HEARING FIRST
Powering Potential

Entrain the Brain

Optimize Listening and Spoken Language Outcomes of Children With Hearing Loss

2020

Any professional working with children who have hearing loss knows that those who grow up in language-rich environments achieve far better outcomes than those who don't. Parents who narrate everyday life, who read aloud, and who describe the world around them raise children who thrive in the hearing world.

In the following paper, research scientist and audiologist, Dr. Jace Wolfe, guides us through groundbreaking studies that explore the neuroscience behind Listening and Spoken Language. Drawing on landmark imaging studies and the work of leading researchers in the field, Dr. Wolfe explains the relationship between auditory brain development and Listening and Spoken Language outcomes. In the last section of the paper, Dr. Wolfe offers actionable steps that parents and professionals can take to optimize auditory brain development for incredible results.

At Hearing First, we are unwavering in our mission to empower children who are deaf or hard of hearing to reach their full potential. Whether you are a professional, a family member of a child with hearing loss, or you have hearing loss yourself, I hope that you find the following report inspiring and affirming.

With you on the journey,
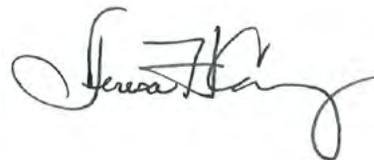
Dr. Teresa H. Caraway, PhD, CCC-SLP, LSLS Cert. AVT
CEO, Hearing First

Congenital Hearing Loss is a Neurodevelopmental Emergency

Fifteen years ago, I heard Dr. Carol Flexer, an esteemed pediatric audiologist and Listening and Spoken Language Specialist, deliver an excellent presentation on the importance of early identification and early intervention for children with hearing loss. Although I was impressed by several of the lessons Dr. Flexer imparted on that day, one of her statements particularly stood out. She exclaimed, "Congenital hearing loss is a neurodevelopmental emergency!"

At that time, I associated her statement with the well-known critical period of language development that acknowledges the fact that children must be exposed to a robust model of intelligible speech during the first few years of life in order to acquire age-appropriate listening and spoken language skills. Additionally, I associated Dr. Flexer's neurodevelopmental emergency and auditory brain development with functional changes that occur in the auditory cortices.

More recently, as I have immersed myself into the latest neuroscience literature, I have broadened my understanding of the importance of the lesson Dr. Flexer was providing when she spoke about hearing loss as a neurodevelopmental emergency. Fascinating neuroscience studies have demonstrated that many areas across the entire brain are active when we listen to and comprehend spoken language (HASSON ET AL., 2008, 2010, 2012; KRAL, 2013; KRAL ET AL., 2017, 2019; NATASE ET AL., 2019; YUSUF ET AL., 2017). From these studies, we understand that the neurodevelopmental emergency associated with congenital hearing loss does not just reside within the

auditory cortex, but also in complex neural networks that underlie listening and spoken language (LSL) and that exist throughout the brain. Moreover, we now understand that auditory brain development is reliant upon the formation of reciprocal networks between the auditory cortices and several other areas of the brain that govern higher-order functions. Subsequently, we also understand that the creation of auditory neural networks during the critical period not only cultivates LSL abilities but also fosters the development of many other vital skills including literacy aptitude, executive function, social-emotional skills, sensory integration, sequential processing, etc. (FATZER & ROBERTS, 2012; HOLMES ET AL., 2015; KRAL ET AL., 2016; SIPAL & BAYHAN, 2011).

Neural Entrainment Is Necessary For Comprehension During Human Communication

Additionally, from the brilliant work of neuroscientist Uri Hasson and colleagues, we know that the areas of the brain that are involved when we read and comprehend a story are the same areas of the brain that are active when we tell that story to a friend or colleague; likewise, the same areas of the listener's brain are active when she/he listens to and comprehends the story we are telling. Professor Hasson uses the word *neural entrainment* to refer to the intersubject similarity in neural responses that occurs in the brains of a talker and listener when the listener understands the message of the talker (i.e., intersubject neural alignment, intersubject correlation of neural responses) (HASSON 2016). Indeed, Hasson and colleagues (HASSON ET AL., 2008, 2010, 2012; HONEY ET AL., 2012; LERNER ET AL., 2011; NATASE ET AL., 2019; STEPHENS ET AL., 2010; YESHURUN ET AL., 2017) have shown that neural entrainment is necessary for comprehension during human communication. A more detailed description of neural entrainment and its relationship to auditory brain development will be provided later in this paper.

Historically, research studies examining the outcomes of children with hearing loss have been characterized by a great deal of variability with some children demonstrating age-appropriate LSL abilities, whereas others exhibit significant delays (CHING ET AL., 2013, 2018; GEERS ET AL., 2003, 2011; NIPARKO ET AL., 2010). More recently, however, research has suggested that the majority of children who receive a cochlear implant prior to 1 year of age develop age-appropriate LSL skills and achieve outcomes that are superior to children who receive cochlear implants between 1 to 3 years of age. Furthermore, many early-implanted children achieve age-appropriate LSL skills (CHING ET AL., 2018; DETTMAN ET AL., 2016; HOFF ET AL., 2019; LEIGH ET AL., 2016). The provision of a cochlear implant during the first 6 to 12 months of age allows for immediate access to speech and a language-rich listening environment, which subsequently allows for typical auditory brain development and the formation of auditory neural networks that span throughout the brain (KRAL ET AL., 2013, 2016, 2017, 2019).

Optimize Auditory Brain Development

Collectively, the spoken language outcomes studies of Dettman, Ching, Hoff, Leigh, and colleagues, as well as the neuroscience studies of renowned auditory physiologist Professor Andrej Kral and other neuroscientists, suggest that the outcomes of children with hearing loss are intimately dependent upon early access to intelligible speech and the consequent auditory brain development that follows. When pediatric hearing healthcare clinicians provide early and sufficient access to intelligible speech via the prompt provision of appropriately selected and fitted hearing technology and when caregivers are coached to create a language-rich listening environment, age-appropriate LSL outcomes are not just possible, they are probable. The primary objective of this paper is to highlight the vital relationship between auditory brain development and the LSL outcomes of children with hearing loss. The relationship between auditory brain development and LSL outcomes will be discussed from a neuroscience perspective with a focus on the following specific topics:

1. A basic discussion of elementary neuroanatomy and neurophysiology,

2. A review of auditory connectomes, neural networks, and neural entrainment,

3. A review of landmark imaging studies exploring auditory brain function of cochlear implant recipients,

4. A review of physiologic mechanisms underlying changes that potentially occur in the brains of children with hearing loss when auditory deprivation occurs during the critical period of language development (e.g., cross-modal reorganization),

5. A description of the functional implications of auditory brain development, *and*

6. A discussion of basic steps to optimize auditory brain development.

When pediatric hearing healthcare clinicians provide early and sufficient access to intelligible speech via the prompt provision of appropriately selected and fitted hearing technology and when caregivers are coached to create a language-rich listening environment, age-appropriate listening and spoken language outcomes are not just possible, they are probable.

Purpose

The purpose of this paper is to highlight the vital relationship between auditory brain development and the listening and spoken language outcomes of children with hearing loss.

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A (Very) Basic Primer on Neuroanatomy and Physiology

The Basics of Neuroanatomy

The bulk of the brain is comprised of the **cerebrum**, which is made up of two halves called **cerebral hemispheres** (SEE FIGURE 1). The cerebral hemispheres are separated by a deep groove known as the longitudinal fissure. The surface of the brain is called the **cortex**, and it possesses a gray appearance (hence the term *gray matter*) because it is comprised of neurons that are not covered with myelin at the brain's surface. The width of the cortex is thin (1.5 to 4.5 mm), but it consists of six layers of neurons. The arrangement and operation of these cortical layers serve a very important purpose in the development and function of neural networks and will be discussed in detail later. Of note, the cerebral cortex is comprised of folded tissue, which allows a larger volume of cerebral matter to fit into the skull. The ridges of the folded tissue are called **gyri** (which is the plural form of **gyrus**), whereas the grooves between the ridges are called **fissures** or **sulci** (which is the plural form of **sulcus**) (ANDREATTA, 2020; BHATNAGAR, 2002; MUSIEK, 1986A; MUSIEK & BARAN, 2020).

FIGURE 1

## Cerebal Hemispheres Divided by the Longitudinal Fissure

Longitudinal Fissure

Right Cerebral Hemisphere

Left Cerebral Hemisphere

Superior View
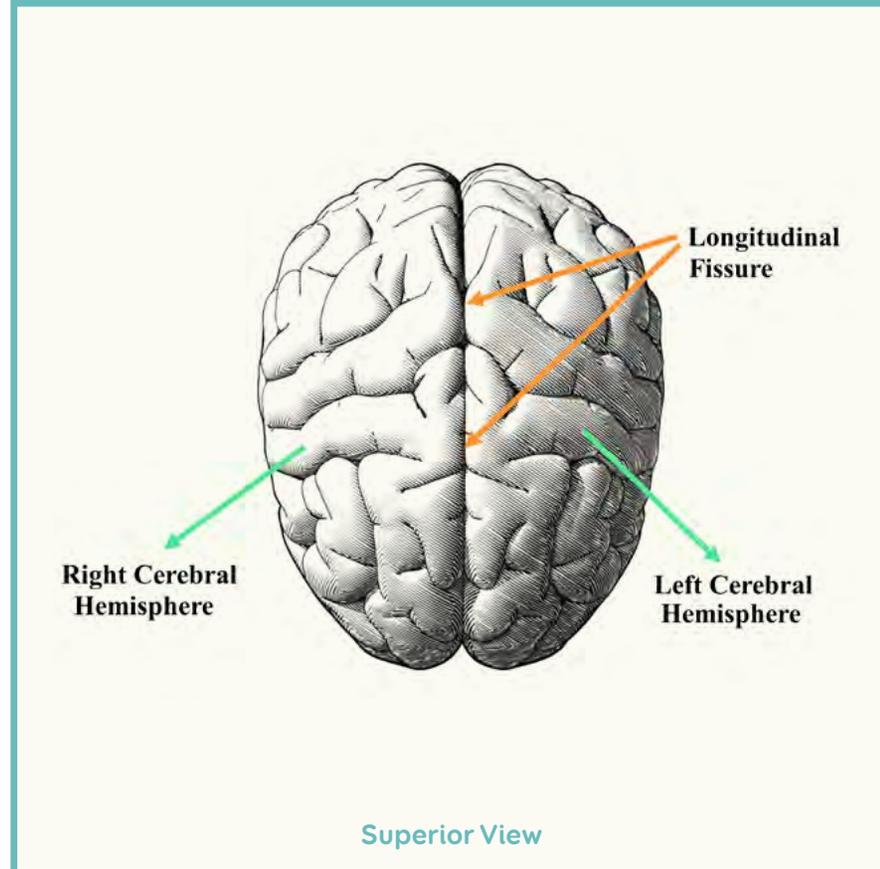
Primary Lobes of the Brain
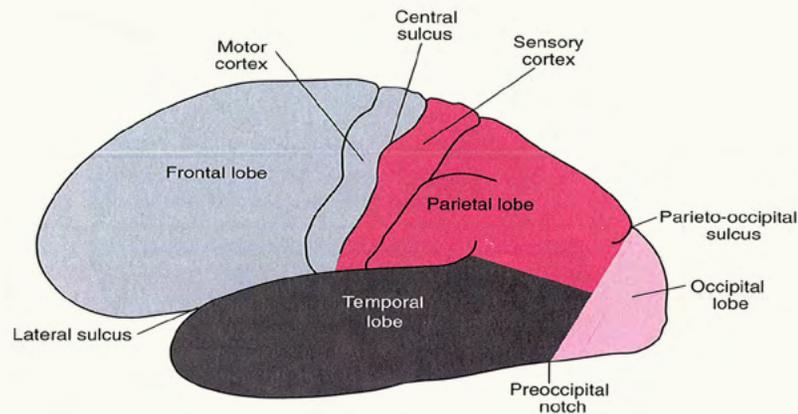
The lateral surface of the left cerebral hemisphere is shown in FIGURE 2 along with the functional lobes of the brain. The frontal lobe is the largest lobe of the brain, and it is involved in a wide variety of functions. The anterior (front) portion of the frontal lobe, known as the prefrontal cortex, has been shown to serve cognitive functions including higher-order thinking, executive function, reasoning, intelligence, decision making, problem solving, impulse control, abstract thinking, formation of memories, emotional expression and regulation, managing attention, regulation of personality, etc. (SEE ANDREATTA, 2020, AND MUSIEK & BARAN, 2020 FOR REVIEW). The inferior prefrontal cortex is also known to serve an important role in communication as it has been shown to be active during speech production, speech perception, and reading. The inferior prefrontal cortex in the left cerebral hemisphere is also known as Broca's region. When an individual suffers an injury to Broca's region (e.g., a stroke), she/he often experiences difficulty with producing intelligible speech. Broca's region has also been shown to play an important role in phonemic awareness (i.e., an understanding of the sound-to-letter relationship wherein the *A* says /ah/, the *B* says /buh/, etc.). Additionally, the posterior portion of the frontal lobe (i.e., the gyrus that resides just in front of the central sulcus), known as the motor cortex, is the primary area of the brain responsible for regulating motor function across the body, including speech movements.

The parietal lobe resides posterior (behind) the central sulcus. The gyrus that sits just behind the central sulcus, known as the primary sensory cortex, is responsible for somatosensory sensation (i.e., the sense of touch, pain, tactile sensation). The remainder of the parietal cortex plays a role in synthesizing and integrating the input from all of our sensory systems. For instance, the parietal lobe also provides sensory feedback to the muscles that control articulation to allow for speech production. Furthermore, the parietal lobe contributes to the integration of auditory stimuli with other sensory information.

As a result, the parietal lobe plays a role in pairing the sounds of life with the sources that create those sounds (e.g., repeatedly brushing my hand across my sleeve makes a "shh, shh, shh" sound).

Additionally, the parietal lobe has been shown to support spatial orientation and the processing of visual input in the peripheral field (BUCKLEY & TOBEY, 2011). Moreover, the parietal lobe most likely contributes to higher-order cognitive functions (but to a much lesser extent than the frontal lobe), such as attention, memory, etc.

The occipital lobe resides at the most posterior (rearward) location of the cerebrum. The occipital lobe is the smallest lobe of the brain, but it is vitally important as it houses the visual centers of the brain. The occipital lobe processes visual information, assists in regulating memory of visual stimuli, assists in spatial orientation, and interacts with the rest of the brain so that visual information may be integrated with other sensory information and brain regions.

The temporal lobe is located below and primarily behind the frontal lobe, below the parietal lobe (i.e., just below the lateral fissure/Sylvian fissure), and just in front of the occipital lobe. The temporal lobe is primarily responsible for processing auditory stimuli. It is important to note, however, that auditory stimuli are also processed in regions outside the temporal lobe (particularly the frontal and parietal lobes). The auditory cortex is made up of two somewhat loosely defined regions: the **primary auditory cortex** and the **secondary auditory cortex**.

Figure 3 provides a visual depiction of some of the areas that are thought to make up the primary and secondary cortices.

FIGURE 3

A Lateral View of the Left Cerebrum with Representation of Primary and Secondary Auditory Cortices
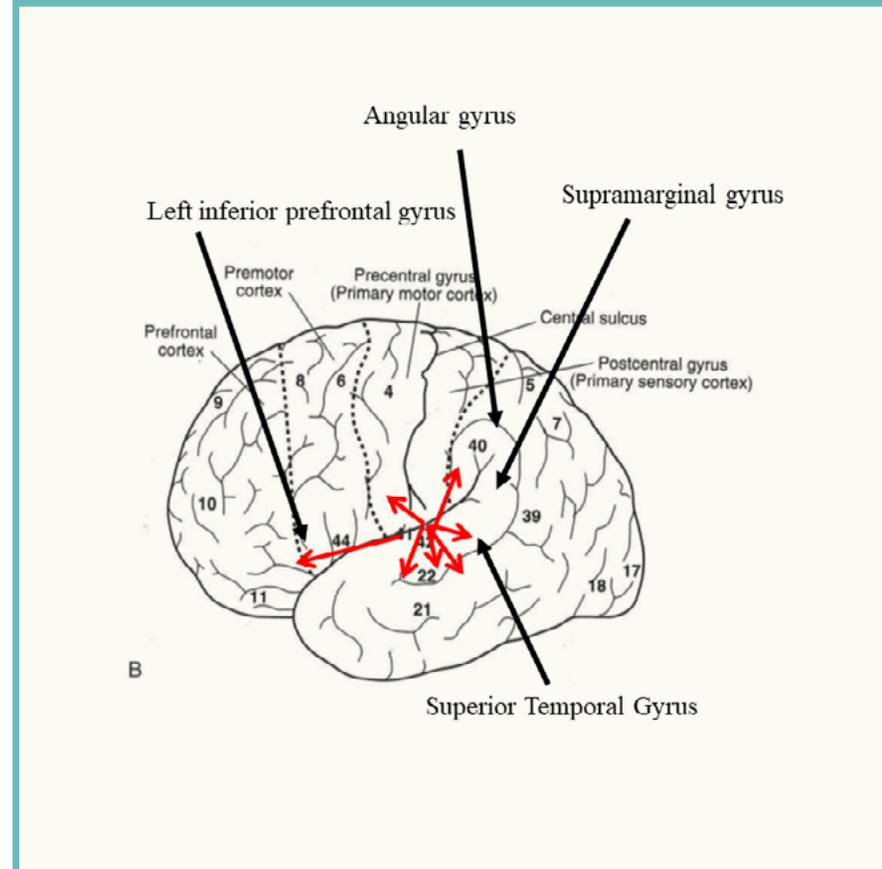
The Auditory Cortices

The borders of the primary auditory cortex are more clearly defined than those of the secondary auditory cortex. Primary auditory cortex is generally considered to reside at Brodmann area 41 (from the German anatomist Korbinian Brodmann's numbered map of the brain based on the structure and organization of the brain's cells, i.e., neuronal structure/cytoarchitecture, within given regions [BRODMANN, 1909]; SEE FIGURE 3). However, the vast majority of primary auditory cortex cannot be viewed from the lateral surface of the brain. Upon removal of portions of the frontal and parietal lobes, **Heschl's gyrus**, which is widely considered to be the location of the primary auditory cortex, may be clearly visualized (SEE FIGURE 4). Like the remainder of the auditory system before it, the primary auditory cortex is tonotopically organized with low-frequency auditory signals processed at particular locations of Heschl's gyrus and high-frequency auditory information processed in other locations (SEE FIGURE 3). The tonotopic arrangement of the primary auditory cortex is relevant because it likely plays an important role in the auditory system's exquisite ability to code the unique acoustical characteristics (e.g., spectral/frequency/pitch, temporal, and intensity properties) that represent the almost infinite number of sounds we encounter in our daily lives.

FIGURE 4

Portions of the Frontal and Parietal Lobes Have Been Removed to Reveal the Primary Auditory Cortex (Heschl's Gyrus)
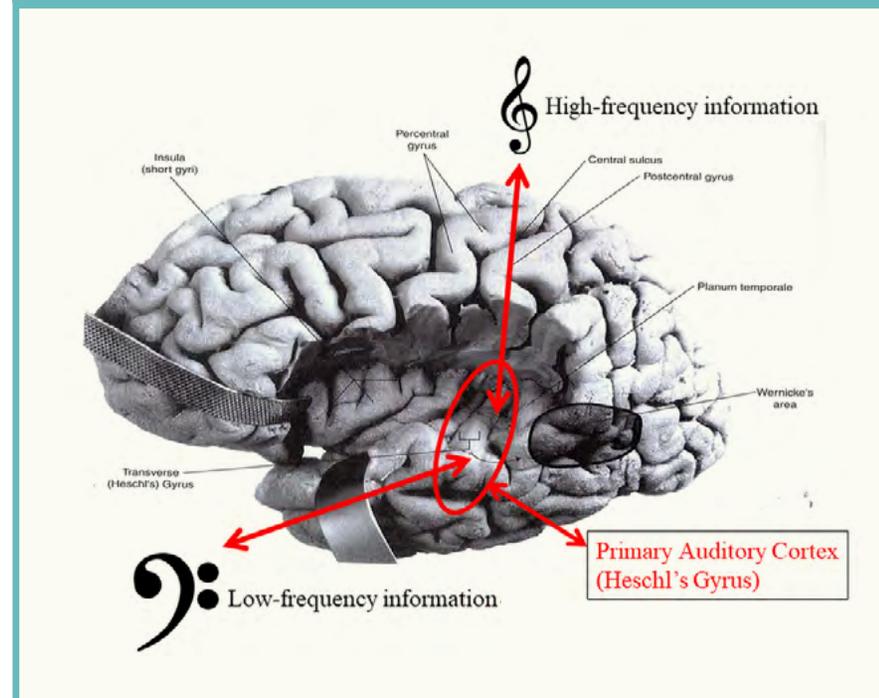
FIGURE 5

# A Coronal View of the Auditory System
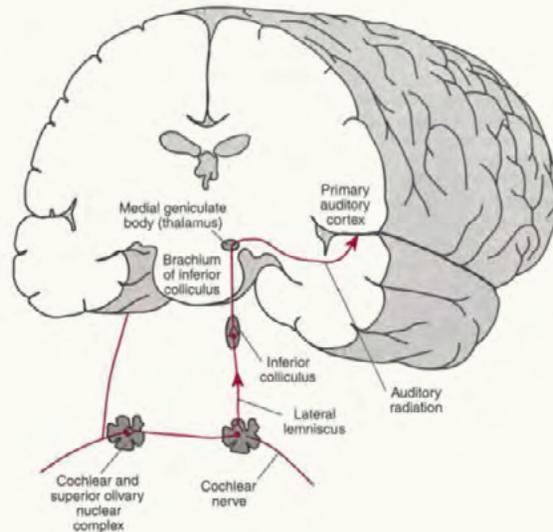
Figure 5 Shows the majority of the auditory response to left-ear simulation arriving at the primary auditory cortex in the right hemisphere.

The primary auditory cortex receives most of its auditory information from the auditory neurons in the thalamus, specifically within the ventral portion of the medial geniculate nucleus of the thalamus (SEE FIGURE 5).

The majority of the auditory information from each ear crosses in the lower brainstem and eventually arrives at the primary auditory cortex on the opposite side of the head

(i.e., the majority of the information from the right ear eventually arrives at the primary auditory cortex within the left hemisphere).

Secondary auditory cortex is far less well-defined than primary auditory cortex. Secondary auditory cortex is thought to primarily consist of the areas of the brain that surround or encapsulate primary auditory cortex. In fact, some researchers have suggested that secondary auditory cortex resembles a belt that surrounds primary auditory cortex (HACKETT, STEPNIEWSKA, & KAAS, 1998; KAAS & HACKETT, 1998; KAAS, HACKETT, & TRAMO, 1999; HACKETT, PREUSS, & TRAMO, 2001). However, the belt concept may not entirely account for the fact that some sound-responsive areas within and around the temporal lobe are not immediately adjacent to Heschl's gyrus.

Nonetheless, secondary auditory cortex is believed to include the following areas of the brain: superior temporal gyrus, supramarginal gyrus, angular gyrus, planum temporale, insula, medial temporal gyrus, inferior temporal gyrus, the inferior precentral and postcentral gyri, and the posterior-inferior frontal gyrus. Of note, injury to Wernicke's area (BRODMANN AREA 42; SEE FIGURE 4), which is thought to exist within the superior temporal gyrus and planum temporale on the left side of the brain, results in the affected individual's inability to comprehend speech.

The primary functions of the secondary auditory cortex are potentially more important than its anatomical boundaries. In grossly simplified terms, the secondary cortex most likely serves two primary purposes:

1. To serve as a "launching pad" to distribute auditory information to the rest of the brain, *and*

2. To provide feedback from higher-order areas of the brain back to primary auditory cortex to sharpen the latter's ability to focus ("tune in") on the most relevant properties of the auditory signal and inhibit ("tune out") the less important auditory information.

Interhemispheric and Intrahemispheric Tracts

To understand how the secondary auditory cortex potentially serves as the "launching pad" to distribute sound to the rest of the brain for integration with other sensory systems and areas of higher-order processing, it is necessary to discuss ***interhemispheric*** and ***intrahemispheric fiber tracts***. Most individuals who work within the speech and hearing profession are familiar with the primary interhemispheric tract of the brain, the ***corpus callosum***, which is a large, myelinated bundle of nerve fibers that transmit information between the right and left cerebral hemispheres (ANDREATTA, 2020; BHATNAGAR, 2002; MUSIEK, 1986B; MUSIEK & BARAN, 2020). Fewer individuals may be familiar with ***intrahemispheric tracts***, which are bundles of nerve fibers that carry information (neural impulses) from one region of the brain to another within the same cerebral hemisphere (BHATNAGAR, 2002; MUSIEK, 1986B; MUSIEK & BARAN, 2020).

Intrahemispheric fiber tracts exist between the primary and secondary auditory cortices to allow for an exchange of information from primary regions of the auditory cortex to higher-order areas.

The arcuate fasciculus is a good example of an intrahemispheric fiber tract. The arcuate fasciculus is a bundle of nerve fibers that transmit information from secondary auditory cortex to the frontal lobe, including the inferior prefrontal cortex (BRODMANN AREA 44/BROCA'S REGION) (SEE FIGURE 6). The exchange of auditory information from the auditory cortex to inferior prefrontal cortex is critically important because the latter is known to contribute to speech production, phonemic awareness, and literacy development, among other functions. Infants learn to speak by listening to others talk. As a result, the transfer of auditory information from secondary auditory cortex to left inferior prefrontal cortex is essential to the process of spoken language development as well as phonemic and phonological awareness (i.e., understanding the letter to sound relationship; e.g., the "B" says /buh/), which are necessary for a child to learn to read. In short, intrahemispheric tracts are of vital importance because without their presence, auditory information would be confined to the primary auditory cortex. It is the exchange of auditory information from primary auditory cortex to secondary auditory cortex and then to the rest of the brain that allows sound to "come to life" and possess higher-order meaning. In short, it is the "launching pad" function of secondary auditory cortex that "brings sound to life" and allows sound to be meaningful (KRAL, 2013; KRAL ET AL., 2007, 2012, 2016, 2017, 2019).

FIGURE 6

A Midline Sagittal View of the Brain with Depiction of Intrahemispheric Tracts, Including the Arcuate Fasiculus

Superior longitudinal fasciculus

Arcuate fasciculus

Uncinate fasciculus

Inferior longitudinal fasciculus
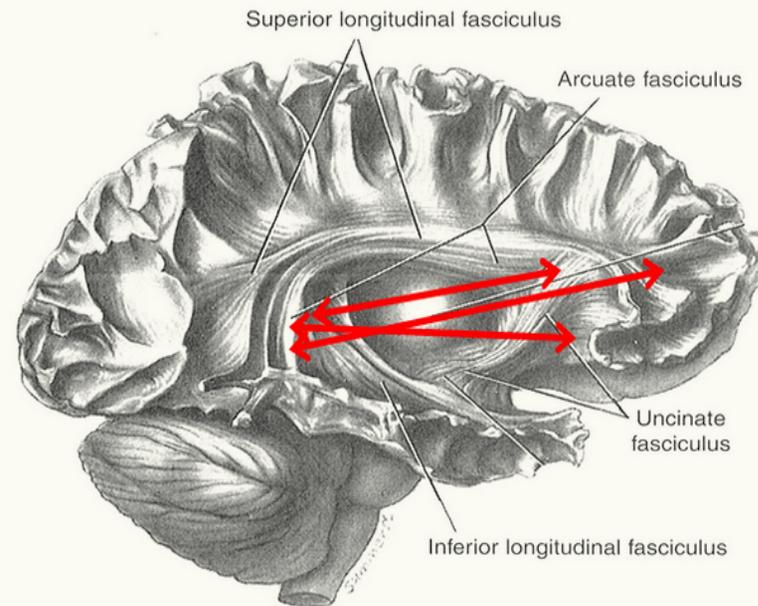
Auditory Features, Objects and Categories

As previously stated, the secondary auditory cortex also exchanges information with primary auditory cortex, and in the process, it modulates and influences the activity and function of primary auditory cortex. To elucidate this interactive relationship between the primary and secondary auditory cortices, it is helpful to first introduce the concepts of auditory features, auditory objects, and auditory categories. The term *auditory features* simply refers to the acoustical features of auditory stimuli.

Figure 7 provides an example of a spectrogram for the sentence, "The pool was filled with dirt and leaves." As shown, the basic acoustical properties of the signal (i.e., intensity, frequency, and temporal) provide physical cues that allow for an identifiable representation of the sound. In other words, the auditory system processes these acoustic features to identify incoming sounds.

FIGURE 7   **Spectrogram of the Sentence, "The Pool Was Filled with Dirt and Leaves."**
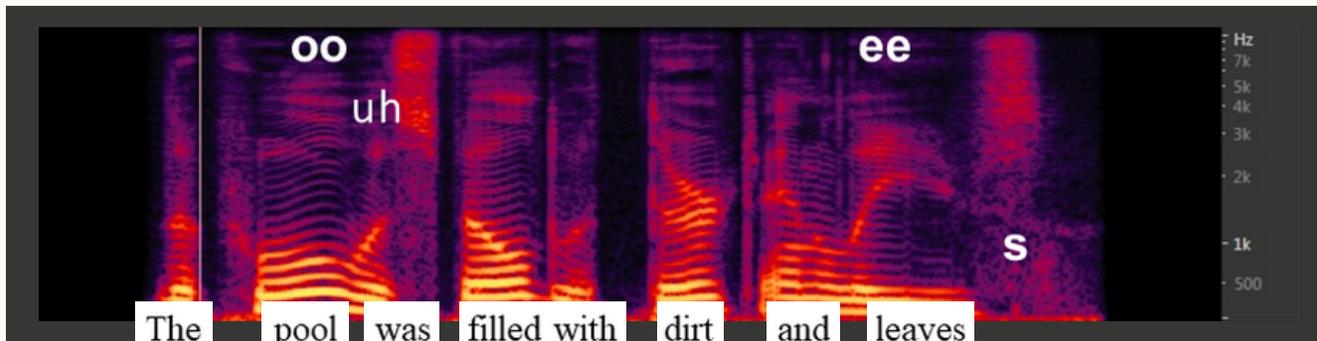
Auditory objects are neuronal representations of delimited acoustic patterns that are subject to foreground-background distinction (KRAL 2013). They are the computational result of the auditory system's ability to classify (group) features of incoming auditory stimuli into perceptual units based on the patterns of neurons that fire in response to the acoustical properties of the stimulus (BIZLEY & COHEN, 2013). For example, an auditory object represents the auditory system's ability to perceive the unit "pool" after decoding the neural response patterns that are elicited by the acoustical features of the phonemes /p/, /oo/, and /l/.

The term **auditory categories** represents groups of auditory objects that share similar common meanings or properties. For instance, when listening to live music at a concert, auditory categories include the musical instruments, the singer's vocals, and the ambient noise. All three of the different types of sounds are present simultaneously, but the listener possesses the ability to segregate each and focus on what she/he prefers to hear. Of note, the musical instruments and vocals may reside in two separate categories, but together, they comprise one auditory object. In contrast, in a busy restaurant, the voices of several people speaking at once all fall within one auditory category (i.e., human speech), but the listener hopefully possesses the ability to separate the speech of each talker into separate auditory objects.

A Basic Primer on Auditory Neurophysiology

Although it is difficult to confirm via modern imaging and electrophysiologic assessments, many neuroscientists believe that the auditory features of incoming sounds are primarily processed and represented in primary auditory cortex, whereas auditory objects and categories are processed and perceived in secondary auditory cortex and higher-order areas of the brain **(BIZLEY & COHEN, 2013; RIESENHUBER & POGGIO, 2000, 2002)**. Specifically, the secondary auditory cortex likely plays several roles in the processing and perception of neural objects. As mentioned earlier, injury to Wernicke's area (Brodmann area 42) has been shown to result in a deficit in the ability to understand speech. Indeed, brain imaging research has shown secondary auditory cortex to be active when subjects listen to speech tokens in isolation **(KRAL & SHARMA, 2012)**. Moreover, and as previously discussed, secondary auditory cortex relays the auditory information to other areas of the brain for analysis and potentially for comprehension.

Furthermore, renowned auditory neuroscientist Professor Andrej Kral has proposed and demonstrated

evidence to support the theory that secondary auditory cortex possesses intrahemispheric fibers that project back to primary auditory cortex (KRAL, YUSUF, & LAND, 2017). These types of intrahemispheric fibers are known as *cortico-cortical* connections referring to the fact that neurons at one level of the cortex are transmitting signals to neurons at another area of the cortex. To specify, cortico-cortical connections allow bi-directional exchange of information with primary auditory cortex delivering signals to secondary auditory cortex (i.e., bottom-up processing), while also receiving signals from secondary auditory cortex and other higher-order areas of the brain (i.e., top-down processing). Kral and colleagues (2017) state,

"It is tempting to speculate that primary areas represent auditory features that are used to define auditory objects, whereas higher-order areas synthesize these features into auditory objects."

In Kral's view, however, the features and objects are intimately related and their processing is codependent; the primary and secondary areas instantaneously interact during sensory tasks, forming a functional auditory processing unit.

In addition, the top-down transmission of signals from higher-order areas of the brain to primary auditory cortex likely plays an important role in modulating the activity within primary auditory cortex. For instance, secondary auditory cortex and other higher-order areas may deliver signals that enhance (or "tune") the most important auditory features present within primary auditory cortex. For example, within the first few months of life, infants exhibit a preference for their mother's voice and for their native language (KUHL ET AL., 2003, 2004). It is possible that secondary auditory cortex is "sharpening" the acoustic features within primary auditory cortex that are associated with the mother's voice and native language. Likewise, in a noisy classroom or social setting, higher-order auditory areas may "tune in" to the acoustical features within primary auditory cortex that coincide

with the talker of interest. Further, even higher-order language areas (potentially in the frontal lobe) may leverage the listener's predictive powers to "fill in the gaps" when noise or insufficient audibility prevents the detection and recognition of certain acoustic elements in the signal. For instance, in a noisy veterinarian's office, a listener may not hear the /t/ and /s/ in the word *cats* but can still surmise that the word *cats* was spoken when someone nearby exclaims, "The cats are hissing!"

Top-down cortico-cortical projections may also be inhibitory in function. We live in a noisy world in which we are inundated with a cacophony of sounds. The typical auditory system has an impressive ability to suppress "background noise" and focus on the most relevant sounds within the listener's environment. The cortico-cortical projections most likely also serve to inhibit neural responses that occur to less unimportant auditory signals so that the auditory system may "focus" on the most germane signals.

Of note, secondary auditory cortex also contains pluripotent neurons. Pluripotent neurons are capable of responding to multiple sensory modalities. For instance, some neurons in associative regions, such as in the posterior region of the temporal lobe and in the parietal lobe, have been shown to be responsive to auditory, visual, and somatosensory

stimuli. The exact function of pluripotent neurons of the brain is unknown. However, it is plausible to suggest that pluripotent neurons in associative areas serve to integrate stimuli from multiple sensory systems.
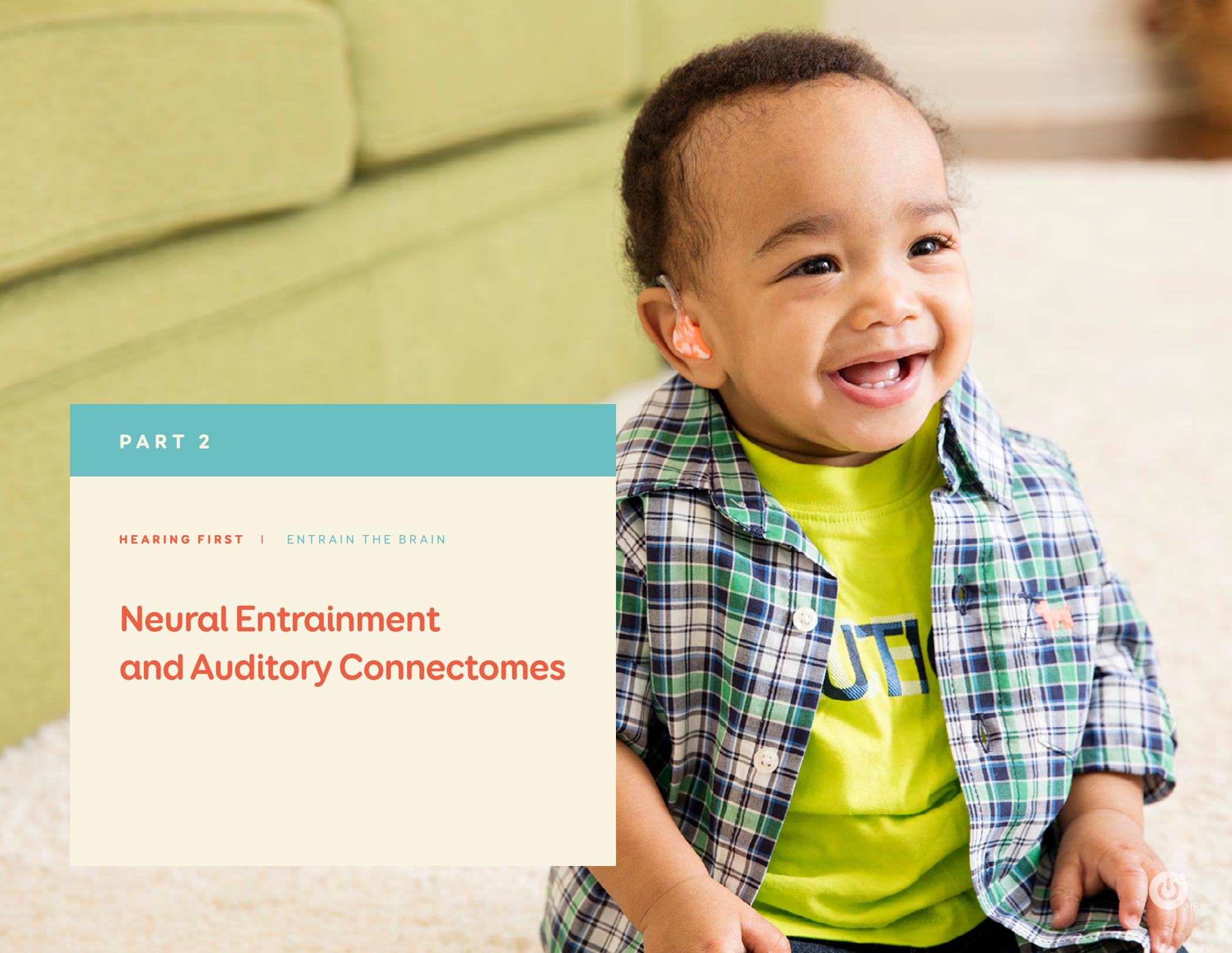
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# Neural Entrainment and Auditory Connectomes

Conscious Thought Represented as Patterns of Neural Activities

Clinical geneticist Kyle Kai-How Farh, M.D. **(2019)** stated, **"Everything that comes into our minds reduces to patterns of neural activities."** Stated differently, every sensory stimulus that is delivered to the brain elicits its own unique response from a specific set of neurons across the brain. In regard to the auditory system, every unique auditory object we perceive is associated with its own similarly unique pattern of neurons that responds to and ultimately produces the auditory object we perceive.

Figure 8 provides an elementary and grossly oversimplified illustration of the pattern of neural activities (i.e., neuronal responses) that may occur throughout the brain when a listener hears the word *green* in a conversation. In this example, please envision the stars as specific neurons that respond to the word *green*. As shown, a strong neuronal response is seen in primary and secondary auditory cortices, but neurons are also firing in higher-order areas such as what is depicted in the parietal lobe and particularly in the frontal lobe.

FIGURE 8

An Oversimplified Visual Representation of Neurons Responding to the Word *Green* When Spoken in a Conversation

The Stars are Intended to Represent Neural Activity
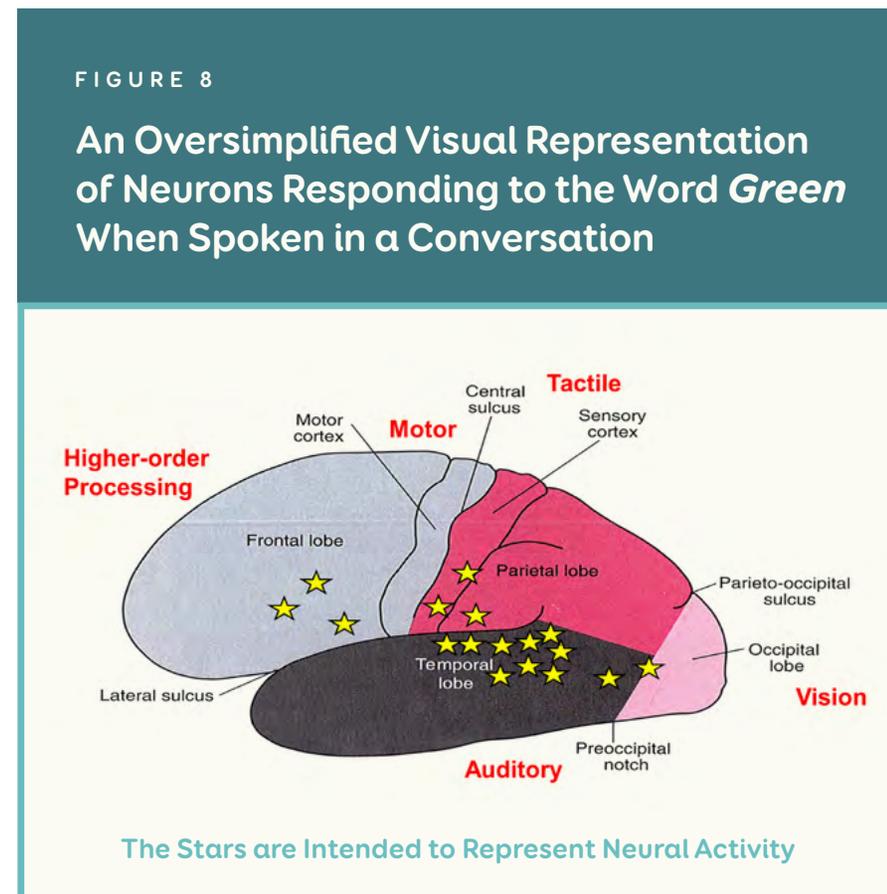
The activity in the primary auditory cortex is likely responsible for the processing of acoustical information in the acoustic elements (/guh/, /r/, /ee/, /n/) that make up the word *green*. The activity in secondary auditory cortex most likely contributes to the processing that is necessary to surmise the word (i.e., the auditory object) *green* from the acoustic elements. The engagement of neurons in the frontal lobe and parietal lobe, as well as the pluripotent neurons near the boundary of the temporal and occipital lobes, allows the sound to come to life and take on a higher-order meaning. The activity in the frontal lobe is what allows the listener to determine whether she/he likes or dislikes the color green. The responses in the inferior prefrontal cortex facilitate awareness of the phonemic units of *green*, which supports the ability to read the word *green* when the letters are seen in print and say the word *green* when speaking. Activity in pluripotent neurons in and around the occipital lobe allows the listener to see the color green in her/his mind's eye. When the word *green* is mentioned in a story, activity across the brain allows the listener to derive meaning from the word *green*. Depending on the context, the conversation, and the listener's previous experiences and predispositions, hearing the word *green* in conversation may cause the listener to think of money (if thinking about the U.S. dollar), Kermit the Frog, the Incredible Hulk, or a lush fairway at the Augusta National Golf Club. Engagement of the frontal lobe and other centers of the brain that govern opinions, emotions, and memories may cause the listener to have a wide range of thoughts including, *"Who would wear green jeans?," "I do not like the color green,"* or *"I need to eat more green vegetables so I can lose some weight and be healthier!"*

The more engaging, meaningful, or provocative a conversation, the more likely it is that a more robust pattern of neural activity will be elicited in response to the stimulus.

Figure 9 intends to represent the pattern of neural firing that may occur when a listener hears a chef talk about the best way to perfectly fry an egg while eggs sizzle in a pan. As shown, a larger number of neurons respond in this scenario compared to the response to the word *green*. When hearing the sound of the egg sizzling, the listener can likely close her/his eyes and see an image of an egg frying in a pan in her/his mind's eye. The engagement of higher-order areas of the brain may cause the listener's stomach to grumble because she/he begins to think about how much she/he loves eggs with cheese for breakfast. However, frontal lobe activity may also cause the listener to lament the high cholesterol present in fried eggs and question whether she/he should eat just one egg or maybe exercise on the treadmill for an extra 30 minutes after eating three eggs. The listener's mouth may water from the idea of how the eggs may feel in her/his mouth because of activity that occurs in the parietal lobe.

FIGURE 9

An Oversimplified Visual Representation of Neurons Responding to a Lesson on Frying the Perfect Egg as an Egg Sizzles in a Frying Pan
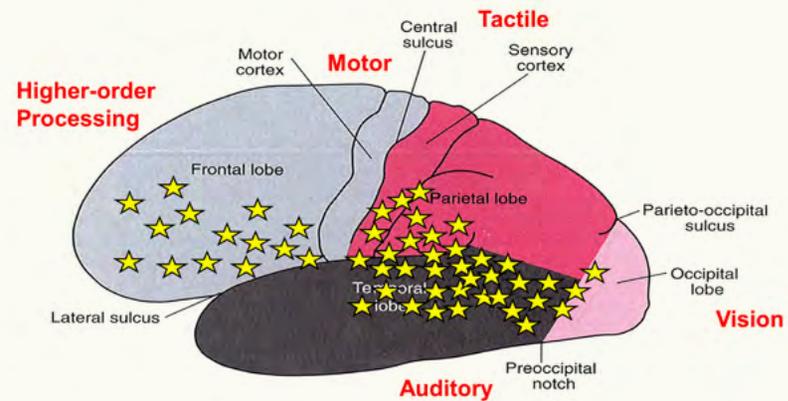
The Stars are Intended to Represent Neural Activity

Of note, the pattern of neural responses seen in the scenario in which the chef provides a demonstration of frying eggs is different than the pattern that occurs in response to the word *green*. As Dr. Farh said,

"Everything that comes into our minds reduces to a pattern of neural activities."

These patterns are uniquely associated with each individual auditory object we encounter in our lives. The pattern of neural activities is analogous to the bar codes that exist on price tags. At first glance, the bar codes all look similar. However, subtle nuances in the lines on the bar code allow for the coding of hundreds of thousands of products that are sold in a large big-box retail store. Similarly, the cortex of the human brain has tens of billions of neurons. The pattern in which these neurons fire allows listeners to code an infinite number of auditory objects.

Basic Neuronal Physiology

Neurons deliver signals across the brain by sending electrical impulses from one neuron to another. Neurons contain three basic components: a cell body, an **axon**, and **dendrites**.

(SEE FIGURE 10 FOR AN EXAMPLE OF A BIPOLAR NEURON)
(CAMPBELL, 1990)

The axon delivers the neural impulse from the cell body to neighboring neurons. The primary function of the dendrites is to receive the neural impulse being delivered from the axon. Each neuron contains only one axon but has many dendrites that branch out in several different directions to create a large surface area over which the neuron can receive electrical impulses from neighboring neurons. The tip of the axon resides in close proximity to a dendrite of a neighboring neuron, but the two do not make physical contact. The small space between the axon of the stimulating neuron and the dendrite of the receiving neuron is called a **synapse** (or a synaptic juncture).

FIGURE 10

An Example of a Bipolar Neuron with its Cell Body, Axon, and Dendrites
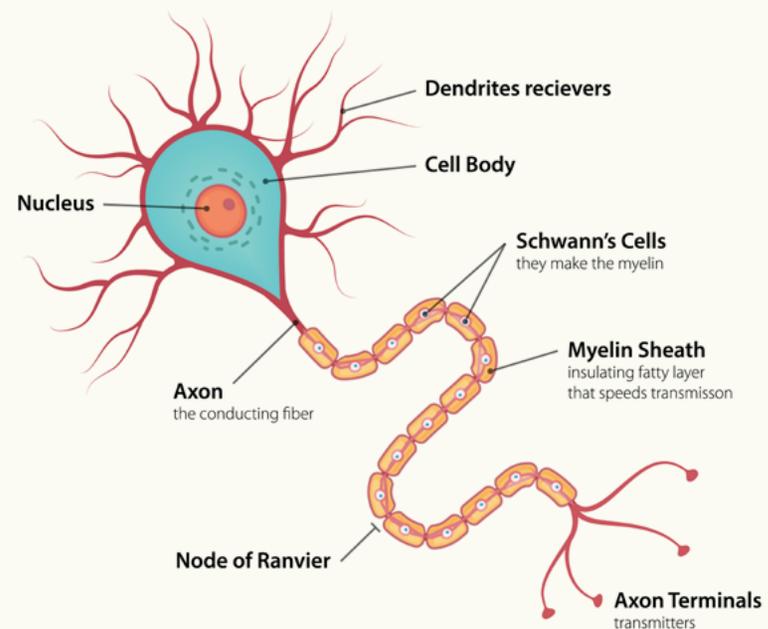
Dendrites recievers

Cell Body

Nucleus

Schwann's Cells
they make the myelin

Axon
the conducting fiber

Myelin Sheath
insulating fatty layer
that speeds transmisson

Node of Ranvier

Axon Terminals
transmitters

FIGURE 11

An Example of a Neuronal Synapse with Neurotransmitters Being Delivered into the Synaptic Junction to Stimulate the Receiving Neuron
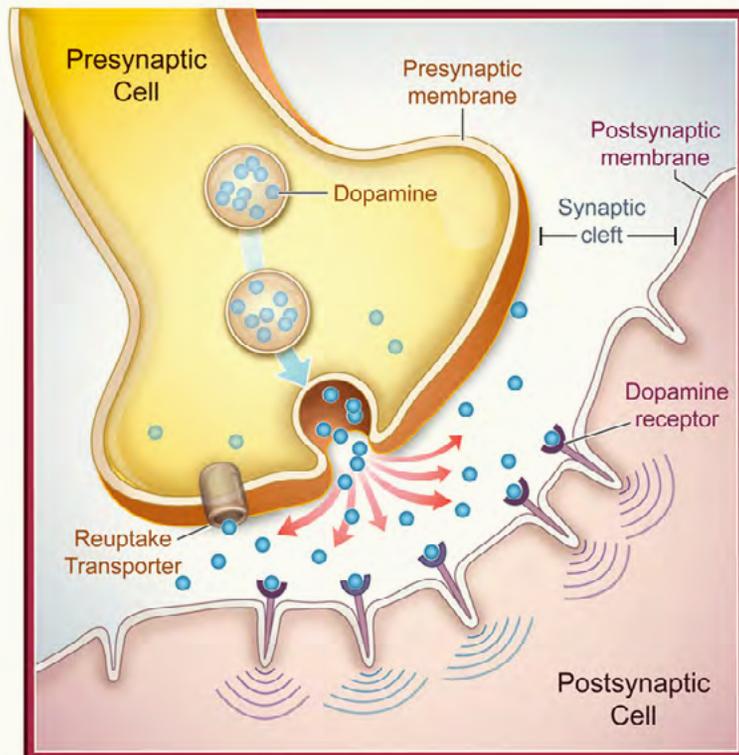
When the electrical impulse reaches the tip of an axon, a chemical called a ***neurotransmitter*** is released from the axon into the synapse (SEE FIGURE 11). The neurotransmitter can stimulate (i.e., an excitatory neurotransmitter) or inhibit (i.e., an inhibitory transmitter) the receiving neuron, causing it to either respond and generate its own electrical impulse or fail to respond, respectively. Neurotransmitters that cause the receiving neuron to generate its own electrical impulse are called ***excitatory neurotransmitters***, whereas neurotransmitters that prevent a receiving neuron from firing are called ***inhibitory neurotransmitters***. When the receiving neuron is sufficiently stimulated by excitatory neurotransmitters, it generates an electrical impulse that travels from the cell body down its axon and eventually causes the release of a neurotransmitter that stimulates another neighboring cell. Through this process, neural information may be exchanged in the form of electrical impulses delivered via synapses from neuron to neuron across and throughout the brain (CAMPBELL, 1990).

Neural Circuits and Networks

Neuroscientists use the terms **neural circuits** and **neural networks** to describe the manner in which groups of neurons work together to convert sensory stimuli into complex perceptions and thoughts (PURVES, 2011). The term **neural circuits** describes groups of neurons that are interconnected through numerous synapses to execute a particular function (e.g., process the acoustical features within a speech token, decode the acoustical features into auditory objects) (PURVES, 2011). Neural networks are comprised of a number of neural circuits that are interconnected via synapses and intrahemispheric fiber tracts. Consistent with Kai-How Farh's premise that "everything that comes into our minds reduces to a pattern of neural activities," neural networks manifest through a pattern of neural firings that occur across the different functional centers of the brain as we process sensory stimuli into perceptual thought.

Figure 12 provides an example of a neural network that supports a variety of vital functions.

FIGURE 12

A Simplified Illustration of Neural Networks that Govern Numerous Functions that Support Everyday Activities
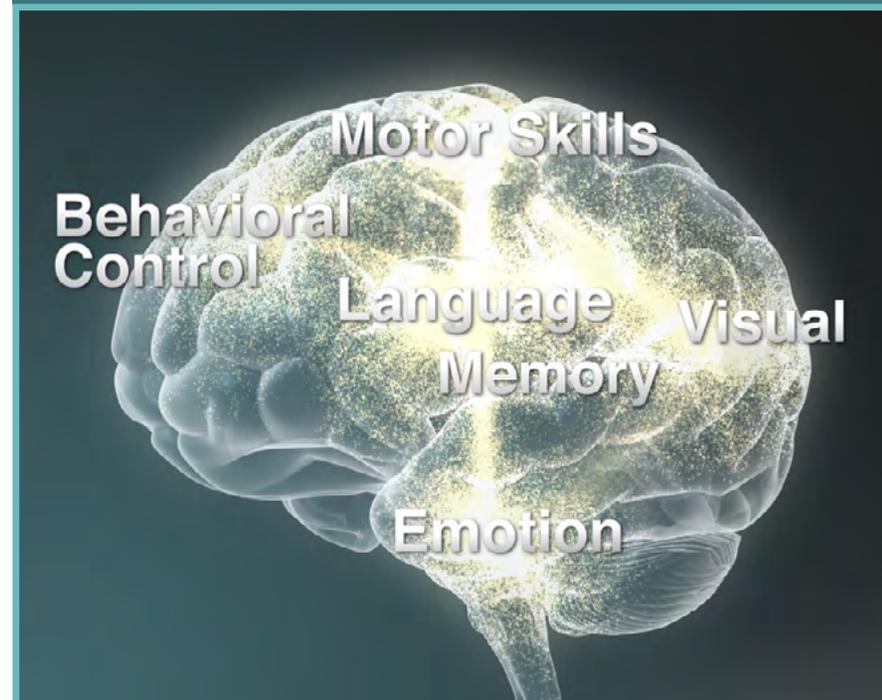
Professor Hasson and Neural Entrainment

Recent work by acclaimed neuroscientist Professor Uri Hasson of Princeton University has demonstrated the powerful role that neural networks play in supporting listening and spoken language that occurs during human communication (HASSON ET AL., 2008, 2010, 2012; HONEY ET AL., 2012; LERNER ET AL., 2011; NATASE ET AL., 2019; STEPHENS ET AL., 2010; YESHURUN ET AL., 2017). Dr. Hasson and colleagues have used functional magnetic resonance imaging (fMRI) and electroencephalography (EEG "brainwaves") to explore the responses that occur during listening and spoken language.

Figure 13 provides an example of EEG activity that was recorded while a group of listeners were at rest (i.e., no stimulus was presented) (HASSON, 2016). As shown, there is no relationship between the brain activity (i.e., EEG waveforms are completely out of sync and phase) when the subjects are at rest.

FIGURE 13

A Visual Depiction of a Lack of Neural Entrainment That Manifests as EEG Signals That Are Out of Phase with One Another When Five Participants Are at Rest

Listener 1   Listener 2   During Rest

LISTENER 1
LISTENER 2
LISTENER 3
LISTENER 4
LISTENER 5
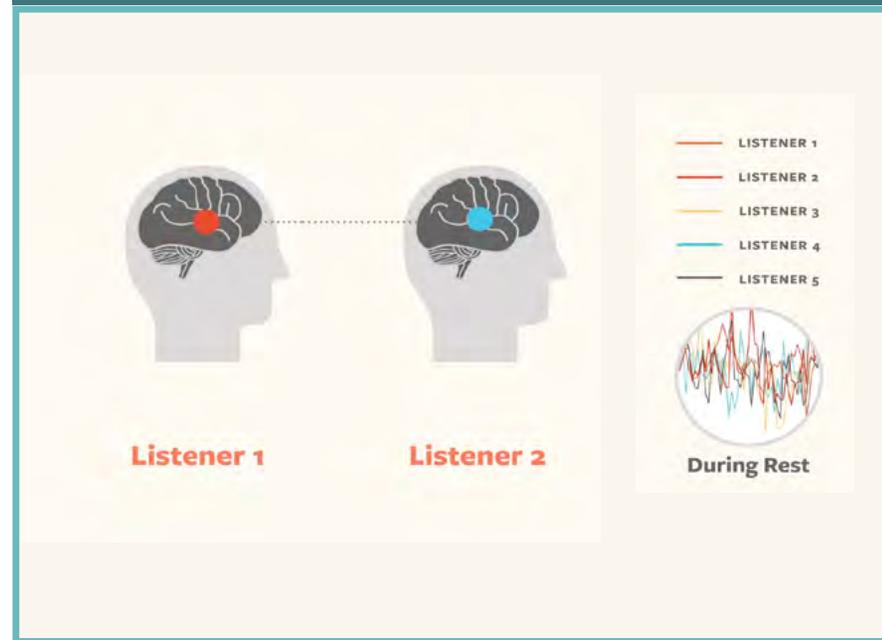
FIGURE 14

A Visual Depiction of the Presence of Neural Entrainment that Manifests as EEG Signals that Possess a High Level of Correlation as Five Listeners Comprehend the Same Story
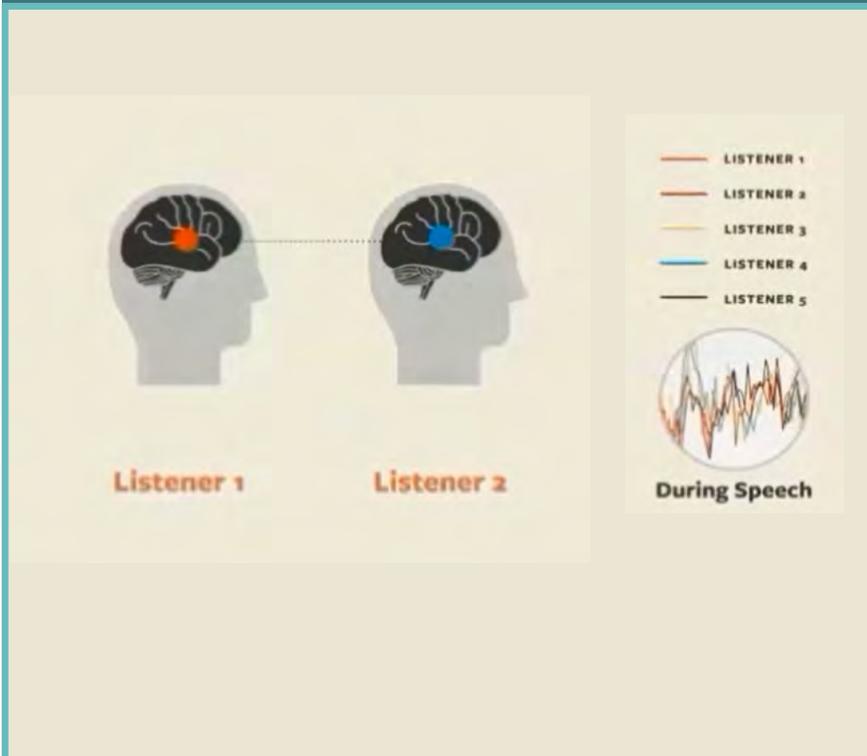
In contrast, once the listeners begin to listen to the same story, the EEG brainwaves become locked in phase (SEE FIGURE 14).

Professor Hasson uses the term ***neural entrainment*** to describe the phenomenon in which an outside stimulus (e.g., the story) causes the brains of several subjects to align with one another and operate in phase/sync in response to the stimulus.

(HASSON, 2016)

Not only do the neural patterns of activity respond in phase across the brains of the different listeners, but Professor Hasson and colleagues have also shown a high degree of correlation in the areas of the brain that are responding to the same story (HASSON ET AL., 2008, 2010, 2012; HONEY ET AL., 2012; LERNER ET AL., 2011; NATASE ET AL., 2019; STEPHENS ET AL., 2010; YESHURUN ET AL., 2017).

Figure 15 provides an example of very similar response patterns (i.e., neural networks) that exist across the brain when different listeners respond to the same story. As shown in Professor Hasson's work (SEE FIGURE 15 FOR A VISUAL DEPICTION), when listeners comprehend a story, neural activity is present across broad areas of the brain including primary and secondary auditory cortices, as well as the frontal and parietal lobes (HASSON, 2016). The similarity in the regions of the listeners' brains that are responding to the story is another example of neural entrainment.

Additional research from Professor Hasson and colleagues sought to determine whether the similarity of the brain regions that were responsive to the story across listeners was attributed to a passive response to the acoustics of the auditory signal or, instead, to comprehension of the story. Hasson et al. reversed the audio file of the story so that the words of the story were presented backwards, which resulted in the words being completely unintelligible (i.e., it sounded like modulated noise). The noise-like signal elicited activity that mostly resided within the primary auditory cortex (SEE FIGURE 16).

FIGURE 15

A Visual Depiction of Neural Entrainment within the Brains of Two English-Speaking Speaker-Listeners Who Listened to a Story that They Were Both Able to Comprehend

Listener 1   Listener 2

FIGURE 16

A Visual Depiction of Neural Activity that Occurs within the Brains of Two English-Speaking Speaker-Listeners Who Listened to a Running Passage of Unintelligible Words (i.e., Reversed Speech)

Listener 1   Listener 2

Next, Hasson et al. presented the story with the words in a scrambled order so that the listener heard intelligible words without the syntactic structure associated with normal conversation. fMRI measures showed activity confined to the primary and secondary auditory cortices and inferior frontal cortex (SEE FIGURE 17). However, activity was not observed throughout the brain as it was when the story was presented intact and comprehended by the listeners.

FIGURE 17

A Visual Depiction of Neural Entrainment within the Brains of Two English-Speaking Speaker-Listeners Who Listened to Intelligible Words That Are Scrambled in an Order That Produces a Message That Carries No Meaning
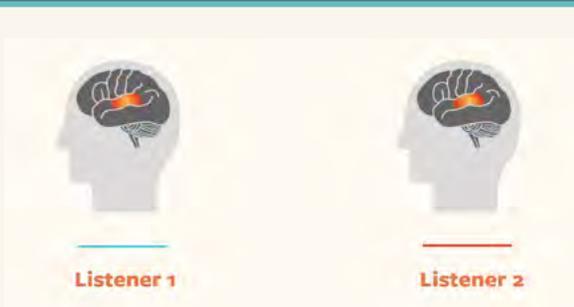
Listener 1   Listener 2

To further establish the importance of language comprehension in facilitating engagement of broad neural networks, Hasson and colleagues presented the same story in two different languages: English for English-speaking listeners and Russian for Russian-speaking listeners (STEPHENS ET AL., 2010). Although the acoustics were different because the story was presented in two different languages, the meaning of the story remained the same, and as a result, fMRI scans showed two remarkable findings:

1. Regardless of the fact that the story was presented in two different languages, neural responses were distributed across several functional centers of the brain (i.e., a broad neural network) that are active during communication, *and*

2. A high level of correlation existed in the responsive areas of the brains of the English and Russian listeners (SEE FIGURE 18), a finding that Hasson et al. acknowledged as support of the notion that comprehension of language is the primary driving force in the development of broad neural networks that are effective for successful communication.

In short, the neural entrainment that spans across the brain is driven primarily by comprehension of the auditory signal (STEPHENS ET AL., 2010).

FIGURE 18

A Visual Depiction of Neural Entrainment within the Brains of an English-Speaking Speaker and a Russian-Speaking Listener When Each Comprehends a Story Told in Her Native Langage

Frontal cortex

English Listener

Russian Listener

TRANSLATION

So I'm banging out my story and I know it's good

Я расскажу вам историю о моем друге китайский парень по имени Ю
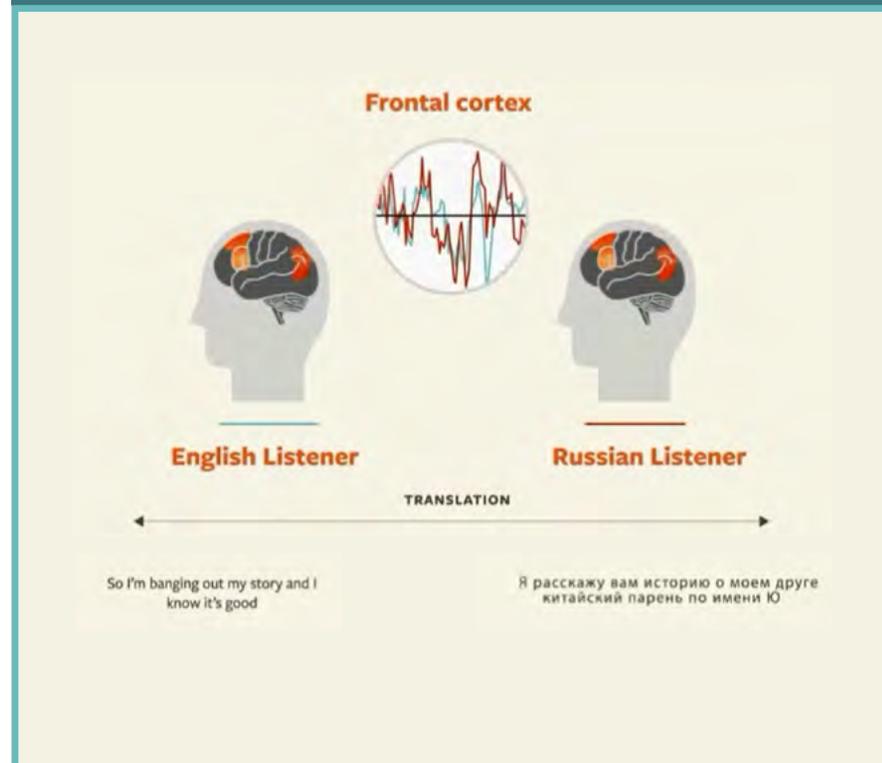
A subsequent study provided additional evidence of the importance of neural entrainment in human communication. Hasson and colleagues conducted fMRI measures while a talker told a story. Then, an fMRI measure was completed while a recording of the talker's story was presented to a different listener.

As shown in Figure 19, high levels of neural entrainment were observed between the areas of the talker's brain that were active when telling the story and the areas of the listener's brain when comprehending the story.

The degree of neural entrainment (i.e., the degree of intersubject correlation in neural activity) was greatest when the listener was able to achieve a full level of understanding of the talker's spoken message. When a listener fails to comprehend a spoken message or when two listeners interpret a spoken message differently, neural entrainment diminishes. To summarize the findings of Professor Hasson and colleagues, neural entrainment represents a high degree of correlation in the temporal neural response properties and a high level of synchrony in the responding areas of the brains of listeners who are all comprehending the same message of a story.

Neural entrainment must be present in order for successful spoken communication to occur in a typical manner. The formation of neural networks is the physiologic underpinning of neural entrainment.

FIGURE 19

A Visual Depiction of Neural Entrainment that Occurs between a Talker and Listener When the Latter Comprehends the Message of the Former

Speaker   Listener
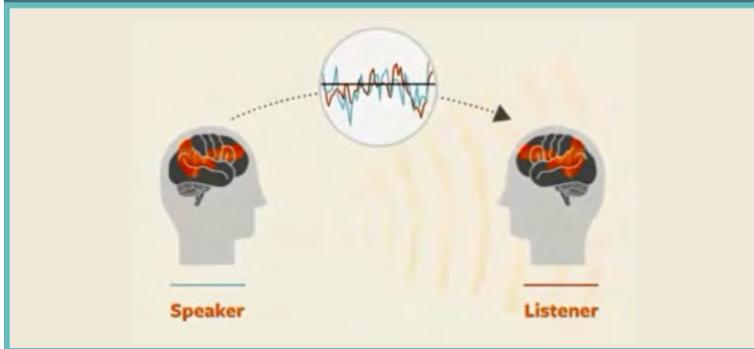
The Functional Implications of Neural Entrainment

Of note, neural entrainment is vitally important because it serves as the foundation for basic human communication, which is necessary not only for the simple exchange of thoughts, wants, and needs, but also for social development and for a child to be able to learn through listening and spoken language.

Neural entrainment must occur for a child to tell her/his parent that she/he is hungry, cold, or tired and for the parent to understand the child's specific needs. Neural entrainment is a critical component in social interactions, such as what may occur when a child smiles after her/his parent says, "I am so proud of you, and I love you so much," or when the bond between two friends grows stronger as they reminisce about the great times they had at summer camp. When a couple is dating and they feel like they could spend all day together

because she/he "just gets me," neural entrainment has almost certainly occurred. In fact, the existence of neural entrainment in the social domain has probably been inherently understood for decades. The origin of the idiom, "we are on the same wavelength," dates back to 1927 (STACK EXCHANGE, 2019). The Cambridge Dictionary defines "on the same wavelength" as "thinking in the same way as someone else" (CAMBRIDGE DICTIONARY, 2019). From Professor Hasson's research, we now understand that "on the same wavelength" not only has a figurative meaning, but it also literally means that our brainwaves are physically aligned when we successfully communicate.

Furthermore, neural entrainment is an essential component that allows for learning through LSL. Professor Hasson et al. have shown that an individual may read a book or watch a television program and then relay the story they experienced to a listener. The activity in the brain of the talker is similar to the activity that was present when she/he read the story or watched the television program (i.e., neural entrainment occurs within the same person from a personal experience sharing that experience with another individual). Also, the activity in

the talker's brain is similar to the activity in the listener's brain when the latter understands the story told by the former.

Given the findings of Professor Hasson's research, it is not difficult to realize the role of neural entrainment in learning and education. Parents can tell a child about the time they burned their hand on the stove and how badly it hurt. Although the child did not burn her/his hand, she/he can envision the painful experience in her/his mind's eye because of neural entrainment. Similarly, a history teacher studies history and world events at a university and then eventually lectures on world wars and politics to students. Neural entrainment allows the relevant details of world history to be relayed from the college textbook author's mind to the college student who then becomes a teacher and passes along that information to a teenage history student. It doesn't matter that the teacher and student never experienced the signing of the Declaration of Independence or the storming of the beaches of Normandy during World War II's D-Day; the history student will almost feel like she/he was present if the teacher effectively portrays the events. A list of your favorite teachers will almost assuredly include those who were able to establish the neural entrainment necessary for comprehension of the lecture. In order to communicate, socialize, and learn, we must develop robust neural networks that enable the establishment of neural entrainment with the world at large.

Professor Kral and the Auditory Connectome

Professor Andrej Kral and colleagues have proposed that the importance of broad neural networks and neural entrainment extends beyond basic human communication. In their research on the impact of congenital hearing loss on brain development, Kral et al. (2016) discuss the term *connectome*, which he defines as a "network map of effective synaptic connections and neural projections that comprise a nervous system and shape its global communication and integrative functions." They make a compelling case that the development of the brain's connectome is reliant on the input children receive from their sensory systems. When sensory deprivation occurs during the critical period of LSL development, the neural circuits and networks that underlie a connectome develop atypically and form atypical connections throughout the brain, which also affects non-auditory functions. More specifically, sensory deprivation may lead to more robust connections within and across sensory systems that are intact during the critical period of development,

reorganization, and weakening of the areas of the brain typically associated with processing the input from the impaired sensory system, and a potential for cross-modal reorganization (e.g., use of the secondary auditory cortex to process visual and/or somatosensory information).

The reorganization and restructuring that occurs within the areas of the brain associated with the sensory deprivation (e.g., changes in the auditory cortices in the case of congenital hearing loss), as well as other areas of the brain, are likely to lead to a disruption in developmental processes beyond the affected sensory system (BUTLER & LOMBER, 2013; FATZER & ROBERTS, 2012; HOLMES ET AL., 2015; KRAL ET AL., 2016; NISHIMURA ET AL., 1999; SHAMS & KIM, 2010; SIPAL & BAYHAN, 2011). As a result, a sensory deficit, such as congenital hearing loss, will threaten not only LSL development, but subsequently the development of numerous other non-auditory functions, including cognition.

Figure 20 provides a visual representation (ADAPTED FROM KRAL ET AL., 2016) of a part of the auditory component of the brain's connectome. The proposed "connectome model of deafness" illustrates the manner in which the development of neural circuits extending from and to the auditory cortices may potentially influence the development of a variety of higher-order tasks that are mediated in other brain areas including but not limited to executive function, sensory integration, working memory, attention, motor planning, sequence processing, object identification and concept formation, social pragmatics, etc.

FIGURE 20

An Illustration of the Auditory Component of the Brain's Connectome

Executive function refers to the mental processes that enable individuals to plan and undertake volitional activities, focus attention, follow instructions, and successfully execute multiple tasks in sequence or in tandem (BARKLEY, 2012). Research has shown deficits in the executive function of children with hearing loss (BOTTING ET AL., 2017; CONWAY ET AL., 2009; FIGUERAS, EDWARDS, & LANGDON, 2008; KROENBERGER ET AL., 2013, 2014; ULANET ET AL., 2014). Research with children with hearing loss has also shown an increased incidence of sensory processing disorder (ALLEN & CASEY, 2017), delays in working memory (LYXELL ET AL., 2008; NITTROUER ET AL., 2017; ORTMANN ET AL., 2013; WASS ET AL., 2008), and potential deficits in domains that influence social pragmatics, such as Theory of Mind (NETTEN ET AL., 2017). In short, the work reviewed above and numerous other research studies have indicated that congenital hearing loss and language deprivation have a cascading effect that extends beyond delays in spoken communication.

Auditory deprivation during the critical period of language development impairs the growth of auditory neural circuits and networks, resulting in disruption of the neural connectome that supports not only LSL development but a number of other cognitive and behavioral functions.
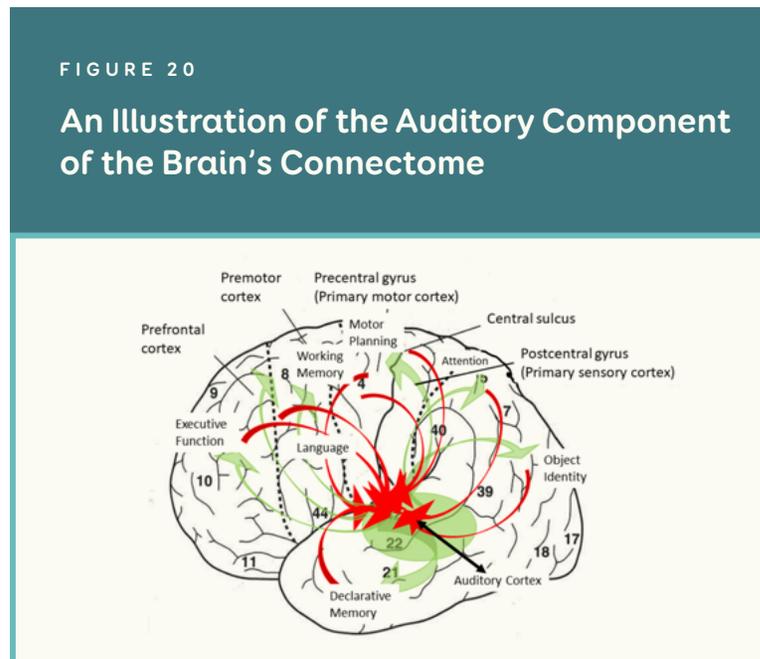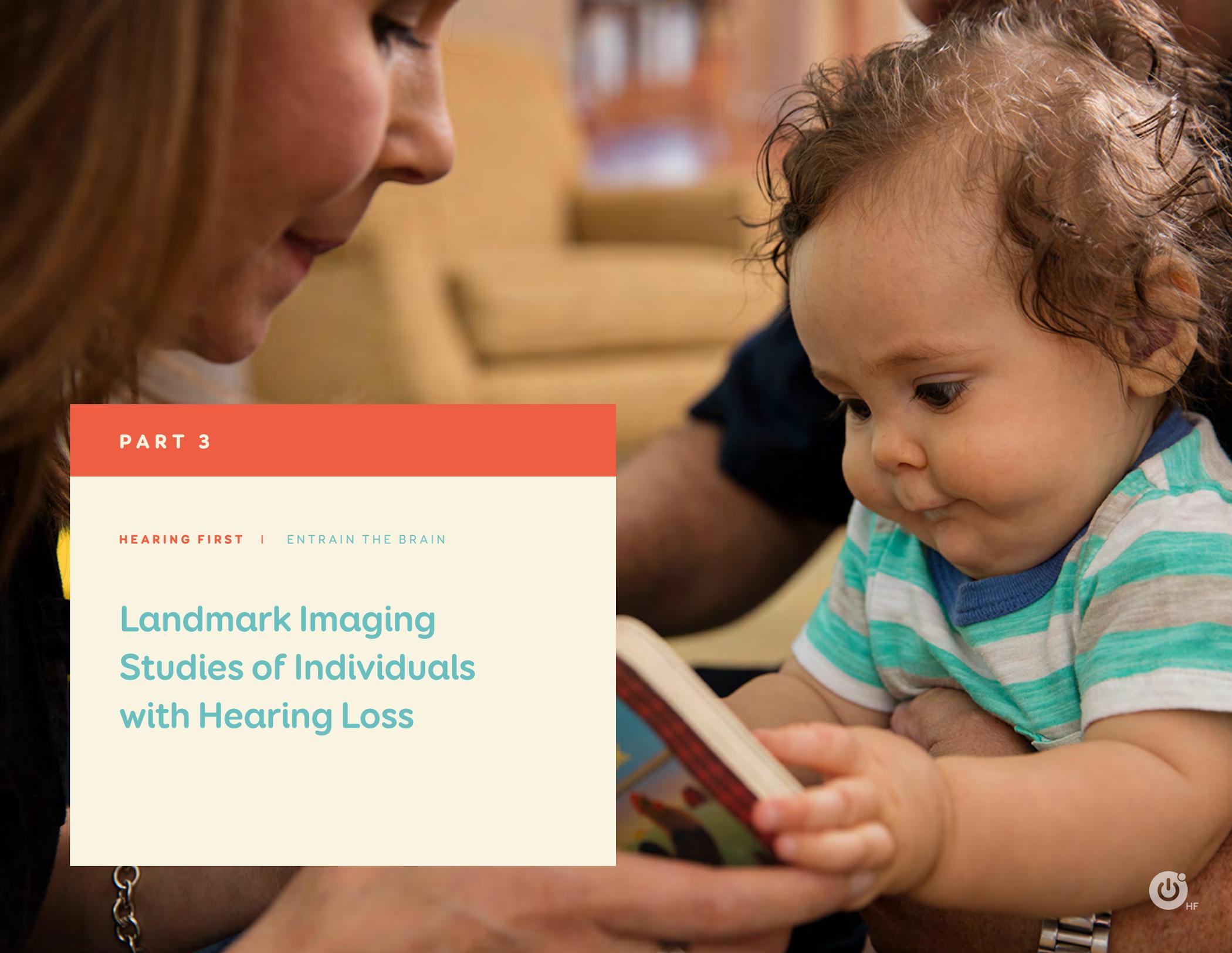
Landmark Imaging Studies of Individuals with Hearing Loss

In the following section, a brief review will be provided of a number of landmark studies that have shown the impact of congenital hearing loss on auditory brain development. To gain an understanding of the effect of congenital hearing loss on brain development, one must first understand how the auditory areas of the brain typically respond to speech inputs.

GREEN ET AL. (2005)

Typical Auditory Response of a Listener Who Had Ample Access to Intelligible Speech During the Critical Period of Language Development

Green et al. (2005) used positron emission tomography (PET) scan imaging to record the brain activity of 18 adults who had typical hearing abilities throughout childhood but developed severe-to-profound hearing loss in adulthood. PET scan imaging was completed while the participants listened to speech. All of the study subjects had received a cochlear implant in one ear.

Figure 21 provides an example of a typical response obtained from the brain of a subject who used a cochlear implant in the left ear. As shown, auditory stimulation of one ear elicits a broad and strong response from primary and secondary auditory cortices of both ears. Specifically, a broad portion of the auditory and language areas of the brain respond to the speech signal.

Note the bilateral responsiveness of primary auditory cortex (in the bright yellow/white shading) as well as the activation of secondary auditory cortices (in the darker yellow and orange shading).

FIGURE 21

A PET Scan Image of Brain Activity Superimposed on an MRI Image of the Brain of an Individual Who Is Listening to Speech with a Cochlear Implant for the Left Ear
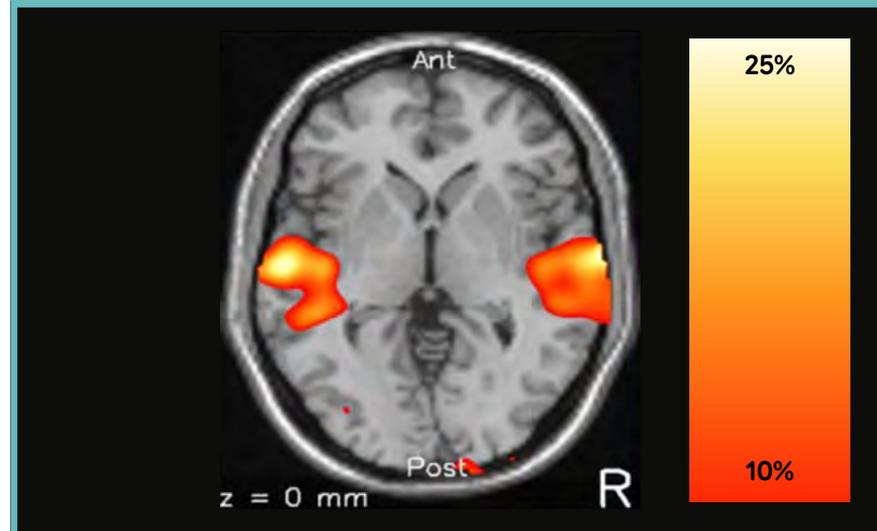
NISHIMURA ET AL. (1999)

Evidence of Cross-Modal Reorganization When Listeners are Deprived of Intelligible Speech During the Critical Period of Language Development

Nishimura and colleagues (1999) also conducted a PET scan imaging study to measure the response of the auditory cortices during communication. Nishimura et al. evaluated congenitally deafened adults who were deprived of access to sound during the critical period of listening and spoken language development, communicated via sign language throughout their school years, and then received a cochlear implant in adulthood. Nishimura and colleagues completed PET scan imaging during three functional tasks:

1. The participant used the cochlear implant to listen to a story told via spoken language,

2. The participant watched a story being told with sign language and no auditory input, *and*

3. The participant watched a tester moving her/his hands in a meaningless manner (with no auditory input).

The brain activity recorded in response to the three conditions is shown in **Figure 22**.

FIGURE 22

Neural Responses Recorded via PET Scan and Superimposed on an MRI Scan
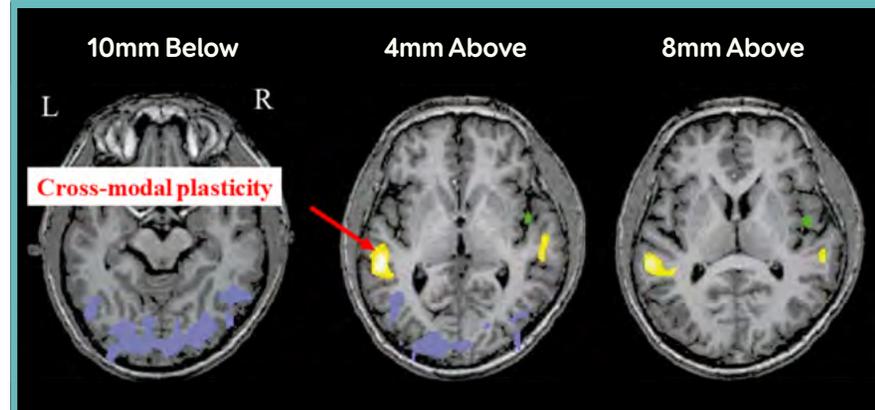
Blue: Activated by visual stimuli (meaningless hand movement)
Green: Activated by spoken language (CI: Left Ear)
Yellow: Activated by sign language

The blue-shaded regions in Figure 22 show the brain's response to the meaningless hand movements. As one might expect, the brain's response was primarily confined to the occipital regions of the brain (i.e., visual centers).

The green-shaded regions in Figure 22 indicate the brain's response to the story told via spoken language. As shown, the response to spoken language is confined to the primary auditory cortex in the hemisphere opposite the implanted ear. The lack of activity in the secondary auditory cortex in response to speech is concerning given the role of secondary auditory cortex in distributing the auditory signal to the rest of the brain. Without a robust engagement of the secondary auditory cortex, the listener will likely be unable to develop the neural circuits and networks and the auditory component of the connectome required to support the development of LSL skills as well as other higher-order cognitive and behavioral functions. In short, the imaging study of Nishimura et al. demonstrated the dire consequences of auditory deprivation during the critical period of LSL development, specifically a dismantling of the connection between primary and secondary auditory cortices.

The yellow-shaded regions in Figure 22 represent the brain's response to the story being told via sign language. As shown, the secondary auditory cortices were highly engaged with exposure to sign language, a finding Nishimura and colleagues attributed to ***cross-modal reorganization*** of the secondary auditory cortex. In other words, during the critical period of development, the brain determined that a valuable piece of its real estate, the secondary auditory cortex, was being underutilized. In response, the brain capitalized on its remarkable improvisational skills and reorganized so that the area normally devoted to processing auditory stimuli could instead be used to process visual (and potentially somatosensory) information. In essence, secondary auditory cortex has been "***colonized***" by another sensory modality. The brain's ability to reorganize is often referred to as brain plasticity.

BUCKLEY & TOBEY (2011)

Evidence of Cross-Modal Reorganization After Auditory Deprivation During the Critical Period of Language Development and its Effect on Auditory Function

A similar research study by Kristi Buckley and Emily Tobey (2011) demonstrated the deleterious effects of cross-modal reorganization on auditory performance. Buckley and Tobey used high-density (64-channel) electroencephalography (EEG) measures to record brain responses while participants viewed a moving visual stimulus that was offset from the center of their visual field. Previous research has shown that this type of visual stimulus typically evokes activity in the occipital and parietal lobes (BAVALIER ET AL., 2000). The amplitude of the P1 component of the visually-evoked potential (i.e., the size of the brain's response to the visual stimulus) as measured over the auditory cortex was also determined.

Buckley and Tobey tested three groups of participants:

1. Adults with normal hearing sensitivity,

2. Adults who were born with typical hearing, developed typical LSL abilities, developed severe-to-profound hearing loss in adulthood, and received a cochlear implant after the onset of deafness (i.e., post-linguistic group), *and*

3. Adults who were born with congenital hearing loss, were deprived of auditory input during the critical period of language development, used sign language as their primary mode of communication, and received a cochlear implant during adulthood (i.e., pre-linguistic group).

As shown in Figure 23, the brain's response for the normal hearing participants primarily occurred within the occipital and parietal lobes.

Similarly, the brain's responses for the majority of the post-linguistic group primarily resided within the occipital and parietal lobes, although a few showed some responsiveness in the secondary cortex as well (SEE FIGURE 24). In contrast, most of the responses of the pre-linguistically-deafened group showed substantial responsiveness in the secondary auditory cortex, which suggests cross-modal reorganization (SEE FIGURE 25). Buckley and Tobey also compared the participants' speech recognition to the amplitude of the P1 component of the visual evoked potential over the auditory cortex. They found that significantly poorer speech recognition was present in the participants who exhibited robust visual responses produced by the auditory cortex (i.e., cross-modal reorganization). In summary, Buckley and Tobey concluded that poorer auditory performance occurred when the secondary auditory cortex had been colonized by the visual system.

FIGURE 23

Neural Responses of Normal Hearing Subjects Recorded via PET Scan and Superimposed on an MRI Scan

Typical Pattern: Response observed over left parietal lobe & occipital lobe

Neural Activity was Recorded in Response to a Visual Stimulus

FIGURE 24

Neural Responses of Post-Linguistically-Deafened Subjects Recorded via PET Scan and Superimposed on an MRI Scan

Most Exhibit: "Normal" response, while others show activity in right temporal lobe
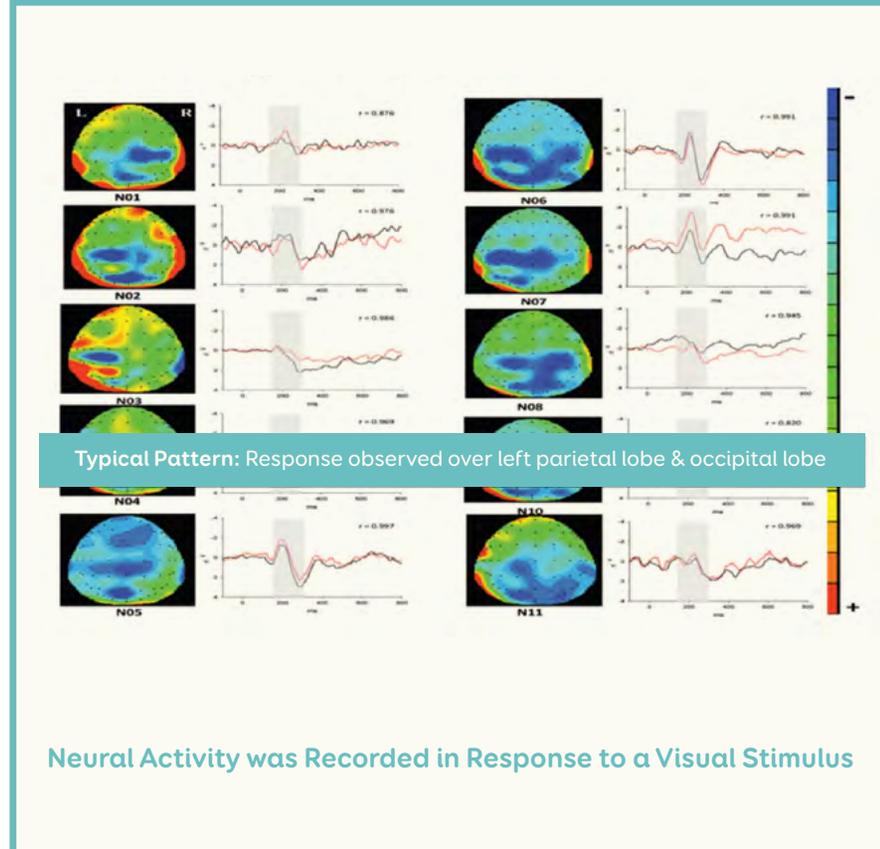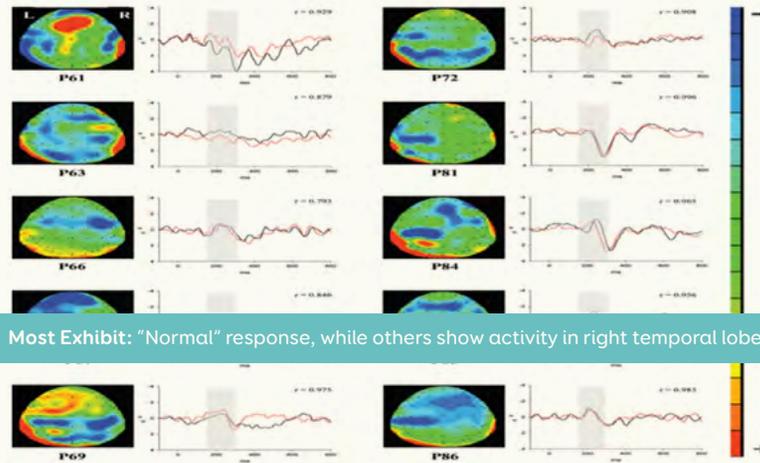
Neural Activity was Recorded in Response to a Visual Stimulus

FIGURE 25

Neural Responses of Pre-Linguistically-Deafened Subjects Recorded via PET Scan and Superimposed on an MRI Scan

Most Show: Activity in right temporal lobe
Talking Point: Auditory deprivation opens the secondary auditory cortex to Cross-Modal Plasticity
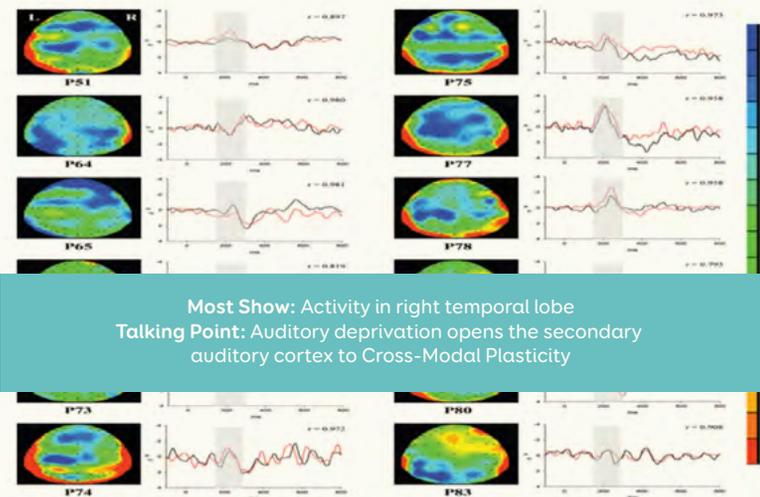
Neural Activity was Recorded in Response to a Visual Stimulus

LEE ET AL. (2001)

Pioneering Evidence of Cross-Modal Reorganization After Auditory Deprivation During the Critical Period of Language Development and its Effect on Auditory Performance

In one of the pioneering studies using brain imaging to evaluate the potential effects of cross-modal reorganization in children with cochlear implants, Lee et al. (2001) used PET scan measures to assess the level of activity in the brains of 15 cochlear implant recipients while at rest (i.e., no stimulus was presented). All study participants had congenital hearing loss and underwent PET scan imaging prior to cochlear implantation. The participants' speech recognition was also evaluated. The participants' age of implantation ranged from 2.2 years old to 20.3 years old. Lee and colleagues found lower levels of brain activity while at rest (i.e., hypometabolism) in the auditory cortices of the brains of the participants who achieved higher speech recognition with their cochlear implants (SEE FIGURE 26). Lee et al. proposed that cross-modal reorganization (i.e., colonization by the visual system and/or somatosensory systems) was responsible for the higher levels of brain activity that occurred during rest for the participants who had poorer speech recognition scores.

FIGURE 26A

PET Scan Images Showing Lack of Brain Activity (Hypometabolism) of Cochlear Implant Recipients at Rest Prior to Cochlear Implantation

| Duration of deafness	CID scores (years of training)
6.5 yr	90% (3.8 yr)
6.5 yr	67% (1.1 yr)
11.2 yr	7% (1.4 yr)
20.3 yr	0% (1.9 yr)
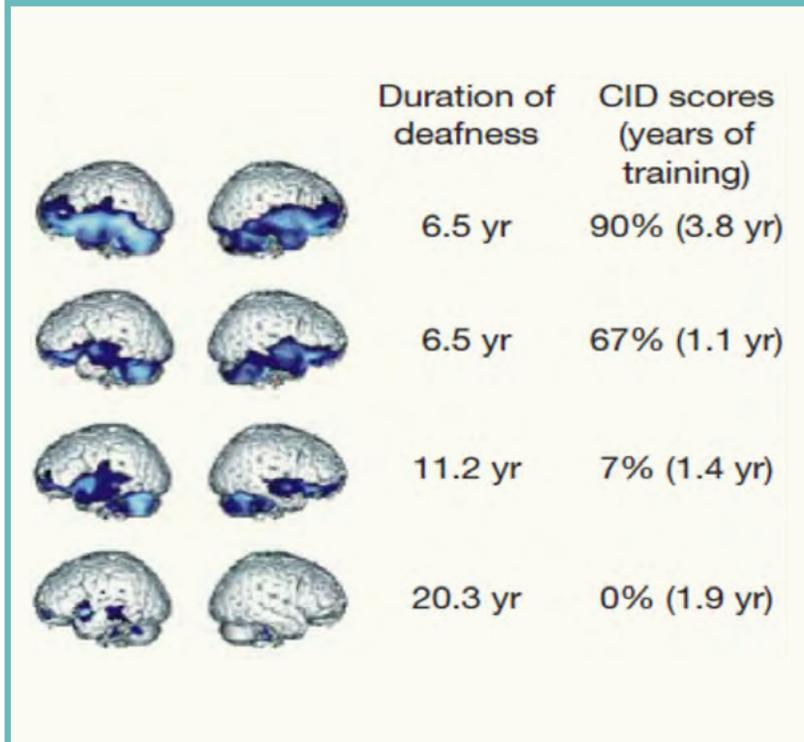
FIGURE 26B

The Relationship between Speech Recognition (% Correct) with Cochlear Implant and Lack of Brain Activity (Hypometabolism) When at Rest Prior to Cochlear Implantation
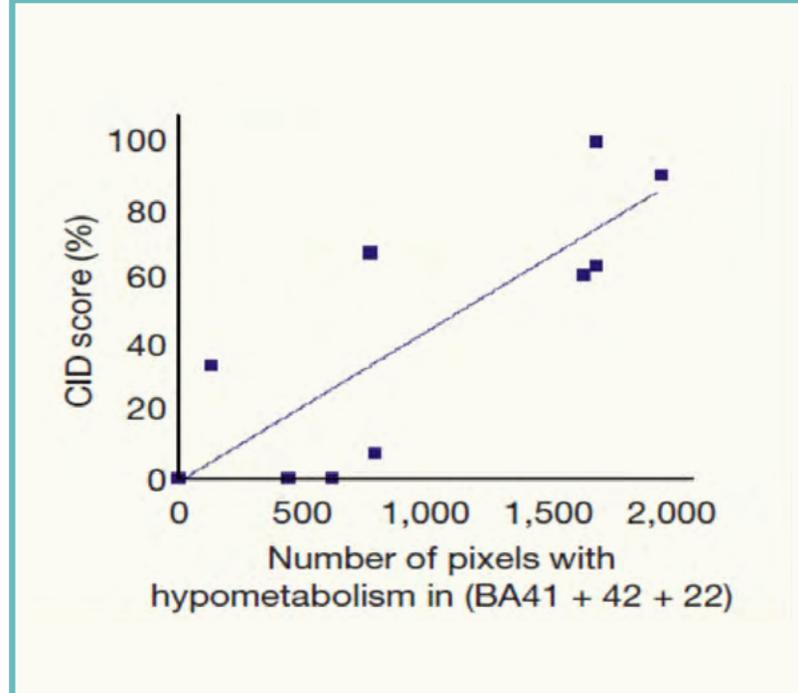
FENG ET AL. (2018)

The Effect of Anatomical Changes Associated with Auditory Deprivation

In a recently published study, Feng et al. (2018) examined pre-operative magnetic resonance imaging (MRI) results for 37 children who received a cochlear implant prior to 3.5 years of age. Feng and colleagues sought to determine whether MRI could reveal neuro-morphological changes (e.g., changes in structure, form, and/or shape) in the brains of children with hearing loss that would predict their speech recognition abilities with their cochlear implants. Neuro-morphological changes were identified by comparing the MRI results of the children with cochlear implants to the MRI findings of a control group of children with normal hearing. The researchers then compared the MRI results to the children's speech recognition scores obtained 6 months after activation of the cochlear implant. Feng and colleagues reported that the most likely area in which a neuro-morphological difference existed between children with cochlear implants and those with normal hearing occurred in the bilateral auditory cortices. They attributed these differences to deficits in neural development that occurred in children with hearing loss secondary to auditory deprivation. Feng et al. also reported less frequent changes occurring in other areas of the brains of children with hearing loss, including the inferior frontal gyrus, the occipital lobe, and other areas governing higher-order processing, memory, and emotion. Importantly, Feng noted that speech recognition after cochlear implantation was best predicted by the lack of neuro-morphological changes in children with hearing loss, particularly in the auditory cortices, but also throughout the brain, including the frontal, parietal, and occipital lobes, as well as deeper brain areas involved in higher-order processing (SEE FIGURE 27).

To summarize, Feng et al. found evidence of neuro-anatomical changes in the brains of children with hearing loss.

These neural changes are likely anatomical substrates of deprivation-based neural degeneration and cross-modal reorganization. Better speech recognition outcomes were found in children whose neural anatomy was more similar to that of children with normal hearing.

FIGURE 27

Color-Coded MRI Images Depicting Regions of the Brain in which Neuroanatomy Was Predictive of Speech Recognition Improvement after Cochlear Implantation
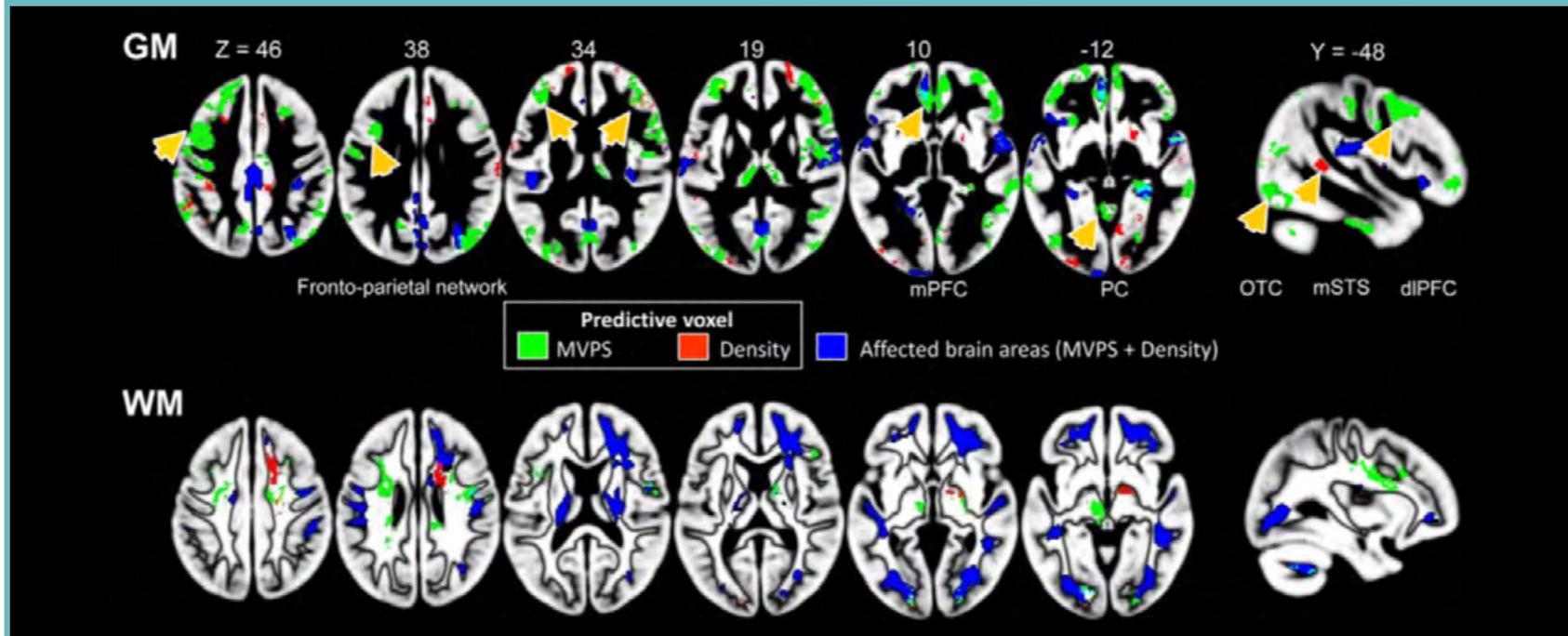
The green and red regions indicate areas in the brains of children with cochlear implants that are similar (e.g., unaltered) to the anatomy of the brains of children with normal hearing. **The yellow arrows** point to areas that had the greatest predictive value. **The blue regions** indicate areas in which the anatomy of the brains of children with hearing loss have been affected by auditory deprivation.

Physiologic Mechanisms Underlying Auditory Brain Development of Children with Hearing Loss

Introduction to Professor Kral's Research on Cortical Layers in White Deaf Cats

The preceding section reviewed a number of research studies that provided evidence of deprivation-related changes in the brains of children with hearing loss.

These neural changes often led to cross-modal reorganization, which subsequently resulted in poorer LSL outcomes (and potentially other cognitive and behavioral deficits) after cochlear implantation. Professor Kral and colleagues (2000) sought to identify the neuro-anatomical and neuro-physiological bases for cross-modal reorganization and the neural network and connectome deficits that occur when children are deprived of rich and robust auditory input during the critical period of LSL development. Kral et al. (2000) identified the specific bases for cross-modal reorganization in their studies of white deaf cats. Kral placed needle electrodes at various depths in the cortex of normal-hearing cats and white deaf cats, presented acoustic signals to the auditory system, and recorded the resultant neural responses at different layers within the auditory cortex.

Cochlear Implant
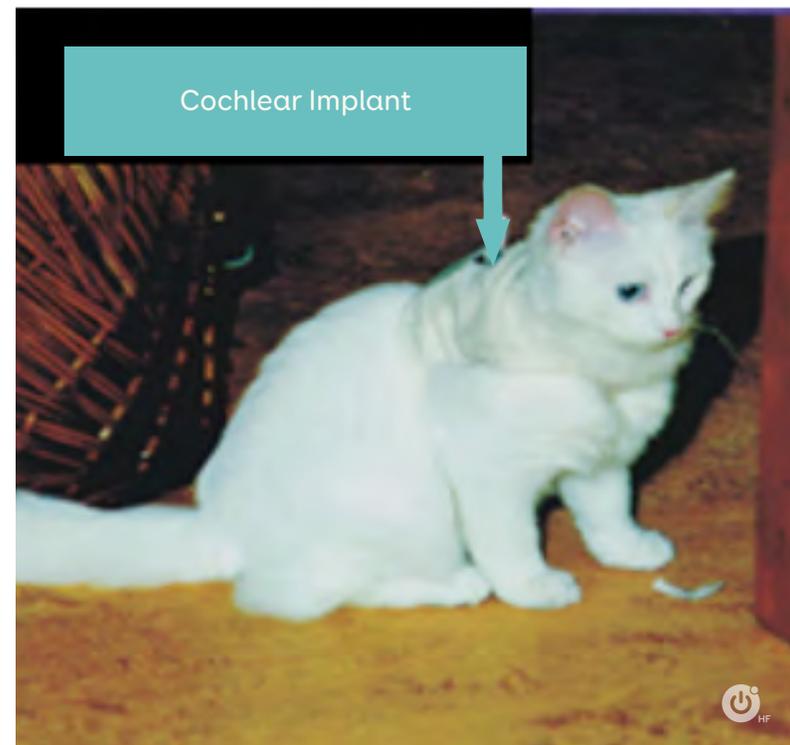
Anatomy and Physiology of Cortical Layers

The cortex is comprised of six layers of neurons that differ in structure and response properties (SEE FIGURE 28). The uppermost layers (I through III) are referred to as the *supragranular layers* (superficial layers). The lowermost layers (V through VI) are referred to as the *infragranular layers* (deep layers). It is important to note that the exact function of each of the layers of the auditory cortex is not conclusively known. However, animal studies, post-mortem research, and imaging studies have provided insight into the probable function of the cortical layers (ADESNIK & NAKA, 2018). Auditory information from the ears primarily arrives from the auditory neurons in the medial geniculate nucleus of the thalamus (REFER BACK TO FIGURE 5). Layer IV is often referred to as the input circuit of the cortex (ADESNIK & NAKA, 2018). The supragranular layers (I through III) of the cortex are generally considered to be involved with processing input from layer IV (BRECHT, 2017). The infragranular layers (V and VI) of the cortex are generally thought to function as the *primary output circuits* of the cortex (ADESNIK & NAKA, 2018). However, research has suggested that the infragranular layers may be better described as the gateway of the cortex (ADESNIK & NAKA, 2018; KRAL,

FIGURE 28

A Visual Representation of the Six Layers of the Brain's Cortex
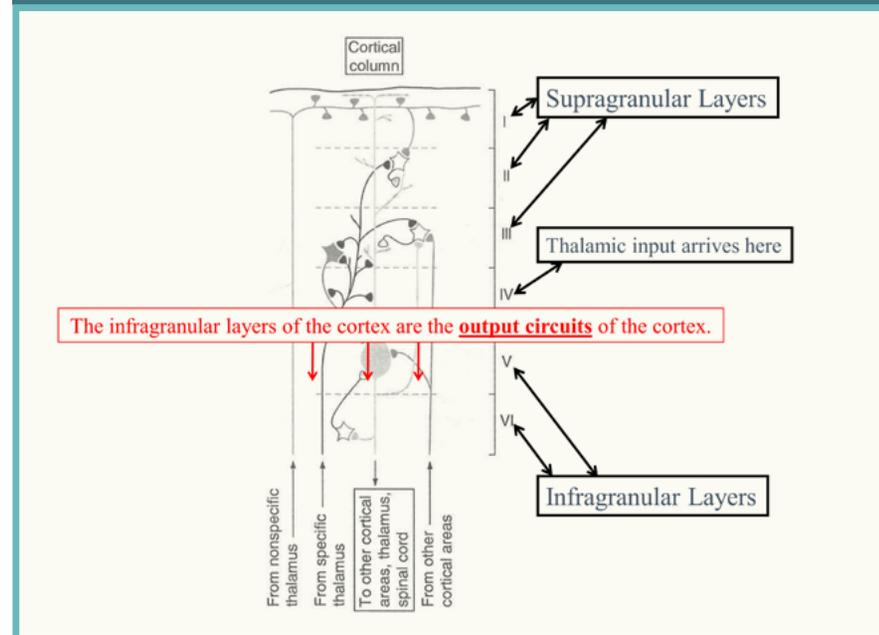
YUSUF, & LAND, 2017; LAND ET AL., 2016). The infragranular layers likely function to not only transmit auditory information from layer IV to other areas of the cortex throughout the brain, but they also most likely receive information from other higher-order areas of the brain within and outside of the auditory cortices. As previously discussed, higher-order areas of the brain (e.g., secondary auditory cortex, frontal lobe, parietal lobe) deliver signals to primary and secondary auditory cortex to "tune" the auditory response toward signals of interest and inhibit the response for signals that are irrelevant. Many of these cortico-cortical projections are thought to terminate in the infragranular layers (ADESNIK & NAKA, 2018; KRAL, YUSUF, & LAND, 2017).

Professor Kral's Research on Cortical Layers in White Deaf Cats

Professor Kral's research with white deaf cats reveals the physiologic underpinning of the decoupling that occurs between primary and secondary auditory cortices after auditory deprivation during the critical period of language development.

In Professor Kral's research with deaf white cats (2000, 2002, 2006, 2007, 2011, 2013), he discovered vigorous activity in all six layers of the auditory cortex of the normal-hearing cats. In contrast, robust activity was recorded in layer IV and the supragranular layers of the white deaf cats, but only weak neural responses were recorded from the infragranular layer of the cortex (SEE FIGURE 28). Kral's team has recently reported that deep layers show dystrophic changes in primary and secondary auditory areas but not in visual areas of deaf cats (BERGER ET AL., 2017). This is likely a consequence of the weaker activity in the infragranular layers in deafness. Kral explained that the lack of activity in the infragranular layers is a consequence of a **functional decoupling** of primary and secondary auditory cortex.

Due to the role of the secondary auditory cortex as the "launching pad" (or "output circuits") of the auditory cortex, this functional decoupling has serious implications. When primary and secondary auditory cortices are functionally decoupled from one another, auditory input is not optimally delivered from primary auditory cortex to secondary auditory cortex where it can be distributed to the rest of the brain so that the sound can "come to life" and possess higher-order meaning. Also, as previously discussed, the infragranular layers serve as the gateway of the primary auditory cortex (e.g., delivering input from layer IV to higher order areas of the brain [bottom-up], receiving and integrating input from higher-order areas of the brain [e.g., cortico-cortical projections, feed-forward input from supragranular layers]). SEE KRAL, YUSUF, & LAND, 2017 AND YUSUF ET AL., 2017. This gateway function of the infragranular layers allows for sensory input to be

integrated with and modulated by top-down influences from secondary and higher order cortical areas (YUSUF ET AL., 2017). When a functional decoupling occurs between primary and secondary auditory cortex, modulatory input cannot be optimally delivered from higher-order areas of the brain to the primary auditory cortex to tune and enhance the processing of the acoustic elements of the incoming auditory signal. Ultimately, the functional decoupling of primary and secondary auditory cortex

results in a dismantling of the auditory neural networks that support neural entrainment and the development of listening and spoken language. The associated dismantling of the auditory component of the brain's connectome leads to potential deficits in a number of higher-order cognitive and behavioral functions including phonological awareness deficits and literacy delays, sensory integration disorder, working memory deficits, executive function delays, and theory of mind deficits.

FIGURE 29A

Recordings by Kral et al. of Neural Activity in the Different Layers of Normal Hearing Cats
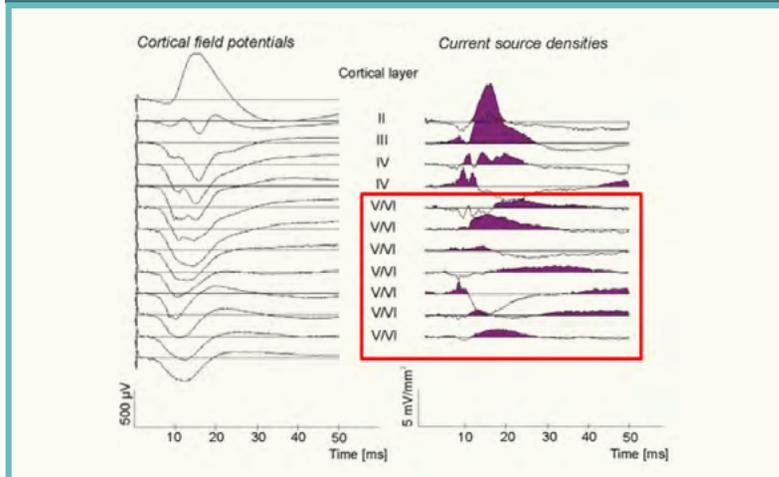

FIGURE 29B

Recordings of Neural Activity in the Different Layers of White Deaf Cats
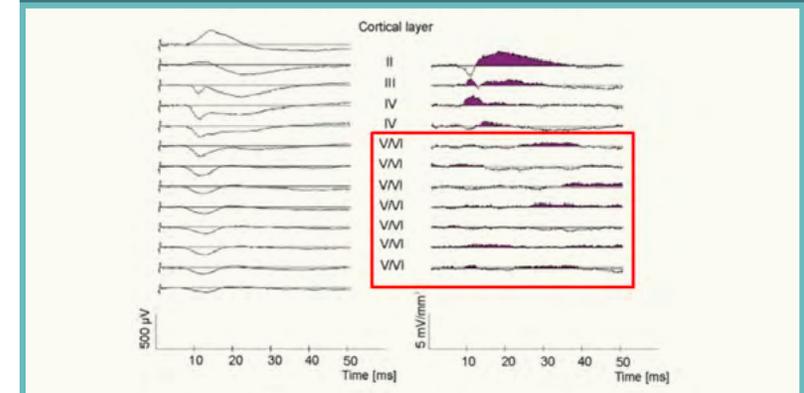
Note: A significant reduction in neural activity was recorded in the infragranular layers (layers V and VI) of the cortex of the deaf cats.

The Building Blocks of Auditory Brain Development and Listening and Spoken Language

The Sounds We Hear Drive Synaptogenesis and Synaptic Pruning

The brain contains billions of neurons (estimates suggest approximately 20 to 26 billion [PELVIG ET AL., 2008]). Genetics provide the basic blueprint of the organization and arrangement of neurons in the brain at birth, but a child's sensory experiences (particularly during the first few years of life) shape the eventual architecture and function of neurons and brain function. As previously discussed, neurons communicate with one another by the delivery of electrical pulses across synapses. The connections between neurons create circuits that provide the foundational structure that supports higher-order thought, processing, and actions. **Synaptogenesis** is a term used to describe the formation of connections between neurons. Neuronal connections (i.e., synapses) that are used more frequently strengthen and become more established. In contrast, neuronal connections that are used less frequently are eliminated through a process known as **synaptic pruning**. Synaptogenesis can occur throughout an individual's lifespan but is most prevalent during the first few years of life.

Research has suggested that the number of synapses in the human brain reaches a maximum between the first and fourth year of life.

(HUTTENLOCHER & DABHOLKAR, 1997; SCHNEIDER, NELSON, & MOONEY, 2014)

Why are Synaptogenesis and Synaptic Pruning so Prevalent in Early Life?

One may wonder why synaptic pruning is so prevalent during the first few years of life. Additionally, one may ask why synaptogenesis and synaptic counts peak so early in life.

The short answer is that the newborn brain must be equipped with the neural infrastructure that allows it to respond to the infinite spectrum of stimuli to which an individual may be exposed, and then it must shape itself so that it responds optimally to the most important stimuli in an individual's environment while also attenuating responses to irrelevant stimuli.

An obvious example is seen in an infant's tendency to prefer their mother's voice over the voices of others during the first few weeks of life. Moreover, during the first few months of life, infants begin to show a preference for the phonemes of their native language while developing a diminished ability to respond to sounds that are not a part of their native tongue (e.g., English-speaking school-age children struggle to roll the /r/ phoneme, whereas children whose native language is Spanish find no difficulty in rolling the /r/ phoneme). During the first few years of life, synaptogenesis and synaptic pruning result in neural networks that optimize processing of the speech sounds present in the child's native language. Development of functional connections between primary and secondary auditory cortices allows secondary auditory cortex to readily receive the acoustic elements associated with the sounds of their native language. Also, synaptogenesis and synaptic pruning develop cortico-cortical connections that allow higher-order brain areas to modulate primary auditory cortex so that it is primed to focus on the acoustic features associated with the sounds of the child's native language.

Furthermore, a child's world is comprised of an almost infinite menu of sounds including speech signals of interest, background speech sounds, cries, laughter,

whispering, hollering, traffic noise, mechanical noise (e.g., HVAC system, refrigerator and other household appliances, running water), music, wind noise, a ticking clock, a dog barking, etc. The auditory system must learn to disregard (i.e., ignore) ongoing, unimportant sounds in order to attend to the most relevant sounds. Once again, the cortico-cortical feedback loops between primary and secondary cortices and between higher-order areas of the brain and secondary cortex likely play an important role in assisting the brain in tuning in to the most important sounds while tuning out the background noise. Further, when competing noise masks the important sounds an individual wishes to hear (e.g., a phoneme in the word-final position is inaudible because of ambient noise), the higher-order area of the brain can leverage cognitive skills to draw upon contextual and linguistic cues to predict the missing speech sound. To allow these sophisticated listening skills to develop, synaptogenesis must facilitate the formation of neural networks that process the sounds that are most important to a child's well-being, development, success, and survival, whereas synaptic pruning must eliminate neural circuits that would contribute unimportant noise that may prevent the listener from identifying the stimuli that promote his/her best welfare.

Congenital hearing loss adversely affects brain development by significantly delaying synaptogenesis beyond the period in which synapses form most efficiently and effectively. Also, congenital hearing loss leads to increased pruning, which disrupts the formation of neural networks (KRAL ET AL. 2005; KRAL & SHARMA, 2012). Sensitive periods of development close after the first 2 to 3 years of life because the neural networks have been established to optimally process the sensory stimuli that are available to the young child. Cortical synaptic development is crucially dependent on sensory input.

The eventual cortical networks resulting from development in deafness and auditory deprivation result in reduced synaptic counts, which leads to reduced computational power of the auditory areas.

(KRAL 2013)

The Big-Box Retail Store Analogy for Auditory Brain Development

An elementary and imperfect analogy may be found in a big-box general merchandise retail store (e.g., Walmart, Target).

If my two young daughters were the store's only customers, the store manager would only need to stock instant macaroni and cheese, chocolate milk, and toys. My daughters would be thrilled if they did not have to eat fruits and vegetables, and they would love it if they didn't have to help with household chores or go to school because the retail store didn't stock cleaning and school supplies.

In reality, big-box stores have to meet the assorted needs of millions of customers, so they must stock more than just macaroni and cheese and chocolate milk to meet the broad demands of their diverse customer base.

Similarly, the brain cannot be pre-wired to only process English speech and the sounds of the big city. It must also be pre-wired to support the development of a tonal language and to process the sounds of the countryside for an infant born in a rural area of China. Moreover, in a big-box store, the best-selling items receive more shelf space and are positioned in locations that get the most customer traffic. In contrast, items that do not sell are placed on clearance and no longer stocked at the store in an effort to make room for items the customers covet and need. In much the same way, synapses that go unused are pruned away, whereas the neurons that are stimulated frequently build strong, permanent synapses and branch out through a process called *arborization* (*arbor* is the Latin word for *tree*; hence, arborization refers to the shape of neural networks being similar to the branches of a tree) to form elaborate neural circuits. These neural circuits are necessary to create neural networks that will support higher-order functions, facilitate neural entrainment, and underlie a connectome that will facilitate optimal sensory processing as well as cognitive and behavioral function.

Growing the Auditory Brain with the Perfect Fertilizer

Intelligible speech is the fertilizer required to optimize the arborization and synaptogenesis necessary to facilitate the development of listening and spoken language.

Remember Kyle Kai-How Farh's observation, "Everything that comes into our minds may be reduced to a pattern of neural firings"? For listening and spoken language, these neural firings represent the activity of synapses within the neural networks and the auditory component of the brain's connectome. These synapses are formed and strengthened by early and continuous exposure to a language-rich listening environment. The spoken words of a child's native language serve as the stimuli that create synapses and neural networks necessary for speech recognition and comprehension. Each individual word, as well as the phonemes that make up that word, elicits its own unique *neural fingerprint*. Exposing young children to an abundance of words during the first few years of life is the most effective way to create the synaptic networks that are essential for speech recognition and comprehension.

Intelligible speech also serves as the driver that establishes the connections between the secondary auditory cortex, the parietal cortex, and the inferior prefrontal cortex (Broca's area), which is the neural network that governs speech production. Similarly, a neural network that includes the visual centers of the brain, the auditory cortices, and the inferior frontal cortex makes up the neural network that supports literacy development. Phonemic awareness is governed at least partially within the inferior frontal cortex. Engagement of the auditory cortices is necessary to foster an understanding of the sound-to-phoneme relationship. Further, the involvement of the visual centers allows for an understanding of the relationship between the letters on a page and the phonemes and sounds to which they are associated.

After a cursory examination of the Nishimura study finding that sign language engaged the secondary auditory cortex, one may erroneously assume that visual input is a sufficient stimulus to build the auditory circuits and neural networks necessary to support LSL development. However, just the opposite is the case. The provision of sign language in the absence of auditory input during the critical period of language development results in a decoupling between primary and secondary auditory cortex. As a result, auditory input is not optimally delivered from primary to secondary auditory cortex where it may then be distributed to the rest of the brain so that the auditory signal may be comprehended. Additionally, the modulatory input from higher order brain centers to the auditory cortex is disrupted by the decoupling of primary and secondary auditory cortex, and consequently, the input to primary and secondary auditory cortex cannot be "tuned" by higher-order areas of the brain. In short, the most effective method to optimize synaptogenesis and the development of the auditory neural networks that allow for the neural entrainment that underlies listening and spoken language, as well as literacy abilities, is to inundate a child with a robust provision of complex, intelligible speech throughout the first few years of life.

Not Just the Cortex

The focus of this paper has centered on the development of the auditory cortices and cortical neural networks that play a vital role in the development of listening and spoken language and other cognitive and behavioral processes.

Of course, auditory deprivation during the critical period of language development also adversely affects many other areas of the auditory nervous system and consequently affects numerous auditory functions. Indeed, research shows that auditory deprivation during the formative years of life leads to structural and functional changes in the neurons in the cochlear nerve, the brainstem, and the thalamus (e.g, changes in the density, size, and response properties of auditory neurons). Auditory deprivation during the critical period of development also hinders the maturation of *myelin* (SEE LONG ET AL., 2018 FOR A REVIEW), which is the insulation that surrounds axons necessary for rapid conduction of neural impulses from one neuron to another. The deprivation-related structural changes that occur in the cochlear nerve, brainstem, and thalamus, as well as to demyelination of the auditory pathways, also contribute to deficits in auditory function observed in children with hearing loss who do not receive appropriate, audition-based early intervention.

It is well known that sound localization and speech recognition in noise are dependent on normal myelination and function within the auditory areas of the brainstem. Indeed, many studies have shown that children with hearing loss experience difficulties with speech recognition in noise and sound localization (CRANDELL, 1991, 1992, 1993; CRANDELL AND BESS, 1986; FINITZO-HIEBER AND TILLMAN, 1978; GRIECO-CALUB & LITOVSKY, 2010; KILLAN ET AL., 2018; WOLFE ET AL., 2013). For instance, Gordon et al. (2008) compared the latencies of the auditory brainstem response (ABR) generated by children who received one cochlear implant during the first 12 months of life and a second cochlear implant more than 6 months later. Gordon and colleagues found a significantly longer latency of the response generated

by the later-implanted ear, a finding that is likely attributable to changes in the structure, function, and myelination of the cochlear nerve and auditory neurons in the brainstem. Not surprisingly, research has shown poorer localization and speech recognition abilities in pediatric bilateral cochlear implant users who receive their second cochlear implant at a much later age than their first (SEE ZHENG ET AL., 2015 FOR A SUMMARY).

In summary, not only does auditory deprivation adversely affect the development of auditory neural networks in the cortex, it also hinders development of sub-cortical auditory structure and function.

HEARING FIRST | ENTRAIN THE BRAIN

Optimizing Auditory Brain Development

HF

Auditory brain development, neural entrainment, and the optimization of LSL skills are reliant upon access to a language-rich listening environment replete with intelligible speech during the first years of a child's life. The following section provides a brief summary of some of the most important factors influencing auditory brain development.

Every Single Day Counts

In Kral's experiments with deaf white cats, decoupling occurred between primary and secondary auditory cortices when cochlear implantation was not provided prior to 4 to 5 months of age (KRAL ET AL., 2000, 2002, 2006). One might suggest that the critical period of language development for a white deaf cat is 4 to 5 months; however, the developmental sequence in cats is much faster than in humans. Research with children has suggested the critical window of language development spans from birth to somewhere between 2 to 4 years old (SHARMA ET AL., 2002; SHARMA, DORMAN, & KRAL, 2005). One must be careful, however, to avoid the false conclusion that a cochlear implant may be provided on a child's third birthday and typical listening, spoken language, cognitive, and behavioral development will be achieved.

Rather, we must adopt Dr. Carol Flexer's mindset that congenital hearing loss is a neurodevelopmental emergency and that every minute, day, and month matter.

An emerging body of research reinforces the notion that every single day counts. In their landmark prospective study on the outcomes of children with congenital hearing loss, Longitudinal Outcomes of Children with Hearing Impairment (LOCHI), Ching et al. (2013) found that beginning at 6 months of age, every 6-month delay in cochlear implantation resulted in a half standard deviation reduction in language outcomes measured at 3 years of age. In other words, if a child is implanted at 12 months of age rather than 6 months of age, she/he would be expected to suffer a 7.5-point reduction in her/his score on a standardized assessment of language administered on the child's third birthday. Children must have access to intelligible speech during the first year of life. Every single day counts! Of note, Ching et al. (2018) also found significantly better language outcomes at 5 years of age for children who received their hearing aids and cochlear implants at earlier ages.

Similarly, Dettman and colleagues (2016) evaluated speech and language outcomes in 403 children who received cochlear implants between 6 months to 6 years of age. They found that 81% of children implanted prior to 12

months old achieved age-appropriate vocabulary development at school-age entry, whereas only 52% of children achieved age-appropriate vocabulary outcomes when implanted between 13 to 18 months of age. Dettman et al. found significantly better speech recognition, speech production, and language outcomes for children implanted prior to 12 months of age relative to children implanted between 13 to 18 months of age. Moreover, a systematic decline in listening and spoken language outcomes was observed with every additional 6-to-12-month delay in implantation. Every day counts.

Leigh and colleagues (2016) sought to determine the optimal age for cochlear implantation by evaluating the language outcomes of 78 children who received cochlear implants between the ages of 6 months and 6 years old. Leigh et al. reported a remarkable finding: Prior to cochlear implantation, the language growth of infants and toddlers with a severe-to-profound congenital hearing loss develops at a rate of 0.3 years of language growth per calendar year. In contrast, children who receive cochlear implants during the first few years of life achieve about 1 year of language development per calendar year. Consequently, children who are implanted at 6 months of age never have a chance to fall behind! They have early access to intelligible speech, make 1 year of language growth in 1 chronological year, and develop in a lockstep fashion with their peers with typical hearing. On the other hand, when implanted at 12 months of age, children with severe-to-profound hearing loss typically have about a 6-to-9-month delay in their language development. Children who receive cochlear implants at 2 years of age are likely to have almost an 18-month delay in their language abilities. Indeed, Leigh and colleagues found that a child's language delay closely mirrored their age at implantation and concluded that the results of their study provide

"compelling evidence that a cochlear implant should be offered as young as possible in order to minimize this language delay as long as a child meets the audiological guidelines outlined above, and other medical and otological issues have been considered."

An abundance of other well-designed research studies have provided strong evidence of the critical importance of early hearing aid fitting (prior to 3 to 6 months of age) and early implantation (prior to 12 months of age) (CHU ET AL., 2016; HOFF ET AL., 2018; NIPARKO ET AL., 2010; TOMBLIN ET AL., 2015).

Every day counts!

Bullseye!

Research has also demonstrated the vital importance of well-fitted hearing technology. The Outcomes of Children with Hearing Loss (OCHL) study evaluated the quality of hearing aid fittings for 288 children with mild-to-severe hearing loss. They found that over 50% of the children in their study were fitted with hearing aids that produced a sound level output that was more than 5 dB removed from the prescribed value for the child's hearing loss for each of the four sessions in which the hearing aid fittings were evaluated (MCCREERY ET AL., 2015). The OCHL team also found that the language outcomes for the children whose hearing aids provided the most audibility (upper quartile) were almost a full standard deviation better than the children whose hearing aids were the furthest removed from the prescribed output level (lowest quartile) (TOMBLIN ET AL., 2015).

In the LOCHI study, Incerti et al. (2018) also found large differences in the stimulation levels used by children with cochlear implants. Although there is not a readily acceptable standard to which optimal pediatric cochlear implant stimulation levels may be compared, the finding of disparate stimulation levels across children warrants

further investigation to determine if cochlear implant sound processors are programmed to optimally meet the needs of each child. In short, research has conclusively demonstrated the important relationship between the outcomes of children with hearing loss and the appropriateness of a child's hearing technology settings.

Children with hearing loss should be served by experienced pediatric audiologists who adhere to evidence-based, best-practice clinical standards to ensure the children are equipped with properly selected and well-fitted hearing technology.

Eyes Open, Ears On

Hearing aids and cochlear implants can be provided at an early age and optimally programmed by the child's audiologist, but all of that is for naught if the child is not supported in consistent use of the hearing technology. The OCHL team also evaluated the relationship between language outcomes and the consistency in which the children used their hearing aids. Tomblin et al. (2015) reported that children who used their hearing aids more than 10 hours per day achieved language

outcomes that were almost a half standard deviation better (almost 7 to 8 points on a standardized measure of language assessment) than the outcomes of children who used their hearing aids fewer than 10 hours per day.

Researchers have suggested that children typically hear about 45 to 50 million words during the first 4 years of their lives (HART & RISLEY, 1995), an estimate that suggests children are exposed to about 2,500 words per hour while awake. If a child uses her/his hearing aids an average of 8 hours per day rather than throughout an entire 14-hour waking day, she/he will hear almost 22 million fewer words during the first 4 years of life.

Spoken words are the fertilizer that grows the auditory neural networks necessary for the neural entrainment and the development of listening and spoken language skills.

Appropriately selected and well-fitted hearing technology must be worn during all waking hours to optimize auditory brain development.

Coach 'em Up With a Sound Game Plan and a Little TLC

Several recent research studies have also unequivocally shown the important role that caregivers provide in the outcomes of children with hearing loss. In the OCHI study, Ambrose and colleagues found significantly better language outcomes for children whose parents talked to their children with elaborate, lengthy, and complex utterances as compared to those who spoke with direct utterances (e.g., "Stop that!," "No!," "Hurry!,"). Take, for instance, the following disparate examples. Parent A is a radio commentator who narrates every waking hour of the child's life. For example, she may say, "On no, please don't kick the puppy! Come here, puppy. Did that hurt you? I'm so sorry, puppy. Let me give you a hug. See, the puppy likes hugs. Oh Johnny, we don't kick the puppy. That will hurt the puppy and make him sad. He also might get mad and bite you. If you want to kick something, then kick this ball. Watch me kick it. Whee!" In response to the same situation in which Johnny kicks the dog, Parent B may say, "No!" and spank Johnny. In the first scenario with Parent A, Johnny was exposed to 68 words, whereas with Parent B, Johnny was exposed to one word.

Numerous other research studies have shown a significant link between caregiver involvement and children's outcomes (CHU ET AL., 2016; NIPARKO ET AL., 2010). Some caregivers are naturally inclined to create a language-rich listening environment for their children. Others are not as verbose. All caregivers will be better language models for their children with guidance, support, and coaching from a Listening and Spoken Language Specialist (LSLS). An experienced LSLS is familiar with adult learning styles and adept at connecting with adults of all walks of life so that coaching may be customized to capitalize on the unique strengths of each individual caregiver with the goal of creating a language-rich listening environment for the child.

To optimize auditory brain development and neural entrainment, the caregivers of children with hearing loss should connect with an LSLS to receive the support and coaching necessary to provide their children with an optimal model for listening and spoken language development.

Of note, research has also suggested that listening and spoken language outcomes are poorer for children whose parents have lower income levels and education levels. Also, outcomes are typically poorer for children with additional disabilities other than hearing loss. For children and their families who are particularly vulnerable, some additional tender love and care (TLC) may be needed to address the caregivers' most pressing issues so that the family is able to then focus on the child's listening and spoken language needs. For families who are really struggling with serious basic life needs and issues (e.g., homelessness, no operational utilities, food deprived, domestic abuse), the pediatric hearing healthcare clinician should seek the assistance of a social worker who can aid in supporting the family's general welfare. For children who have additional disabilities (e.g., autism, cerebral palsy, visual impairment), the pediatric hearing healthcare clinician should collaborate with other professionals who specialize in meeting the unique needs of the child.

Scrap the Screen and Crack Open a Book–or 10

Recent research has indicated that excessive exposure to electronic screen time (e.g., tablets, smart phones, televisions, computers) during the first few years of life results in significant delays in children's language, social, behavioral, and motor development as well as deficits in brain white matter integrity (HUTTON ET AL., 2019; MADIGAN ET AL., 2019). Experts suggest that infants and toddlers are unable to intellectually translate the input they receive from a two-dimensional screening into real-life learning experiences. A full discussion of the potential risks involved with excessive screen time during the critical period of development is beyond the scope of this paper. However, it is worthwhile to note that the American Academy of Pediatrics (AAP, 2016) has recommended no screen time for children between birth to 18 months. For children between 18 to 24 months, the AAP recommends limited screen time that only occurs when the caregiver can watch with the child and explain and comment on what is happening. For children between 2 to 5 years old, the AAP recommends no more than 1 hour per day of high-quality, educational programming designed for the particular age of the child.

What should caregivers do with all the time made available by scrapping the screen time? One of the best alternatives is to crack open a book.

Research has shown that reading books to young children serves as possibly the best linguistic model to facilitate language development.

(DICKINSON ET AL,. 2012)

Caregivers should select books that are developmentally appropriate for the child. Ideally, the vocabulary of the book should be at or just beyond the child's level. The introduction of new words that occurs within the context of the story and that are paired with the pictures on the pages will facilitate the child's language growth. How many books should caregivers read to the child per day? There is no clear answer, but Dr. Carol Flexer suggests 10 per day. Ultimately, caregivers should not fret about meeting a quota but instead seek to make reading an activity that is a consistent, natural, and enjoyable part of the child's life.

Informed Choice

The parents of children with hearing loss choose how they wish to communicate with their children. It is the parents' right to choose whether they will communicate solely through listening and spoken language, solely through sign language, or through a combination of the two. No professional can or should dictate how parents communicate with their child. Pediatric hearing healthcare clinicians should provide evidence-based information to parents to assist the latter in selecting the communication mode that is most likely to facilitate the outcomes, goals, dreams, and desires they want and have for their children.

Of note, there will never be a perfect study that unequivocally determines the most effective communication mode for optimizing the listening and spoken language outcomes of children. There is simply no ethical way to randomly assign families to a particular communication mode and ensure that researchers are blinded to the mode of communication a family has selected. A full review of recent studies exploring the influence of communication mode on listening and spoken language outcomes, along with the strengths and weaknesses of each study, is beyond the scope of this paper. However, to briefly summarize, a number of recent studies have found significantly

better LSL outcomes for children whose families solely communicate via spoken language (CHING ET AL., 2013, 2018; CHU ET AL., 2016; GEERS ET AL., 2003, 2011, 2017). These findings should be of no surprise. Intelligible speech is the fertilizer that grows the auditory neural networks of the brain. It makes sense that better listening and spoken language outcomes would be obtained by children whose families focus on creating a language-rich listening environment to optimize listening and spoken language development. When families are counseled on the communication modes they may consider for their children with hearing loss, it is important that they are equipped with information that allows them to make an informed choice. Our knowledge of auditory neuroanatomy and physiology (e.g., Professor Kral's research, Professor Hasson's neural entrainment) provide the scientific rationale underlying the link between access to intelligible speech and LSL outcomes. Recent research on the outcomes of children with hearing loss suggests that better outcomes are attained when caregivers focus solely on listening and spoken language development and refrain from the use of sign language. Parents should and will choose the communication mode they will use with their children. If parents' goal is to optimize their children's LSL skills, then they should be aware of the steps and actions they should take to achieve their goal.

Radio Makes the Listening Star!

Research has demonstrated that children with hearing loss experience greater difficulty hearing in noise than their typical-hearing counterparts.

Intelligible speech is the fertilizer that grows the auditory neural networks and facilitates neural entrainment necessary for human communication. Children are frequently exposed to high-level noise environments. Crukley, Scollie, and Parsa (2011) reported that daycare noise levels were routinely around 70-75 dB SPL and that almost 75% of a toddler's day consisted of listening to speech in noise. In order to ensure that children with hearing loss have access to 45 to 50 million words during the first 4 years of life, pediatric hearing healthcare clinicians must stress the importance of using modern noise management hearing technologies in noisy settings. Adaptive directional microphones, digital noise reduction, and adaptive frequency-gain responses are all potentially effective tools to improve a child's listening

experience in noise. Remote microphone systems (SEE FIGURE 30) are often the most effective technology for improving a child's access to intelligible speech.

Figure 30: The remote microphone/transmitter is worn near the mouth of the talker (ideally about 6 to 8 inches from the mouth). The talker's speech is captured by the remote microphone, converted into a digital radio frequency signal, and transmitted to the radio receiver of a hearing aid or cochlear implant sound processor. The radio receiver captures the digital radio frequency signal and delivers it to the hearing aid/cochlear implant sound processor.

Benitez-Barrera, Angley, and Tharpe (2018) studied remote microphone use in the home for pre-school children with hearing loss. They found that the children were exposed to 5,280 more words per day when the caregiver used the remote microphone at home. If these 5,280 words are extrapolated over the first 4 years of life, remote microphone use would result in the child hearing more than 7 million additional words. Benitez-Barrera and colleagues also reported that the caregivers spoke more frequently while using the remote microphone. Additionally, caregivers generally had a favorable opinion of remote microphone use. In summary, early use of remote microphone technology will optimize access to intelligible speech, which will facilitate the development of auditory neural networks and improve LSL outcomes.

FIGURE 30

A Depiction of a Remote Microphone System

Digital Radio Frequency Transmission

Radio Receiver Coupled to Hearing Aid

Remote Microphone/Transmitter
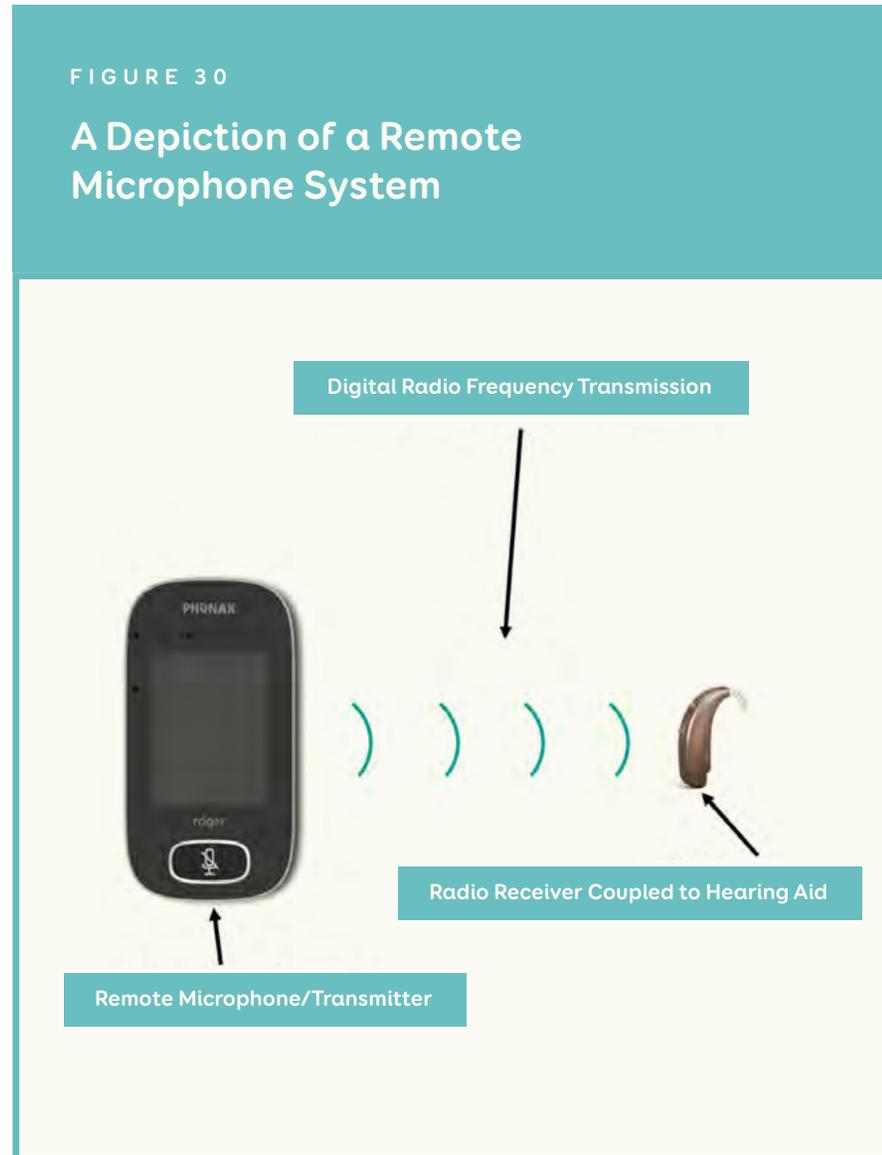
Listening and spoken language outcomes are intimately associated with auditory brain development. To optimize auditory brain development, children must have access to a robust, language-rich listening environment that is replete with intelligible speech.

The spoken word serves as the fertilizer that optimizes synaptogenesis as well the growth and development of the auditory circuits and neural networks that underlie the neural entrainment necessary for successful communication through listening and spoken language. When children with hearing loss are provided with a language-rich listening environment, age-appropriate LSL outcomes are not just possible, they are probable. When we entrain the brain through early access to a robust model of intelligible speech, the sky's the limit for children with hearing loss.

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FIGURE REFERENCES

Figure 1
Cerebral hemispheres divided by the longitudinal fissure. Reprinted from *Neuroscience for the Study of Communicative Disorders* (2nd ed.) (p. 25), by S.C. Bhatnagar, 2002, Philadelphia: Lippincott Williams. Reprinted with permission.

Figure 2
Primary lobes of the brain. Reprinted from *Neuroscience for the Study of Communicative Disorders* (2nd ed.) (p. 26), by S.C. Bhatnagar, 2002, Philadelphia: Lippincott Williams & Wilkins. Reprinted with permission.

Figure 3
A lateral view of the left cerebrum with representation of primary and secondary auditory cortices. Reprinted from *Neuroscience for the Study of Communicative Disorders* (2nd ed.) (p. 28), by S.C. Bhatnagar, 2002, Philadelphia: Lippincott Williams & Wilkins. Reprinted with permission.

Figure 4
Portions of the frontal and parietal lobes have been removed to reveal the primary auditory cortex (Heschl's gyrus). Reprinted from *Neuroscience for the Study of Communicative Disorders* (2nd ed.) (p. 204), by S.C. Bhatnagar, 2002, Philadelphia: Lippincott Williams & Wilkins. Reprinted with permission.

Figure 5
Figure 5. A coronal view of the auditory system. Reprinted from *Neuroscience for the Study of Communicative Disorders* (2nd ed.) (p. 203), by S.C. Bhatnagar, 2002, Philadelphia: Lippincott Williams & Wilkins. Reprinted with permission.

Figure 6
Figure 6. A midline sagittal view of the brain with depiction of intrahemispheric tracts, including the arcuate fasciculus. Reprinted from *Neuroscience for the Study of Communicative Disorders* (2nd ed.) (p. 60), by S.C. Bhatnagar, 2002, Philadelphia: Lippincott Williams & Wilkins. Reprinted with permission.

Figure 7
Spectrogram of the sentence, "The pool was filled with dirt and leaves." J. Wolfe, 2020.

Figure 8
An oversimplified visual representation of neurons responding to the word *green* when spoken in a conversation. Adapted from *Neuroscience for the Study of Communicative Disorders* (2nd ed.) (p. 26), by S.C. Bhatnagar, 2002, Philadelphia: Lippincott Williams & Wilkins. Adapted with permission.

Figure 9
An oversimplified visual representation of neurons responding to a lesson on frying the perfect egg as an egg sizzles in a frying pan. Adapted from *Neuroscience for the Study of Communicative Disorders* (2nd ed.) (p. 26), by S.C. Bhatnagar, 2002, Philadelphia: Lippincott Williams & Wilkins. Adapted with permission.

Figure 10.
An example of a bipolar neuron with its cell body, axon, and dendrites. IconicBestiary. (2015). Brain neuron cell diagram stock illustration [Online image]. iStock.com. https://www.istockphoto.com/vector/brain-neuron-cell-diagram-gm500676432-80677237.

Figure 11.
An example of a neuronal synapse with neurotransmitters being delivered into the synaptic junction to stimulate the receiving neuron. Reprinted from *Cochlear Implants: Audiologic Management and Considerations for Implantable Hearing Devices*, by J. Wolfe, 2020, Plural Publishing, Inc. Reprinted with permission.

Figure 12.
A simplified illustration of neural networks that govern numerous functions that support everyday activities. Reprinted from Experiences Build Brain Architecture, In *Center on the Developing Child at Harvard University*, 2011. Retrieved from https://developingchild.harvard.edu/resources/experiences-build-brain-architecture. Copyright 2011 by Center on the Developing Child at Harvard University. Reprinted with permission by Dr. Uri Hassan.

Figure 13
A visual depiction of a lack of neural entrainment that manifests as EEG signals that are out of phase with one another when five participants are at rest. Reprinted from This is Your Brain on Communication, In *TED*, n.d., Retrieved May 1, 2019 from https://www.ted.com/talks/uri_hasson_this_is_your_brain_on_communication?language=en. Copyright XXXX by TED. Reprinted with permission.

Figure 14
A visual depiction of the presence of neural entrainment that manifests as EEG signals that possess a high level of correlation as five listeners comprehend the same story. Reprinted from This is Your Brain on Communication, In *TED*, n.d., Retrieved May 1, 2019 from https://www.ted.com/talks/uri_hasson_this_is_your_brain_on_communication?language=en. Reprinted with permission by Dr. Uri Hassan.

FIGURE REFERENCES

Figure 15
Visual depiction of neural entrainment within the brains of two English-speaking speaker-listeners who listened to a story that they were both able to comprehend. Reprinted from This is Your Brain on Communication, In *TED*, n.d., Retrieved May 1, 2019 from https://www.ted.com/talks/uri_hasson_this_is_your_brain_on_communication?language=en. Reprinted with permission by Dr. Uri Hassan.

Figure 16
Visual depiction of neural activity that occurs within the brains of two English-speaking speaker-listeners who listened to a running passage of unintelligible words (i.e., reversed speech). Reprinted from This is Your Brain on Communication, In *TED*, n.d., Retrieved May 1, 2019 from https://www.ted.com/talks/uri_hasson_this_is_your_brain_on_communication?language=en. Reprinted with permission by Dr. Uri Hassan.

Figure 17
Visual depiction of neural entrainment within the brains of two English-speaking speaker-listeners who listened to intelligible words that are scrambled in an order that produces a message that carries on meaning. Reprinted from This is Your Brain on Communication, In *TED*, n.d., Retrieved May 1, 2019 from https://www.ted.com/talks/uri_hasson_this_is_your_brain_on_communication?language=en. Reprinted with permission by Dr. Uri Hassan.

Figure 18
Visual depiction of neural entrainment within the brains of an English-speaking speaker and a Russian-speaking listener when each comprehends a story told in her native language. Reprinted from This is Your Brain on Communication, In *TED*, n.d., Retrieved May 1, 2019 from https://www.ted.com/talks/uri_hasson_this_is_your_brain_on_communication?language=en. Reprinted with permission by Dr. Uri Hassan.

Figure 19
Visual depiction of neural entrainment that occurs between a talker and listener when the latter comprehends the message of the former. Reprinted from This is Your Brain on Communication, In *TED*, n.d., Retrieved May 1, 2019 from https://www.ted.com/talks/uri_hasson_this_is_your_brain_on_communication?language=en. Reprinted with permission by Dr. Uri Hassan.

Figure 20
An illustration of the auditory component of the brain's connectome. Reprinted from *Cochlear Implants: Audiologic Management and Considerations for Implantable Hearing Devices*, by J. Wolfe, 2020, Plural Publishing, Inc. Reprinted with permission.

Figure 21.
A PET scan image of brain activity superimposed on an MRI image of the brain of an individual who is listening to speech with a cochlear implant for the left ear. Reprinted from "Auditory Cortical Activation and Speech Perception in Cochlear Implant Users: Effects of Implant Experience and Duration of Deafness," by K.M.J. Green, P.J. Julyan, D.L. Hastings, R.T. Ramsden, 2005, *Hearing Research*, p. 184-192. Reprinted with permission.

Figure 22
Neural responses recorded via PET scan and superimposed on an MRI scan.Reprinted from "Sign Language 'Heard' in the Auditory Cortex," by Nishimura et al., 199, *Nature, 397*, p. 116. Reprinted with permission.

Figure 23
Neural responses of normal hearing subjects recorded via PET scan and superimposed on an MRI scan. Reprinted from "Cross-modal Plasticity and Speech Perception in Pre- and Post-lingually Deaf Cochlear Implant Users," by K.A. Buckley, E.A. Tobey, 2011, *Ear and Hearing,* 32(1), p. 2-15. Reprinted with permission.

Figure 24
Neural responses of post-linguistically-deafened subjects recorded via PET scan and superimposed on an MRI scan. Reprinted from "Cross-modal Plasticity and Speech Perception in Pre- and Post-lingually Deaf Cochlear Implant Users," by K.A. Buckley, E.A. Tobey, 2011, *Ear and Hearing,* 32(1), p. 2-15. Reprinted with permission.

Figure 25
Neural responses of pre-linguistically-deafened subjects recorded via PET scan and superimposed on an MRI scan. Reprinted from "Cross-modal Plasticity and Speech Perception in Pre- and Post-lingually Deaf Cochlear Implant Users," by K.A. Buckley, E.A. Tobey, 2011, *Ear and Hearing,* 32(1), p. 2-15. Reprinted with permission.

Figure 26a
PET scan images showing lack of brain activity (hypometabolism) of cochlear implant recipients at rest prior to cochlear implantation. Reprinted from "Cross-Modal Plasticity and Cochlear Implants," by Lee et al., 2001, *Nature.* 409(6817), p. 149-150. Reprinted with permission.

FIGURE REFERENCES

Figure 26b
The relationship between speech recognition (% correct) with cochlear implant and lack of brain activity (hypometabolism) when at rest prior to cochlear implantation. Reprinted from "Cross-Modal Plasticity and Cochlear Implants," by Lee et al, 2001, *Nature.* 409(6817), p. 149-150. Reprinted with permission.

Figure 27
Color-coded MRI images depicting regions of the brain in which neuroanatomy was predictive of speech recognition improvement after cochlear implantation. Reprinted from "Neural Preservation Underlies Speech Improvement from Auditory Deprivation in Young Cochlear Implant Recipients," by Feng et al., 2018, *Proceedings of the National Academy of Sciences of the United States of America*, 115(5), e1022-e1031. Reprinted with permission.

Figure 28
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Figure 30.
Figure 30. A depiction of a remote microphone system. Adapted from *Phonak*, n.d., Retrieved from https://www.phonak.com/us/en.html. Copyright 2019 by Phonak. Reprinted with permission.

Acknowledgement

JACE WOLFE, PH.D. CCC-A

Dr. Jace Wolfe is the Director of Audiology and Research at the Hearts for Hearing Foundation in Oklahoma City, Okla. He also is an adjunct Assistant Professor in the Audiology Department at the University of Oklahoma Health Sciences Center and Salus University. He previously served as the editor for the American Speech Language Hearing Association's Division 9 journal and is currently a co-editor for the Plural Publishing, Inc. Core Clinical Concept Series on Cochlear Implants.

Dr. Wolfe is a member of the Better Hearing Institute's Pediatric Advisory Board as well as the Audiology Advisory Boards for Cochlear Americas, Advanced Bionics, and the Phonak Hearing Aid Company. He also serves on the Editorial Board of The Hearing Journal. Additionally,

Dr. Wolfe co-authors a periodic column entitled *The Top Ten in The Hearing Journal,* and he has published numerous book chapters and articles in professional peerreviewed and trade journals. He is the author of the textbook entitled *Cochlear Implants: Audiologic Management and Considerations for Implantable Hearing Devices,* and he is co-editor (with Carol Flexer, Jane Madell, and Erin Schafer) of the textbooks *Pediatric Audiology: Diagnosis, Technology, and Management, Third Edition* and *Pediatric Audiology Casebook, Second Edition.* He is also a co-author of the textbook *Programming Cochlear Implants, Second Edition.* His areas of interests are pediatric amplification and cochlear implantation, personal remote microphone technology, and signal processing for children. He provides clinical services for children and adults with hearing loss and is also actively engaged in research in several areas pertaining to hearing aids, cochlear implants, hybrid cochlear implants, and personal remote microphone systems. Dr. Wolfe is also contributing author of another Hearing First white paper, *"Mission Probable: Age-Appropriate Listening and Spoken Language Abilities for Children with Hearing Loss."* published in 2019. Mission Probable is available on the Hearing First website, **www.hearingfirst.org**.

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