 2021).

3.2.3 Posterior superior temporal sulcus (pSTS)

The STS is situated in the lateral fissure, separating the temporal lobe from the parietal lobe from the frontal lobe (Bui & Das, 2021). In research by Leroy et al. (2015), left and right hemispheres of the STS have asymmetric structures: The STS is longer in the left hemisphere, but it is deeper in the right hemisphere **(Figure 1G)**. In observations by Allison et al. (2000), it was discovered that the right pSTS has crucial participation in detecting, predicting, and reasoning about social actions. Besides these functions, this particular area showed activation in speech production based on the following review.

Yamamoto et al. (2019) aimed to investigate the right pSTS and other auditory processing regions' association with speech production. They hypothesised that the mentioned areas are more activated in speech production by the subjects' speech than another's speech. However, their hypothesis was based on Christoffels et al. (2007) and Agnew et al. (2013) studies. Nevertheless, based on their experiment, it can be clarified that the right pSTS gets more activated during speech production, and by hearing another's speech, the right pSTG and left pSTG get activated more while listening to another's speech. However, their experiment illustrated that the right pSTS activates during speech production. Additionally, according to a recent multi-factorial fMRI study, left pSTS contributes to speech production, while its activity was higher with non-semantic stimuli than semantic stimuli (Ekert et al., 2021).

Another recent study by Yamamoto et al. (2019) explored right-lateralised response in pSTS during speech production. Based on their findings, this specific region participated in auditory feedback and internal representation of speech and was involved in bottom-up auditory feedback. Additionally, they depicted that pSTS was more activated in speech production than hearing an audio stimulus, whereas for pSTG, listening to audio stimuli activated the region more than speech production.

3.2.4 Putamen

The putamen is located in the forebrain, forming the dorsal striatum combined with the globus pallidus **(Figure 1H)**. Additionally, this area is associated with learning and movement (Ghandili & Munakomi, 2021; Hanlon et al., 2016). The putamen is involved with functions such as speech articulation and language functions. However, this area is associated with other tasks that are not involved in learning, such as reward, cognitive functioning, and addiction (Ghandili & Munakomi, 2021).

In 2019, Wang et al. investigated putamen in children with dyslexia disorder, in which they found that low activity of the left putamen is associated with phonological deficits (Wang et al., 2019).

3.2.5 Left Superior Parietal Lobule

Above the lateral sulcus, posterior to the central sulcus, is the location of the partial lobe (Johns, 2014) **(Figure1I)**. This region is known for its contribution to activities such as control of actions and attention. However, it is also known as the language area (Brownsett & Wise, 2009). In a recent study, Geva et al. (2022) tried to investigate patients with damaged putamen to observe which brain would contribute to speech production; they used tasks that were needed over speech production and semantic decision tasks. They found that the left superior parietal was activated during tasks that needed more speech production.

3.2.6 Thalamus

According to López-Bendito & Martini (2020), the thalamus is a big structure that is located between the midbrain and telencephalon **(Figure 1J)**. This area is reported to involve functions such as consciousness, sleep, cognition, and language (Rangus et al., 2021). There were some contradictory claims about the association of this area with speech production. In 2004, a study on brain regions involved in speech production by Dronkers & Ogar (2004) revealed that this region plays a role in speech production. However, this claim was rejected by a study by Klostermann et al. (2013) that depicted no activity of the region in any linguistic functions.

In addition, Wang et al. (2022) investigated the possible role of the thalamus in spoken word production (Grapheme-to-phoneme conversions) in the reading-aloud task. They found brain activity in the thalamus, and the activation was higher than in Broca's area in their experiment.

Overall, cerebral cortex regions, namely, parietal, frontal, and temporal lobes, showed participation in speech production, each with its specific role, as seen in **Figure 2**. Additionally, other brain areas were involved in speech production, such as the lateral sulcus, basal ganglia, and forebrain (**Figure 3)**.

4.0 BRAIN ACTIVATION OF DIFFERENT SPEECH TYPES

Brain region activations and their role in speech production are already covered. However, speech production does not explicitly mean overt speech; there is also silent or covert speech. Hence, whether these speech production types activate the pSTG requires further knowledge. In addition, as Palmer et al. (2001) claimed, there is not enough knowledge about the distinctions between inner and overt speech processes, including their neural mechanisms.

Topper et al. (1998) illustrated that some tasks involving speech production components (overt or covert) activate the left pSTG. They also stress that both types of speech production (overt or covert) activate the left pSTG through functional imaging studies. The left pSTG activates with cover and overt speech components during the following tasks.

- Reading (Price et al., 1996)
- Word Generation (Wise et al., 1991)
- Object naming (Bookheirmer et al.,1995; Hickok et al., 1999)
- Syllable rehearsal (Paus et al.,1996).

However, based on other scholars, the network activated during overt speech will not activate during covert or silent speech. (Barch et al., 1999; Bookheimer et al., 1995; Huang et al., 2001; Price et al., 1994). Price et al. (2011) did a functional imaging study that analysed the activation of vocalisation, auditory feedback, and movement in the articulators under control. They aimed to investigate the brain's neural activities linked to the internal model of speech production. During the silent speech, Broca's area in the left dorsal pars opercularis and Wernicke's region in the left pSTS were activated. Furthermore, both Broca's and Wernicke's areas get activated in silent speech.

5.0 SPEECH PRODUCTION MECHANISM

5.1 Role of Neuro-motor planning

In speech production, the articulatory movement creates an intermediate representation between neuro-motor planning (high level) and speech acoustics (low level) (Whiteside et al., 1993). Neuro-motor planning is in human brains, and its central role is to express linguistic information. This linguistic information is known to be discrete abstract units (Singh et al., 2020). In addition, motor nerves act as a way that the data can be passed to activate vocal muscles. As a result of this activation, various momentarily overlapping gestures of speech articulators, such as lips, tongue tip, tongue body, tongue dorsum, velum, and larynx, occur. Each speech articulator modulates its constriction in various parts of the vocal tract (Goldstein & Fowler, 2003; Gomez-Vilda et al., 2019). Thus, a speech sound wave is created by modulating the acoustic signal's spectrum, done by articulatory gestures.

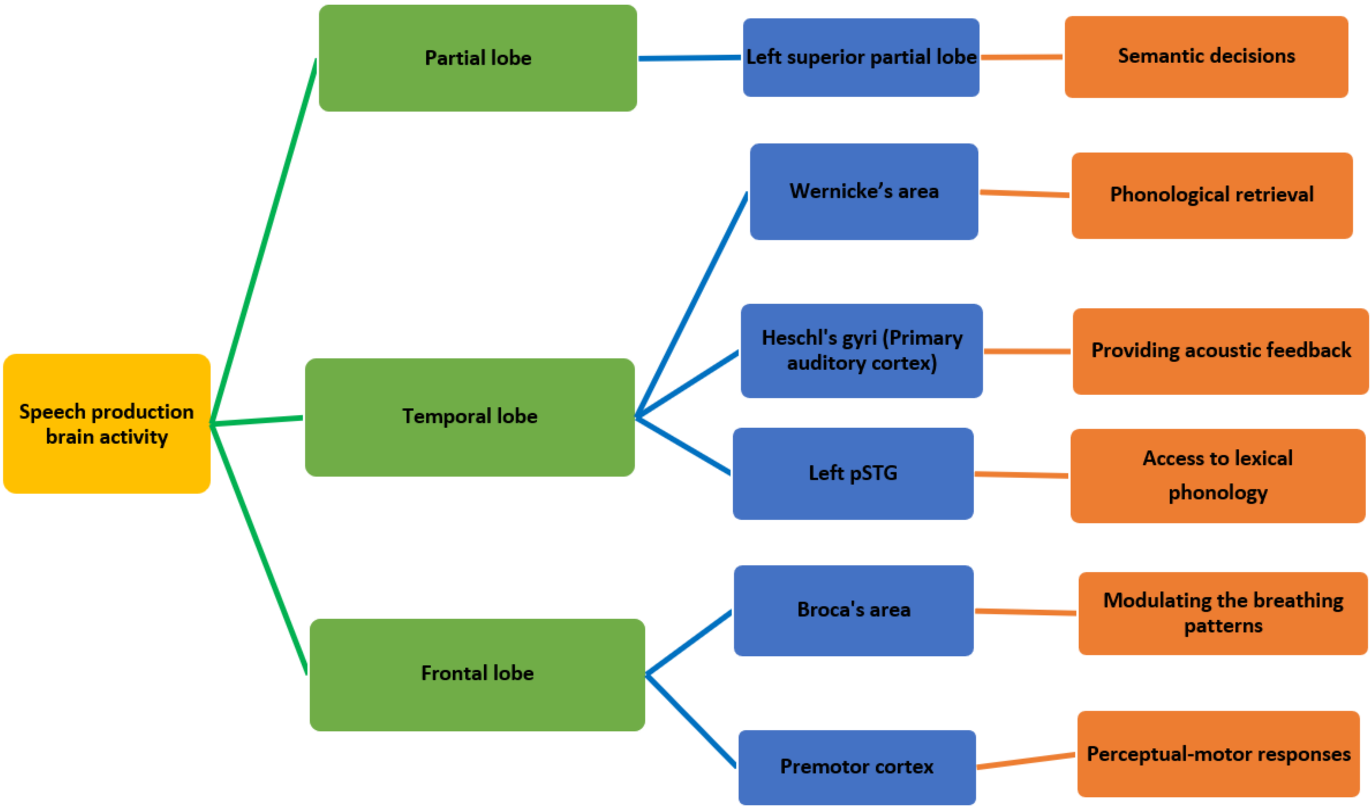

Figure 2. The brain activity of the cerebral cortex regions during speech production

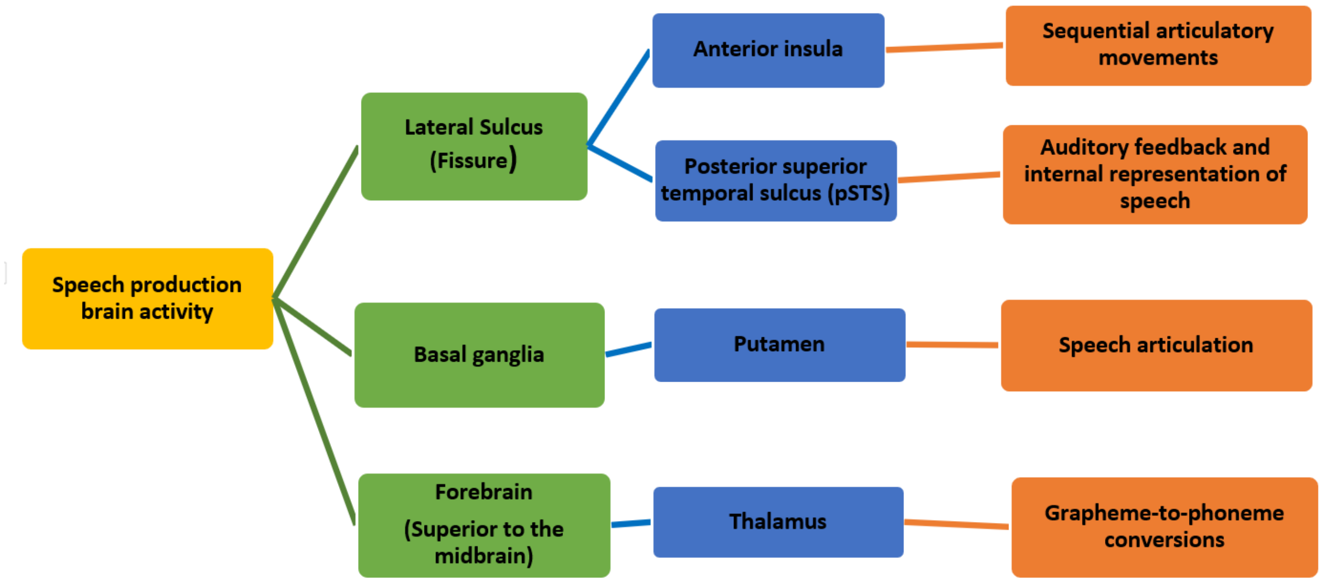

Figure 3. The brain activity of other brain regions during speech production.

5.2 Creation of sounds

Moreover, Honda (2003) describes speech production by claiming that the cyclic puffs make air sounds due to the airflow vibration, which passes through an opening in the vocal cords. However, this is not the case for the unvoiced sounds. According to Honda (2003), unvoiced sounds like the syllable "sa" are produced by a turbulent flow of air created because the airflow passes through a narrow space formed by the tongue inside the mouth. Human beings can control sound resonance characteristics simply by changing the shape of the vocal tract, which can be done by changing the position of the mouth. The inhalation phase by mouth opening is a speech preparation stage (Rasskazova et al., 2019). Additionally, breathing through the mouth instead of nasal inhalation during speech production is more typical because it can cover more air volume, and coordination between inhalation and glottal aperture is another effective factor in creating audible noise (Werner et al., 2021).

6.0 SPEECH DEVELOPMENT

According to Kurdiukova and Suntsova (2020), speech is not an innate human skill, unlike expectations. In fact, during children's development, speech gets formed. Additionally, thought development and the development of speech are primarily associated. What is more, the early years of life are crucial to speech development, as motor adaptation abilities are formed during these years (Ohashi & Ostry, 2021). There are some critical stages involved in the development of speech. Here are the stages:

6.1 Speech development stages

6.1.1 The pre-verbal stage

This stage is the most critical year in speech development (the infant's communicative stage), which takes place between 10 and 11 months up to two years (Baskaran, 2004). However, the stage's time occurrence might be described differently, as Kurdiukova and Suntsova (2020) claimed this stage takes place in the first year of a child's life. During this stage, the sounds or vocalisations can alter and are changeable (Baskaran, 2004). Based on the study by Kurdiukova and Suntsova (2020), the infant learns sounds from interacting with others. It has been postulated that some experience of the social role of speech is provided for the children at this stage due to the parent's responses to children's vocalisations. However, these vocalisations might not be coherent (Yule, 1994), as well as the actions that the children observe from others are caused by the sounds that children make (Sobirjonovich & Qizi, 2021). According to Bonte et al. (2016), the primary brain functions of voice and speech perception appear in the first year of children's lives. Hence, this first stage of development is crucial for speech development.

6.1.2 The transition to active speech

This stage happens in the second year of a child's life. During this stage, the child's first words and basic phrases get pronounced by the child, and the development of phonemic hearing occurs in this stage (Kurdiukova & Suntsova, 2020). In this stage, children can pronounce all vowel sounds, which might not be understandable sometimes, and some consonants could also be pronounced (Sobirjonovich & Qizi, 2021).

However, the transition to active speech consists of two stages. The first stage occurs between 12 and 18 months (one-word or holophrastic stage); children can produce recognisable single units of utterances and recognise objects in this stage (Yule, 1994). While the second stage (two-word stage) occurs between 18 to 20 months, infants can manage to form combined words (Braine, 1976; Brown, 1973; Ingram, 1989; Pinker, 1984).

6.1.3 Refinement of speech

This stage arises in the third year of life when the child becomes familiar with the principal means of interaction. At this stage, the child can perfectly reflect his intentions through speech and convey the content and overall context of the events he is reflecting on. In addition, grammar, pronunciation, and vocabulary size grow in this stage (Kurdiukova & Suntsova, 2020). Additionally, each child doesn't develop speech at the same rate. Moreover, according to Brauer (2014), genetic conditions might influence the progress of language abilities.

At birth, preconditions for certain language functions are not well-developed. These preconditions grow as the infant grows. Furthermore, the network of brain connections between the language regions is well-established in 7-year-old children, compared to infants that have merely an essential connection within the language network (Brauer, 2014). As children and adolescents grow, fine-grained morphological and functional characteristics continue to evolve, while the rudimentary cortical networks for speech and voice perception are established early. (Bonte and Blomert, 2004; Bonte et al., 2013; Giedd et al., 1999; Gogtay et al. 2004)

6.2 Brain regions related to speech development

In infants between 3 to 7 months, regions of the right ST cortex of their brain get activated while listening to voiced sounds compared to non-vocal sounds. These regions are also linked with part of voice-sensitive regions in adults. (Belin et al., 2000; Blasi et al., 2011; Grossmann et al., 2010). Imada et al. (2006) examined 6-month-old and 12-month-old infants while they listened to nonspeech, harmonics, and syllables using the MEG (magnetoencephalography). Dehaene-Lambertz et al. (2006) also studied 3-month- old infants as they listened to t sentences. In addition, they used fMRI to scan their neural activities. Dehaene et al. (2006) observed activities in motor speech areas at three months in their experiment.

In response to the speech and the auditory and motor cues, synchronised activities were reported at 6 and 12 months of age (Imada et al., 2006). The newborn did not exhibit any activation in the motor speech area of the brain as a response to auditory speech when brain activity was recorded in auditory and motor brain areas. However, in 6-12-month-old infants, activity in the auditory and motor brain regions became more synchronised (Imada et al., 2006). In both experiments, the inferior frontal and Broca's area, which participate in speech production, showed activation in response to auditorily presented speech.

7.0 CONCLUSIONS

Communication might be one of the crucial elements of humans' survival; without it, individuals might encounter many obstacles in their lives, and speech may be the best way to communicate appropriately with others. Based on reviews, there is a clear understanding that speech production begins in the human brain, not the lungs.

Dronkers & Ogar (2004) and Wise et al. (1999) investigated brain areas linked with speech production, in which they could only find Broca's area and anterior insula activation during speech production. Furthermore, this review paper confirms the previous studies (Dronkers & Ogar, 2004) and Wise et al. (1999) that Broca's area and anterior insula participate in speech production. In addition, the current review paper revealed that there are six other brain regions associated with speech production, namely the Wernicke's area, primary auditory cortex, Heschel's gyri, pSTS, putamen, and left parietal lobule. Hence, the study done by Dronkers & Ogar, (2004) seem incomprehensive.

What is more, in 2004, Nota measured brain activities during speech production in an fMRI study. His study seemed more comprehensive than the study done by Dronkers & Ogar (2004), who claimed that the motor cortex, putamen, thalamus, midbrain and cerebellum are involved in articulation. Our review paper confirms that the motor cortex and putamen are involved in speech production based on studies by previous literature (Buchsbaum et al., 2001; Flinker et al., 2015; Hanlon et al., 2016; Ghandili & Munakom, 2021). There seems to be a significant lack of studies; furthermore, this review paper neither confirms nor denies that the midbrain has a role in speech production, as further studies need to be carried out. Participation of the thalamus was rejected by Klostermann et al. (2013), claiming that this area was not involved in any linguistic functions; however, our review paper rejected the claim by Klostermann et al. (2013), as in 2022, Wang et al. illustrated that this region is involved with speech production. In addition, Nota (2004) also claimed that the anterior insula was not activated in articulation, whereas the current paper illustrated that the anterior insular is involved with speech production according to studies by previous literature (Dronkers, 1996; Tomaiuolo et al. 2021; Wise et al., 1999) .

This literature depicted that frontal, temporal, and parietal lobes are involved during speech production, suggesting that speech production is not supported merely by one lobe but three. Moreover, STG regions (Wernicke's area, Heschl's gyri, and primary auditory cortex) showed significant participation in speech production, especially the left pSTG. These regions also showed activations in speech perception. However, when the left pSTG was impaired in an experiment, the speech perception was not limited. Although other brain regions outside the STG were also involved in speech production, namely, Broca's area and anterior insula, posterior superior temporal sulcus (pSTS), putamen, and left parietal lobule, speech production is supported in other brain areas. This process is not specified and limited to the activation of one or two brain areas. However, different types of speech production had different brain activities, such as activation of the left pSTG in overt and covert speech and activation of Broca's area and Wernicke's area in silent speech.

Regarding the speech mechanism, this review paper depicted that speech does not start from the lungs; it begins in the brain. Furthermore, motor nerves activate the vocal muscles that lead to different gestures of speech articulators. In addition, it was depicted that the way of breathing and the position of the mouth also affects the speech sounds.

Childhood and early years are important for speech development as motor adaptation abilities are formed during these years, which involve three critical stages of development. In the pre-verbal stage, infants learn sounds; in this stage, the right superior temporal gets activated. The transition of active speech, as the second stage, occurs when the infant produces simple words. The last stage is the refinement of speech, in which the infant uses better grammar and pronunciations. In the last two stages, the mentioned regions in the review related to speech production have a more significant role in speech development. During these stages, the inferior frontal and Broca's area showed activation. Additionally, speech development studies showed participation of the inferior frontal and Broca's area.

This review has limitations, such as inadequate studies about the role of the midbrain in speech production and a lack of studies related to speech development and the involved brain areas. Studies comparing activation patterns of the different brain areas during speech production are lacking, and more investigations are needed. This review paper deliberated on which brain regions were linked with speech production and what were the roles of each specific area in speech production. It is helpful for cognitive neuroscience, neurolinguistics, and psycholinguistics researchers, who seek to investigate activities in different brain areas during speech production.

Acknowledgements: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author Contributions: MJ wrote, designed and revised the paper. AJ assisted in collecting data, extracting data, and drawing figures. ZZ supervised the study.

Conflicts of Interest: The authors declare no conflict of interest.

References

Agnew, Z., McGettigan, C., Banks, B., & Scott, S. (2013). Articulatory movements modulate auditory responses to speech. *NeuroImage*, *73*, 191–199. https://doi.org/10.1016/j.neuroimage.2012.08.020

Allison, T., Puce, A., & McCarthy, G. (2000). Social perception from visual cues: role of the STS region. *Trends in Cognitive Sciences*, *4*(7), 267–278. https://doi.org/10.1016/s1364-6613(00)01501-1

Allport, D. A. (1984). Speech Production and Comprehension: One Lexicon or Two? *Cognition and Motor Processes,* 209–228. https://doi.org/10.1007/978-3-642-69382-3_15

Augustine, J. (1996). Circuitry and functional aspects of the insular lobe in primates including humans. *Brain Research Reviews*, *22*(3), 229–244. https://doi.org/10.1016/s0165-0173(96)00011-2

Barch, D. M., Sabb, F. W., Carter, C. S., Braver, T. S., Noll, D. C., & Cohen, J. D. (1999). Overt verbal responding during fMRI scanning: empirical investigations of problems and potential solutions. *NeuroImage*, *10*(6), 642–657. https://doi.org/10.1006/nimg.1999.0500

Baskaran, L. (2004). *Developmental Linguistics: Communication and infancy*. Language and Linguistics Faculty, UM.

Beauchamp, M. S., Argall, B. D., Bodurka, J., Duyn, J. H., & Martin, A. (2004). Unraveling multisensory integration: patchy organisation within human STS multisensory cortex. *Nature Neuroscience*, *7*(11), 1190–1192. https://doi.org/10.1038/nn1333

Behroozmand, R., Oya, H., Nourski, K., Kawasaki, H., Larson, C.R., Brugge, J. F., Howard III, M. A., Greenlee, J. D. W. (2016). Neural correlates of vocal production and motor control in human Heschl's gación y teoría (Psychology of Language Research and theory). Madrid: *Editorial Trotta.* ISBN*:* 84-87699-31-6

Bernstein, L. E., & Liebenthal, E. (2014). Neural pathways for visual speech perception. *Frontiers in Neuroscience*, *8*, 1-18. https://doi.org/10.3389/fnins.2014.00386

Berti, L. C., de Assis, M. F., Cremasco, E., & Cardoso, A. C. V. (2021). Speech production and speech perception in children with speech sound disorder. *Clinical Linguistics & Amp; Phonetics, 36*(2–3), 183–202. https://doi.org/10.1080/02699206.2021.1948609

Bhaya-Grossman, I., & Chang, E. F. (2022). Speech computations of the human superior temporal gyrus. *Annual Review of Psychology*, *73*(1), 79–102. https://doi.org/10.1146/annurev-psych-022321-035256

Binder J. R. (2015). The Wernicke area: Modern evidence and a reinterpretation. *Neurology*, *85*(24), 2170–2175. https://doi.org/10.1212/WNL.0000000000002219

Binder, J. (2000). Human temporal lobe activation by speech and nonspeech sounds. *Cerebral Cortex*, *10*(5), 512–528. https://doi.org/10.1093/cercor/10.5.512

Blasi, A., Mercure, E., Lloyd-Fox, S., Thomson, A., Brammer, M., Sauter, D., Deeley, Q., Barker, G., Renvall, V., Deoni, S., Gasston, D., Williams, S., Johnson, M., Simmons, A., & Murphy, D. (2011). Early specialisation for voice and emotion processing in the infant brain. *Current Biology*, *21*(14), 1220–1224. https://doi.org/10.1016/j.cub.2011.06.009

Bonte, M., & Blomert, L. (2004). Developmental changes in ERP correlates of spoken word recognition during early school years: a phonological priming study. *Clinical Neurophysiology*, *115*(2), 409–423. https://doi.org/10.1016/s1388-2457(03)00361-4

Bonte, M., Frost, M. A., Rutten, S., Ley, A., Formisano, E., & Goebel, R. (2013). Development from childhood to adulthood increases morphological and functional inter-individual variability in the right superior temporal cortex. *NeuroImage*, *83*, 739–750. https://doi.org/10.1016/j.neuroimage.2013.07.017

Bonte, M., Ley, A., Scharke, W., Formisano, E. (2016). Developmental refinement of cortical systems for speech and voice processing. *NeuroImage, 128*, 373–384. http://dx.doi.org/10.1016/j.neuroimage.2016.01.015

Bookheimer, S. Y., Zeffiro, T. A., Blaxton, T., Gaillard, W., & Theodore, W. (1995). Regional cerebral blood flow during object naming and word reading. *Human Brain Mapping*, *3*(2), 93–106. https://doi.org/10.1002/hbm.460030206

Braine, M. D. S., & Bowerman, M. (1976). Children's First Word Combinations. *Monographs of the Society for Research in Child Development, 41*(1), 1. https://doi.org/10.2307/1165959

Brauer, J. (2014). The brain and language: how our brains communicate. *Frontiers for Young Minds*, *2*, 14. https://doi.org/10.3389/frym.2014.00014

Brownsett, S. L. E., & Wise, R. J. S. (2009). The contribution of the parietal lobes to speaking and writing. *Cerebral Cortex, 20*(3), 517–523. https://doi.org/10.1093/cercor/bhp120

Buchsbaum, B. R., Hickok, G., & Humphries, C. (2001). Role of left posterior superior temporal gyrus in phonological processing for speech perception and production. *Cognitive Science*, *25*(5), 663–678. https://doi.org/10.1207/s15516709cog2505_2

Bui, T., & M Das, J. (2021). Neuroanatomy, Cerebral Hemisphere. In *StatPearls*. StatPearls Publishing. Leroy, F., Cai, Q., Bogart, S. L., Dubois, J., Coulon, O., Monzalvo, K., Fischer, C., Glasel, H., van der Haegen, L., Bénézit, A., Lin, C. P., Kennedy, D. N., Ihara, A. S., Hertz-Pannier, L., Moutard, M. L., Poupon, C., Brysbaert, M., Roberts, N., Hopkins, W. D., . . . Dehaene-Lambertz, G. (2015). New human-specific brain landmark: The depth asymmetry of superior temporal sulcus. *Proceedings of the National Academy of Sciences*, *112*(4), 1208–1213. https://doi.org/10.1073/pnas.1412389112

Calvert, G. A., Campbell, R., & Brammer, M. J. (2000). Evidence from functional magnetic resonance imaging of crossmodal binding in the human heteromodal cortex. *Current Biology*, *10*(11), 649–657. https://doi.org/10.1016/s0960-9822(00)00513-3

Campbell A. W. (1905). Histological studies on the localisation of cerebral function. *Cambridge: Cambridge University Press*.

Chen, L., Goucha, T., Männel, C., Friederici, A. D., & Zaccarella, E. (2021). Hierarchical syntactic processing is beyond mere associating: Functional magnetic resonance imaging evidence from a novel artificial grammar. *Human Brain Mapping*, *42*(10), 3253–3268. https://doi.org/10.1002/hbm.25432

Christoffels, I. K., Formisano, E., & Schiller, N. O. (2007). Neural correlates of verbal feedback processing: An fMRI study employing overt speech. *Human Brain Mapping*, *28*(9), 868–879. https://doi.org/10.1002/hbm.20315

Coleman, J. (1998). Cognitive reality and the phonological lexicon: A review. *Journal of Neurolinguistics*, *11*(3), 295–320. https://doi.org/10.1016/s0911-6044(97)00014-6

Dehaene-Lambertz, G., Hertz-Pannier, L., Dubois, J., Mériaux, S., Roche, A., Sigman, M., & Dehaene, S. (2006). Functional organisation of perisylvian activation during presentation of sentences in pre-verbal infants. *Proceedings of the National Academy of Sciences*, *103*(38), 14240–14245. https://doi.org/10.1073/pnas.0606302103

Dell, G. S., Schwartz, M. F., Martin, N., Saffran, E. M., & Gagnon, D. A. (1997). Lexical access in aphasic and nonaphasic speakers. *Psychological Review*, *104*(4), 801–838. https://doi.org/10.1037/0033-295x.104.4.801

Dronkers, N. F. (1996). A new brain region for coordinating speech articulation. *Nature*, *384*(6605), 159–161. https://doi.org/10.1038/384159a0

Dronkers, N. F., Plaisant, O., Iba-Zizen, M. T., & Cabanis, E. A. (2014). *Broca's area*. Wikipedia. https://upload.wikimedia.org/wikipedia/commons/b/b4/Broca%27s_area_-_lateral_view.png

Dronkers, N., & Ogar, J. (2004). Brain areas involved in speech production. *Brain*, *127*(7), 1461–1462. https://doi.org/10.1093/brain/awh233

Ekert, J. O., Gajardo-Vidal, A., Lorca-Puls, D. L., Hope, T. M., Dick, F., Crinion, J. T., Green, D. W., & Price, C. J. (2021). Dissociating the functions of three left posterior superior temporal regions that contribute to speech perception and production. *NeuroImage*, *245*, 118764. https://doi.org/10.1016/j.neuroimage.2021.118764

Flinker, A., Korzeniewska, A., Shestyuk, A. Y., Franaszczuk, P. J., Dronkers, N. F., Knight, R. T., & Crone, N. E. (2015). Redefining the role of Broca's area in speech. *Proceedings of the National Academy of Sciences*, *112*(9), 2871–2875. https://doi.org/10.1073/pnas.1414491112

Galaburda, A., & Sanides, F. (1980). Cytoarchitectonic organisation of the human auditory cortex. *The Journal of Comparative Neurology*, *190*(3), 597–610. https://doi.org/10.1002/cne.901900312

Geva, S., Schneider, L. M., Khan, S., Lorca-Puls, D. L., Gajardo-Vidal, A., Hope, T. M. H., Green, D. W., & Price, C. J. (2022). Enhanced left superior parietal activation during successful speech production in patients with left dorsal striatal damage and error-prone neurotypical participants. *Cerebral Cortex,* bhac282. https://doi.org/10.1093/cercor/bhac282

Ghandili, M., & Munakomi, S. (2022). Neuroanatomy, Putamen. In StatPearls. StatPearls Publishing.

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., Nugent, T. F., Herman, D. H., Clasen, L. S., Toga, A. W., Rapoport, J. L., & Thompson, P. M. (2004). Dynamic mapping of human cortical development during childhood

through early adulthood. *Proceedings of the National Academy of Sciences*, *101*(21), 8174–8179. https://doi.org/10.1073/pnas.0402680101
Goldstein, L., & Fowler, C. A. (2003). Articulatory Phonology: A phonology for public language use. *Phonetics and Phonology in Language Comprehension and Production*, 159–208. https://doi.org/10.1515/9783110895094.159
Gómez-Vilda, P., Gómez-Rodellar, A., Vicente, J. M. F., Mekyska, J., Palacios-Alonso, D., Rodellar-Biarge, V., Álvarez-Marquina, A., Eliasova, I., Kostalova, M., & Rektorova, I. (2019). Neuromechanical Modelling of Articulatory Movements from Surface Electromyography and Speech Formants. *International Journal of Neural Systems*, *29*(02), 1850039. https://doi.org/10.1142/s0129065718500399
Gracco, V. L., Tremblay, P., & Pike, B. (2005). Imaging speech production using fMRI. *NeuroImage*, *26*(1), 294–301. https://doi.org/10.1016/j.neuroimage.2005.01.033
Graves, W. W., Grabowski, T. J., Mehta, S., & Gupta, P. (2008). The left posterior superior temporal gyrus participates specifically in accessing lexical phonology. *Journal of Cognitive Neuroscience*, *20*(9), 1698–1710. https://doi.org/10.1162/jocn.2008.20113
Grossmann, T., Oberecker, R., Koch, S. P., & Friederici, A. D. (2010). The developmental origins of voice processing in the human brain. *Neuron*, *65*(6), 852–858. https://doi.org/10.1016/j.neuron.2010.03.001
Hacking, C. (2018). *Location of the posterior superior temporal sulcus*. Radiopaedia.
Häggström, M. (2007). *Location of Primary auditory cortex*. https://upload.wikimedia.org/wikipedia/commons/8/8e/Primary_auditory_cortex.PNG
Hanlon, C., Dowdle, L., & Jones, J. (2016). Biomarkers for success. *International Review of Neurobiology*, 125–156. https://doi.org/10.1016/bs.irn.2016.06.006
Hickok, G. (2000). Speech perception, conduction aphasia, and the functional neuroanatomy of language. *Language and the Brain*, 87–104. https://doi.org/10.1016/b978-0123042606/50006-2
Hickok, G., & Poeppel, D. (2000). Towards a functional neuroanatomy of speech perception. *Trends in Cognitive Sciences*, *4*(4), 131–138. https://doi.org/10.1016/s1364-6613(00)01463-7
Hickok, G., Erhard, P., Kassubek, J., Helms-Tillery, A., Naeve-Velguth, S., Strupp, J. P., Strick, P. L., & Ugurbil, K. (2000). A functional magnetic resonance imaging study of the role of left posterior superior temporal gyrus in speech production: implications for the explanation of conduction aphasia. *Neuroscience Letters*, *287*(2), 156–160. https://doi.org/10.1016/s0304-3940(00)01143-5
Hoefer, P. F. A. (1965). Cerebral localisation and organisation. *Archives of Neurology*, *13*(4), 451. https://doi.org/10.1001/archneur.1965.00470040117026
Honda, M. (2003). Human Speech Production Mechanisms. *NTT Technical Review*, *1*(2), 24–29.
Kurdiukova, S., & Suntsova, A. (2020). Chapter 5: The Neuropsychological Approach to Speech Development. *Journal of Russian & East European Psychology*, *57*(1), 24–33. https://doi.org/10.1080/10610405.2020.1717850
Houde, J. F., Nagarajan, S. S., Sekihara, K., & Merzenich, M. M. (2002). Modulation of the auditory cortex during speech: an MEG study. *Journal of Cognitive Neuroscience*, *14*(8), 1125–1138. https://doi.org/10.1162/089892902760807140
Howard, M. A., Volkov, I. O., Mirsky, R., Garell, P. C., Noh, M. D., Granner, M., Damasio, H., Steinschneider, M., Reale, R. A., Hind, J. E., & Brugge, J. F. (2000). Auditory cortex on the human posterior superior temporal gyrus. *The Journal of comparative neurology*, *416*(1), 79–92. https://doi.org/10.1002/(sici)1096-9861(20000103)416:1<79::aid-cne6>3.0.co;2-2
Huang, J., Carr, T. H., & Cao, Y. (2001). Comparing cortical activations for silent and overt speech using event-related fMRI. *Human Brain Mapping*, *15*(1), 39–53. https://doi.org/10.1002/hbm.1060
Imada, T., Zhang, Y., Cheour, M., Taulu, S., Ahonen, A., & Kuhl, P. K. (2006). Infant speech perception activates Broca's area: a developmental magnetoencephalography study. *NeuroReport*, *17*(10), 957–962. https://doi.org/10.1097/01.wnr.0000223387.51704.89
Johns, P. (2014). Functional neuroanatomy. *Clinical Neuroscience*, 27–47. https://doi.org/10.1016/b978-0-443-10321-6.00003-5
Kaas, J. H., & Hackett, T. A. (1998). Subdivisions of auditory cortex and levels of processing in primates. *Audiology and Neurotology*, *3*(2–3), 73–85. https://doi.org/10.1159/000013783
Khalighinejad, B., Patel, P., Herrero, J. L., Bickel, S., Mehta, A. D., & Mesgarani, N. (2021). Functional characterisation of human Heschl's gyrus in response to natural speech. *NeuroImage*, *235*, 118003. https://doi.org/10.1016/j.neuroimage.2021.118003
Klostermann, F., Krugel, L. K., & Ehlen, F. (2013). Functional roles of the thalamus for language capacities. *Frontiers in Systems Neuroscience*, *7*, 32. https://doi.org/10.3389/fnsys.2013.00032
Kurdiukova, S., & Suntsova, A. (2020). Chapter 5: The Neuropsychological Approach to Speech Development. *Journal of Russian & East European Psychology, 57*(1), 24–33. https://doi.org/10.1080/10610405.2020.1717850
Kurmakaeva, D., Blagovechtchenski, E., Gnedykh, D., Mkrtychian, N., Kostromina, S., & Shtyrov, Y. (2021). Acquisition of concrete and abstract words is modulated by tDCS of Wernicke's area. *Scientific Reports, 11*(1), 1508. https://doi.org/10.1038/s41598-020-79967-8

Leff, A. P., Schofield, T. M., Crinion, J. T., Seghier, M. L., Grogan, A., Green, D. W., & Price, C. J. (2009). The left superior temporal gyrus is a shared substrate for auditory short-term memory and speech comprehension: evidence from 210 patients with stroke. *Brain*, *132*(12), 3401–3410. https://doi.org/10.1093/brain/awp273

Levelt, W. J. M., Praamstra, P., Meyer, A. S., Helenius, P., & Salmelin, R. (1998). An MEG study of picture naming. *Journal of Cognitive Neuroscience*, *10*(5), 553–567. https://doi.org/10.1162/089892998562960

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences*, *22*(01). https://doi.org/10.1017/s0140525x99001776

López-Bendito, G., & Martini, F. J. (2020). Patterning of thalamus. *Patterning and Cell Type Specification in the Developing CNS and PNS*, 69–86. https://doi.org/10.1016/b978-0-12-814405-3.00004-7

MacSweeney, M. (2002). Neural systems underlying British sign language and audio-visual english processing in native users. *Brain*, *125*(7), 1583–1593. https://doi.org/10.1093/brain/awf153

Maratsos, M., & Ingram, D. (1993). First language acquisition: method, description, and explanation. *Language*, *69*(2), 372. https://doi.org/10.2307/416542

Max, L., Guenther, F. H., Gracco, V. L., Ghosh, S. S., & Wallace, M. E. (2004). Unstable or insufficiently activated internal models and feedback-biased motor control as sources of dysfluency: a theoretical model of stuttering. *Contemporary Issues in Communication Science and Disorders*, *31*(Spring), 105–122. https://doi.org/10.1044/cicsd_31_s_105

Meekings, S., & Scott, S. K. (2021). Error in the superior temporal gyrus? a systematic review and activation likelihood estimation meta-analysis of speech production studies. *Journal of Cognitive Neuroscience*, *33*(3), 422–444. https://doi.org/10.1162/jocn_a_01661

Mesgarani, N., Cheung, C., Johnson, K., & Chang, E. F. (2014). Phonetic feature encoding in human superior temporal gyrus. *Science*, *343*(6174), 1006–1010. https://doi.org/10.1126/science.1245994

Mesgarani, N., David, S. V., Fritz, J. B., & Shamma, S. A. (2008). Phoneme representation and classification in primary auditory cortex. *The Journal of the Acoustical Society of America*, *123*(2), 899–909. https://doi.org/10.1121/1.2816572

Mesulam, M. M., Rader, B. M., Sridhar, J., Nelson, M. J., Hyun, J., Rademaker, A., Geula, C., Bigio, E. H., Thompson, C. K., Gefen, T.D., Weintraub, S., & Rogalski, E.J. (2018). Word comprehension in temporal cortex and Wernicke area. *Neurology*, *92*(3), e224–e233. https://doi.org/10.1212/wnl.0000000000006788

Moini, J., & Piran, P. (2020). Cerebral cortex. *Functional and Clinical Neuroanatomy*, 177–240. https://doi.org/10.1016/b978-0-12-817424-1.00006-9

Nath, A., & Beauchamp, M. S. (2011). Dynamic changes in superior temporal sulcus connectivity during perception of noisy audio-visual speech. *Journal of Neuroscience*, *31*(5), 1704–1714. https://doi.org/10.1523/JNEUROSCI.4853-10.2011

Nota, Y. (2004). Brain regions involved in motor control of speech. 2004 by the Acoustical Society of Japan. Retrieved October 7, 2022, from https://www.jstage.jst.go.jp/article/ast/25/4/25_4_286/_article

Ohashi, H., & Ostry, D. J. (2021). Neural development of speech sensorimotor learning. *Journal of Neuroscience, 41*(18), 4023–4035. https://doi.org/10.1523/jneurosci.2884-20.2021

Ozker, M., Schepers, I. M., Magnotti, J. F., Yoshor, D., & Beauchamp, M. S. (2017). A double dissociation between anterior and posterior superior temporal gyrus for processing audio-visual speech demonstrated by electrocorticography. *Journal of Cognitive Neuroscience*, *29*(6), 1044–1060. https://doi.org/10.1162/jocn_a_01110

Palmer, E. D., Rosen, H. J., Ojemann, J. G., Buckner, R. L., Kelley, W. M., & Petersen, S. E. (2001). An event-related fmri study of overt and covert word stem completion. *NeuroImage*, *14*(1), 182–193. https://doi.org/10.1006/nimg.2001.0779

Paus, T., Perry, D. W., Zatorre, R. J., Worsley, K. J., & Evans, A. C. (1996). modulation of cerebral blood flow in the human auditory cortex during speech: role of motor-to-sensory discharges. *European Journal of Neuroscience*, *8*(11), 2236–2246. https://doi.org/10.1111/j.1460-9568.1996.tb01187.x

Pinker, S. (1984). *Language Learnability and Language Development: First Edition (Cognitive Science Series)*. Harvard University Press.

Price, C. (2011). A generative model of speech production in Broca's and Wernicke's areas. *Frontiers in Psychology*, *2, 1-8*. https://doi.org/10.3389/fpsyg.2011.00237

Price, C. J., Wise, R. J. S., Warburton, E. A., Moore, C. J., Howard, D., Patterson, K., Frackowiak, R. S. J., & Friston, K. J. (1996). Hearing and saying. *Brain*, *119*(3), 919–931. https://doi.org/10.1093/brain/119.3.919

Rangus, I., Fritsch, M., Endres, M., Udke, B., & Nolte, C. H. (2021). Frequency and phenotype of thalamic aphasia. *Journal of Neurology*, 269(1), 368–376. https://doi.org/10.1007/s00415-021-10640-4

Rasskazova, O., Mooshammer, C., & Fuchs, S. (2019). Temporal coordination of articulatory and respiratory events prior to speech initiation. *Interspeech*, 884–888. https://doi.org/10.21437/interspeech.2019-2876

Rauschecker, J. P. (2015). Auditory and visual cortex of primates: a comparison of two sensory systems. *European Journal of Neuroscience*, *41*(5), 579–585. https://doi.org/10.1111/ejn.12844

Rivera-Urbina, G. N., Martínez-Castañeda, M. F., Núñez-Gómez, A. M., Molero-Chamizo, A., Nitsche, M. A., & Alameda-Bailén, J. R. (2022,). Effects of tDCS applied over the left IFG and pSTG language areas on verb recognition task performance. *Psychophysiology, 59*, e14134. https://doi.org/10.1111/psyp.14134

Schönwiesner, M., Novitski, N., Pakarinen, S., Carlson, S., Tervaniemi, M., & Näätänen, R. (2007). Heschl's gyrus, posterior superior temporal gyrus, and mid-ventrolateral prefrontal cortex have different roles in the detection of acoustic changes. *Journal of Neurophysiology*, *97*(3), 2075–2082. https://doi.org/10.1152/jn.01083.2006
Seldon, H. (1981). Structure of human auditory cortex. I. Cytoarchitectonics and dendritic distributions. *Brain Research*, *229*(2), 277–294. https://doi.org/10.1016/0006-8993(81)90994-x
Singh, A., Illa, A., & Ghosh, P. K. (2020). A Comparative Study of Estimating Articulatory Movements from Phoneme Sequences and Acoustic Features. *ICASSP 2020 - 2020 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP),* 7334–7338. https://doi.org/10.1109/icassp40776.2020.9053852
Sira, C., & Mateer, C. (2014). Frontal Lobes. *Encyclopedia of the Neurological Sciences*, 358–365. https://doi.org/10.1016/b978-0-12-385157-4.01148-9
Sobirjonovich, S. I. (2021). Speech Education for Children from 1 To 3 Years of Age. *International Journal of Innovative Analyses and Emerging Technology*, *1*(7), 135-141.
Tatham, M., & Morton, K. (2011). A Guide to Speech Production and Perception. *Edinburgh University Press*. https://doi.org/10.1515/9780748636532
Tomaiuolo, F., Campana, S., Voci, L., Lasaponara, S., Doricchi, F., & Petrides, M. (2021). The precentral insular cortical network for speech articulation. *Cerebral Cortex*, *31*(8), 3723–3731. https://doi.org/10.1093/cercor/bhab043
Töpper, R., Mottaghy, F. M., Brügmann, M., Noth, J., & Huber, W. (1998). Facilitation of picture naming by focal transcranial magnetic stimulation of Wernicke's area. *Experimental Brain Research*, *121*(4), 371–378. https://doi.org/10.1007/s002210050471
Uddin, L. Q., Nomi, J. S., Hébert-Seropian, B., Ghaziri, J., & Boucher, O. (2017). Structure and function of the human insula. *Journal of Clinical Neurophysiology*, *34*(4), 300–306. https://doi.org/10.1097/wnp.0000000000000377
Van Atteveldt, N., Formisano, E., Goebel, R., & Blomert, L. (2004). Integration of Letters and Speech Sounds in the Human Brain. *Neuron*, *43*(2), 271–282. https://doi.org/10.1016/j.neuron.2004.06.025
Wang, Z., Yan, X., Liu, Y., Spray, G. J., Deng, Y., & Cao, F. (2019). Structural and functional abnormality of the putamen in children with developmental dyslexia. *Neuropsychologia, 130*, 26–37. https://doi.org/10.1016/j.neuropsychologia.2018.07.014
Wang, D., Lipski, W. J., Bush, A., Chrabaszcz, A., Dastolfo-Hromack, C. A., Dickey, M., Fiez, J. A., & Richardson, R. M. (2022). Lateralized and region-specific thalamic processing of lexical status during reading aloud. *Journal of Neuroscience*, *42*(15), 3228–3240. https://doi.org/10.1523/jneurosci.1332-21.2022
Werner, R., Fuchs, S., Trouvain, J., & Möbius, B. (2021). Inhalations in speech: acoustic and physiological characteristics. *Interspeech*. https://doi.org/10.21437/interspeech.2021-1262
Whiteside, S. P. (1993). Peter B. Denes and Elliot N. Pinson The Speech Chain: The Physics and Biology of Spoken Language, 2nd edition. Oxford: W.H. Freeman and Company, 1993. Pp. 246 Pb. ISBN 0–7167-2344-1. *Journal of the International Phonetic Association*, *23*(2), 98–101. https://doi.org/10.1017/s0025100300004904
Wise, R., Chollet, F., Hadar, U., Friston, K., Hoffner, E., & Frackowiak, R. (1991). Distribution of cortical neural networks involved in word comprehension and word retrieval. *Brain*, *114*(4), 1803–1817. https://doi.org/10.1093/brain/114.4.1803
Wise, R., Greene, J., Büchel, C., & Scott, S. (1999). Brain regions involved in articulation. *The Lancet*, *353*(9158), 1057–1061. https://doi.org/10.1016/s0140-6736(98)07491-1
Wong, P. C., Warrier, C. M., Penhune, V. B., Roy, A. K., Sadehh, A., Parrish, T. B., & Zatorre, R. J. (2007). Volume of left Heschl's gyrus and linguistic pitch learning. *Cerebral Cortex*, *18*(4), 828–836. https://doi.org/10.1093/cercor/bhm115
Yamamoto, A. K., Parker Jones, O., Hope, T. M., Prejawa, S., Oberhuber, M., Ludersdorfer, P., Yousry, T. A., Green, D. W., & Price, C. J. (2019). A special role for the right posterior superior temporal sulcus during speech production. *NeuroImage*, *203*, 116184. https://doi.org/10.1016/j.neuroimage.2019.116184
Yang, J. H., & Kwan, A. C. (2021). Secondary motor cortex: Broadcasting and biasing animal's decisions through long-range circuits. *International Review of Neurobiology*, 443–470. https://doi.org/10.1016/bs.irn.2020.11.008
Yule, G. (1994). *The Study of Language: An Introduction*. Cambridge University Press.
Zaidel, E. (2001). Brain Asymmetry. *International Encyclopedia of the Social & Behavioral Sciences*, 1321–1329. https://doi.org/10.1016/b0-08-043076-7/03548-8
Zevin, J. (2009). Word Recognition. *Encyclopedia of Neuroscience*, 517–522. https://doi.org/10.1016/b978-008045046-9.01881-7