ESTABLISHING A VISUAL GUIDELINE FOR THE LOCUS OF AUDITORY CORTEX IN HUMANS

by

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As members of the Audiology Doctoral Project Committee, we certify that we have read the project prepared by Aaron Whiteley, titled Establishing a Visual Guideline for the Locus of the Auditory Cortex in Humans and recommend that it be accepted as fulfilling the Audiology Doctoral Project requirement for the Degree of Doctor of Audiology.

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Abstract

Given the variability of human brain anatomy, there is a need to develop a guideline for visually identifying important auditory structures. Traditionally, visual guidelines have been taught in order to help clinicians quickly and reliably identify central auditory structures in the brain. However, the reliability of some of these guidelines have been accepted at face value but not necessarily studied extensively. This study examines the location of Heschl's gyrus along the superior temporal plane and the consistency of the "two-thirds rule" – which states that Heschl's gyrus appears in the most posterior third of the superior temporal plane. Heschl's gyrus and intra-hemispheric measures along the superior temporal plane are examined, with new data reported. The relationship between the two-thirds rule and other variables such as: gender, hemisphere, the angle of Heschl's gyrus, the number of Heschl's gyri, and the type of ascending ramus are observed.

Introduction

Historical Perspective

The temporal lobe is the brain's central hub for auditory processing. Its function has been directly studied for nearly a century, beginning with Brodmann's cell staining studies (1909). Brodmann conducted a post-mortem study of human brains, staining the cells and organizing the brain by cytoarchitecture. He identified two particular areas – Brodmann areas 41 and 42 as primary and secondary auditory cortex respectively. Von Economo and Koskinas (1925) would expand upon Brodmann's work and further clarify a map of functional areas within the brain. Shortly after Brodmann, Von Economo, and Koskinas' studies, the location of auditory cortex would be examined most notably through animal studies using electrophysiologic methods. Kornmuller (1937) is frequently credited with first identifying a map of auditory cortex in cats. In 1939, Bremer, Dow, and Moruzzi observed changes in electric potential on the surface of bird and reptile brains in response to acoustic stimuli. They observed certain areas of the brain to have a change in potential compared to other non-responsive areas in the presence of an auditory stimulus. These studies were among the earliest to attempt to delineate areas of the brain that are receptive to auditory information.

In the late 1960's and throughout the 1970's, Gastone Celesia conducted several groundbreaking studies that began to identify exactly which areas of the human brain comprised the auditory cortex. In 1969, Celesia and Puletti recorded P1 potentials on five brain surgery patients – three of which suffered from temporal lobe epilepsy. In this study, they identified the superior temporal plane (STP) as the primary auditory cortex in humans, the same location as the primary auditory cortex in recently-studied monkeys (Ades & Felder, 1942, Walzl & Woolsey, 1943, Walzl, 1947). In 1976, Gastone Celesia recorded electric potentials during surgery on patients who suffered from seizures originating in the temporal lobe. This further elucidated the specific area comprising human primary and secondary auditory cortex.

In this study, the auditory cortex is considered in a general sense. We will specifically focus on a structure within the larger area known as "primary auditory cortex" called Heschl's gyrus (HG). This gyrus has been clinically understood to exist at approximately the posterior third of the STP, but the origin of this guideline is uncertain. Heschl's gyrus has been specifically examined in the context of its role within the auditory cortex, its morphology, and cytoarchitecture. These areas are discussed in greater detail below.

Function of Heschl's Gyrus

Given the present aim of this study to provide a guideline for visually identifying important auditory structures, it is worth discussing the function of Heschl's gyrus in greater detail. Techniques for assessing the function of specific structures in the brain are constantly evolving. Currently, determining functional properties of a specific anatomical region is one method researchers use to examine relationships between structure and function. Others examine functional losses after damage has occurred to a structure. This can indicate what the function the structure had before being damaged. Lesion studies have the disadvantage of not being easily generalized to the population, so healthy brains will be used in this study. It is important to remember that our understanding of the function of brain structures is imperfect, and structures with overlapping roles complicates this area of study.

Heschl's gyrus has been implicated in processing of both speech and non-speech auditory information. Wong et al. (2007) conducted a task in which participants were required to learn and associate a Mandarin word with a picture. The main feature that was changed between the Mandarin words was pitch. They found that participants who performed better on this task tended to have a larger left Heschl's gyrus. The same study found an association between smaller Heschl's gyri and poorer musical and non-lexical pitch perception. When pitch is involved, language ability also appears to be influenced. Warrier et al. (2009) found a positive association between size of Heschl's gyrus and processing of speech cues. They predicted from these results that individuals with larger Heschl's gyri may have greater success learning new speech sounds. These studies demonstrate a functional difference associated with an anatomical change. Additionally, they demonstrate lateralization of the function of Heschl's gyrus.

Gross Morphology of Heschl's Gyrus

Heschl's gyrus presents differently not only across individual brains, but across hemispheres within individual brains. A leftward asymmetry of the superior temporal plane is well-established in the literature (Geschwind & Levitsky, 1968, Campain & Minckler, 1976), leading to HG typically presenting as larger in the left hemisphere than the right. This finding corresponds with a larger planum temporale (PT) on the left hemisphere as well.

Heschl's gyrus can also appear as more than one isolated gyrus per hemisphere. There are two other frequently-identified variations of HG, known as a complete duplication, and a common stem duplication. A complete duplication occurs when there are two gyri anterior to planum temporale, comprising the totality of HG. In these instances, a sulcus splits the two Heschl's gyri completely. If the intermediary sulcus incompletely separates the two gyri, a common stem HG is found. Campain and Minckler (1976) state that the most common configuration is an asymmetry between hemispheres, with a common stem duplication on the right, and a single HG on the left.

Cytoarchitecture of Heschl's Gyrus

As mentioned previously, Brodmann's 1909 cell staining study was the first to examine the cytoarchitecture of the STP. His study, which mapped major areas of the brain and grouped them based on function, identified HG as a primary auditory cortex area. Cytoarchitectonic studies of the brain continued throughout the twentieth century, progressing from animal to human studies. Galaburda and Sanides (1980) further delineated the cytoarchitecture of Heschl's gyrus. Heschl's gyrus comprises koniocortical cells (cells involved in sensation), forming a core. On all sides of this core are parakoniocortical cells. These parakoniocortical cells form the secondary auditory cortex and extend rostrally beyond the anterior border of Heschl's gyrus. The cells in Heschl's gyrus are granular pyramidal cells that primarily occupy layer III in the brain.

Motivation for Study

As their scope of practice expands, it remains important for audiologists to develop and maintain a strong understanding of hearing-related anatomy. In a variety of work settings, audiologists may work with patients who have a concern which originates from some lesion of the brain. In these cases, it is vital that the audiologist have a solid knowledge of what central structures have a role in hearing, and where they are located within the brain.

There is tremendous morphological variability not only between different brains, but also between the two hemispheres of the same brain. This variability can be a source of confusion for clinicians who attempt to examine a patient's MRI and obtain valuable information from it. A rudimentary understanding of the central auditory nervous system can lead a clinician towards an incorrect diagnosis or assumption about a patient's condition. Graduate students who are just beginning to learn about central anatomy may fallaciously assume that certain auditory structures are always located in the same place. There is a clear need for a visual guideline for students and clinicians to refer to when studying images of the brain. A "rule of thumb" for the identification of important auditory neural structures would aid in better education of future audiologists and more accurate diagnosis of auditory central nervous system disorders.

A rule of thumb for quickly identifying the locus of auditory cortex has been stated and referenced in previous literature, which states that Heschl's gyrus can be identified quickly, as it is typically located two-thirds of the way back on the superior temporal plane (Musiek, 1986, Da Costa et al., 2011). This assertion will henceforth be referred to as the Two-Thirds Rule.

In this study, we form several predictions regarding the Two-Thirds Rule:

1. **The HG will be observed at an average location of the posterior third of the STP (two-thirds back on the STP).**
2. **The HG will appear at the same location regardless of hemisphere or gender.**
3. **The location of HG will be influenced by other factors such as the angle and number of HG and AR type.**

Methods

The Two-Thirds Rule was assessed using the following methods:

1. Determining where HG typically begins and ends on the STP and its related apportionment of the STP
2. Evaluating interhemispheric differences in STP anatomy
3. Examining the influence of other factors such as the angle and number of HG on the relative location of HG

A total of 28 (56 hemispheres) normal, high-resolution T1 - weighted brain MRIs were included in this study. Of the 28 brains, 19 were women and 9 were men. Each subject was right-handed. Ages of the brains ranged from 18-57 with a mean of 26.6 years. There parameters for the acquisition of these images was as follows: acquisition matrix 224 × 224 × 104, repetition time (TR) = 5000 ms, echo time (TE) = 2.62 ms, flip angle = 5 deg, field of view (FOV) = 224 mm, voxel size = 0.5 × 0.5 × 0.5 mm.

The brain images were obtained from an online open-access database called Open Science CBS Neuroimaging Repository. The 28 brains included in this study have been previously analyzed in St. George et al. (2017) and Wong et al. (2018). In this present study, the brains were primarily analyzed using software from the NeuroImaging Tools and Resources Collaboratory (NITRC) called MRIcron (2016). This software allows brains to be viewed as two-dimensional slices along the sagittal, coronal, and transverse plane. As a secondary form of analysis, a software called BrainVISA Anatomist (Le Troter, Auzias & Coulon, 2012) was used. This software, also used in Wong et al. (2017), allows the user to manipulate a three-dimensional cortical mesh of the brains, which is useful for cross-checking the location of various anatomical structures. Some structures are difficult to view on two-dimensional slices, as their boundaries do not lie flat in a line with each other. This software remediates that challenge.

Boundaries of various auditory structures were visually identified, and a three-dimensional Cartesian coordinate was obtained for each desired location. Distances between coordinates were calculated using the following formula:

$$d = (((x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2)^{1/2})/2$$

In this formula, *d* equals distance, x_1, y_1, z_1 is the coordinate of the first anatomical location, and x_2, y_2, z_2 is the coordinate of the second location. Before being divided by two, this formula provides the number of voxels between any two points. By dividing the formula by a factor of two, voxels are converted into a millimeter measurement. For ease of presentation, the values of distances in this study will be presented as centimeters. Millimeters were used for the increased accuracy of measurement. As a form of normalization, and to assess the accuracy of the Two-Thirds Rule, the distances could be compared to each other as percentages of some greater distance. The measurements are taken along three separate vectors: lateral, medial, and mid-way. The mid-way vector is identified as a line passing through the STP, equidistant from the lateral and medial vectors.

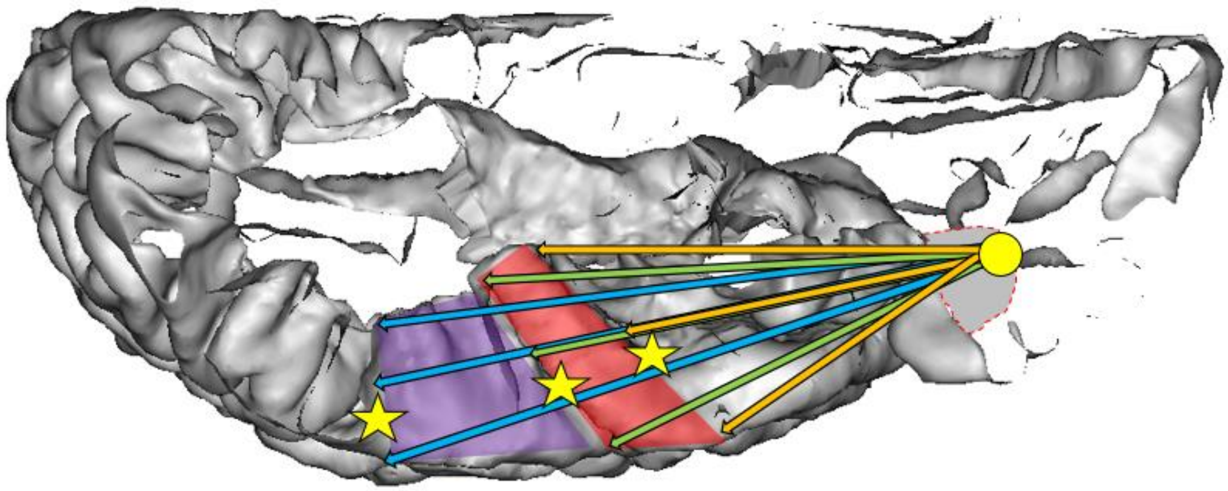


FIGURE 1
A transverse slice of a right hemisphere showing the ten separate points that are measured in this study. The anterior edge of the STP is marked with a yellow dot. The orange arrows show the linear measurement to the anterior edge of HG. The green arrows show the measurements to the posterior edge of HG. The blue arrows show the linear measurement to the end of the STP. There are three arrows for each color, showing the measured lines for the lateral, mid-way, and medial vectors.

Boundaries of Anatomical Landmarks

Superior Temporal Plane

In order to assess the accuracy of the Two-Thirds Rule, a clear definition must be established regarding what constitutes the field along which HG is located. The lateral edge of HG can typically be observed along the sylvian fissure. The sylvian fissure serves as a useful visual landmark for the separation of the temporal and parietal lobes – the temporal lobe existing inferior to the parietal lobe. If the parietal lobe were removed and one were to gaze downward from the top of a brain, the STP would be observed (Musiek and Baran, 2007).

For the purposes of this study, the STP was objectively defined as the cortical area existing between the anterior end of the temporal lobe and the supramarginal gyrus, or the beginning of the posterior ascending ramus (PAR). The temporal lobe comes to a rounded end on the anterior aspect. Given the lack of a sharp ledge with a definitive end, it is necessary to operationally define what will be considered the anterior tip of the STP. Ayberk et al. (2012) refer to this hypothetical tip as the anterior sylvian point. In their anatomical study of the relationship between the anterior sylvian point and the inferior frontal gyrus, they define the anterior sylvian point as the point at which the anterior ascending ramus and the horizontal ramus would hypothetically converge on the temporal lobe. This is visually consistent with Gray's criterion that the anterior sylvian point is the point at which the lateral fissure "divides" the temporal and fronto-parietal lobes. Galaburda et al. (1987) identifies the sulcus directly posterior to PT as the posterior end of the STP. These will be the criteria for the anterior and posterior ends of the STP in this present study.

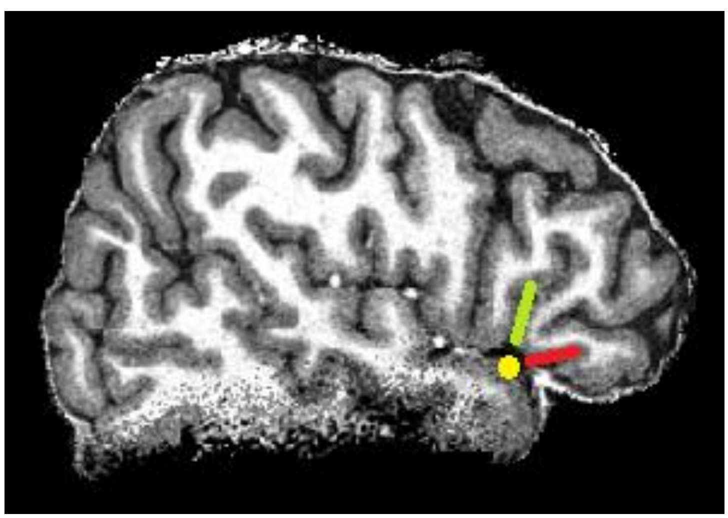


FIGURE 2
A sagittal slice through the medio-lateral temporal lobe shows the criteria used for identifying the anterior sylvian point. If the anterior ascending ramus (green) and horizontal ramus (red) were to continue coursing posteriorly and

inferiorly, they would intersect at the anterior sylvian point (yellow). The anterior sylvian point is considered the anterior edge of the STP for this study.

Heschl's Gyrus

Heschl's gyrus was visually-identified using the MRIcron software. The exact criteria for where the boundaries of HG lie were established using prominent anatomical research. Rademacher et al. (1993) establishes well-defined borders for the location of HG. First, HG exists on the superior temporal plane (which is the temporal lobe's superior surface), lying within the sylvian fissure. The anterior border of HG is demarcated by the first transverse sulcus. The posterior border of HG is identified by the first Heschl sulcus. This sulcus is also commonly referred to as Heschl's posterior sulcus (Musiek & Baran, 2007). Medially, HG is terminated by the medial edge of the temporal lobe, where the insula is found. The lateral edge of HG is defined as the "external lip" of the sylvian fissure.

Heschl's gyrus can appear with several different configurations. Most prominently, HG can appear as one single sulcus, two completely distinct sulci, or as what is referred to as a "common stem duplication" (Rademacher et al., 1993, Leonard et al., 1993). A common stem duplication occurs when the lateral aspect of HG is split by an intermediate sulcus that extends medially from the lateral edge of the sylvian fissure less than one-third of the length of the length of HG (St. George, 2017, Wong, 2018). In this study, the posterior border of HG is defined as the first Heschl sulcus regardless of the classification of number of HG. This decision is supported by a study by Shapelske et al. (1999) in which anatomical borders of auditory structures were operationally-defined.

In front of HG lies the planum polare (PP), which while not directly measured and discussed in this study, will be indirectly examined when looking for the length along the STP that HG first appears. Posterior to Heschl sulcus is planum temporale (PT).

Planum Temporale

Wada et al. (1975) define planum temporale generally as "the area behind Heschl [sic] gyrus." Geschwind and Levitsky (1968) provide the same general delineation of PT, but they proceed further to say that the first Heschl sulcus, which has been established as the posterior border of HG, is the anterior border of PT.

There has been much debate regarding the exact boundaries of important auditory structures. Some, such as Galaburda et al. (1987) have included part of the posterior ascending ramus in their measurement of PT. Steinmetz et al. (1990) utilized a measurement in which the part of PT that extended onto the PAR was included. Using this technique, they referred to their measurement of planum temporale as PT+, indicating the extra area that would be included in this technique. Various factors such as the angle of the PAR and cytoarchitecture of the surrounding tissue have been considered in the decision of where PT terminates.

In 1999, Shapelske et al. established a clearer guideline for the location of the borders of PT by condensing previous research in which the PAR was included and others in which it was not included. Steinmetz' aforementioned 1990 study found a leftward asymmetry to be consistent whether or not the PAR was included. This leftward asymmetry is consistent with other research (Geschwind & Levitsky, 1968, Galaburda et al., 1987, Teszner et al., 1972, Witelson & Pallie, 1973). It is primarily important that the differentiation is made as to whether or not PAR is included as part of the posterior border of PT. In this study, the posterior border of PT will be defined as the sulcus immediately posterior to PT, at which point the PAR begins.

There is greater consensus regarding the lateral and medial borders of PT. The lateral border of PT is defined as the lateral edge of the superior temporal plane, consistent with the lateral border of HG. The medial border is defined as the point at which the medial portion of PT connects with retroinsular white matter. This is consistent with the definition established in Shapelske et al. (1990). Given that PT is often triangle-shaped (Wong, 2018), there may be some instances in which a theoretical medial border may be present, as the medial border would be no greater in length than a point with zero length between anterior and posterior edges.

FIGURE 3
A view of the STP showing the anatomical landmarks discussed in this study. 1 – Anterior edge of STP, 2 – Planum polare, 3 – First transverse sulcus, 4 – Heschl's gyrus, 5 – First Heschl sulcus, 6 – Planum Temporale, 7 – Posterior end of STP (brain image courtesy of Frank Musiek)

Definitions of Additional Categorical Terms

Heschl's Gyrus Type/Number

Heschl's gyrus can appear with multiple different configurations, making it difficult to differentiate HG from PT. Marie et al. (2015) discusses three different variations of HG presentation that can occur: no duplication (single), common stem duplication, and complete duplication (double). The gyrus is identified with no duplication if only a single HG is present. A common stem duplication occurs when HG is partially divided laterally by an intermediate sulcus (Beck's intermedius). Beck's intermedius does not reach the medial edge of HG in a common stem duplication. If the intermediate sulcus completely divides HG in two, a complete duplication occurs. Examples of the three variations of HG can be seen below in figure 3.

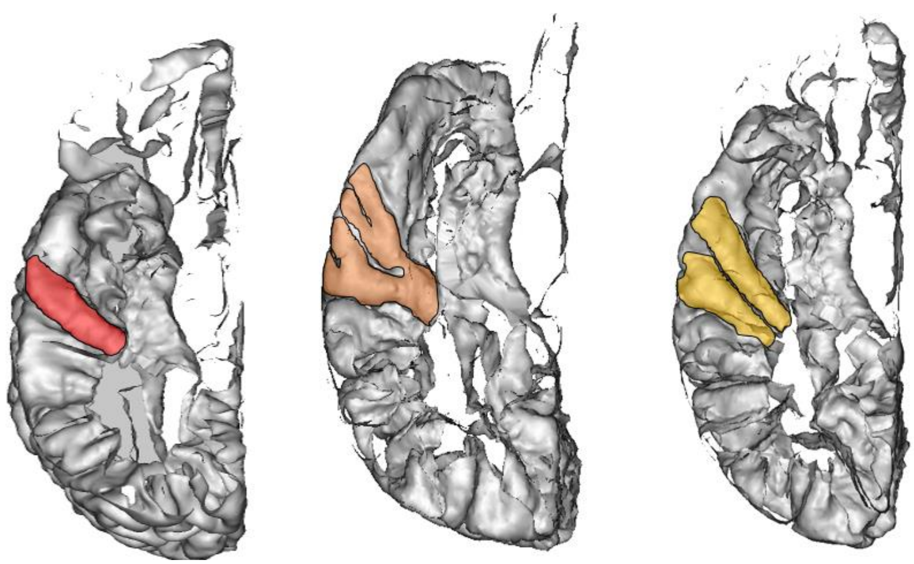


FIGURE 4
A transverse slice of three separate hemispheres. A single HG configuration is seen on the left (red). A common stem duplication, noted by the incomplete separation of the two gyri is in the middle (orange), and a completely duplicated HG is seen on the right (yellow).

Heschl's Gyrus Angle Type

As HG courses from the medial to lateral edge of the STP, it typically migrates anteriorly (Penhune et al., 1996). In order to discover an association between the anterior course of HG and its location, two angle types are defined. By visual examination, it is clear that some HG course anterio-laterally at a straight, linear angle while others have a curve. This study defines two types of angles that HG can possess: straight and curvilinear.

In order to establish the category in which any given HG belongs, angles are measured at two points. Using the anterior medial edge of HG as a vertex, a line is first drawn moving laterally towards the edge of the STP. Two lines are then drawn diagonally through the lateral-anterior and mid-way anterior point of HG. Thus, two angles are formed. If the angles differ by ten degrees or more, HG is classified as curvilinear. If the difference is less than ten degrees, HG has a straight angle. Figure 4 demonstrates the visual manner in which angle type may be identified and different configuration.

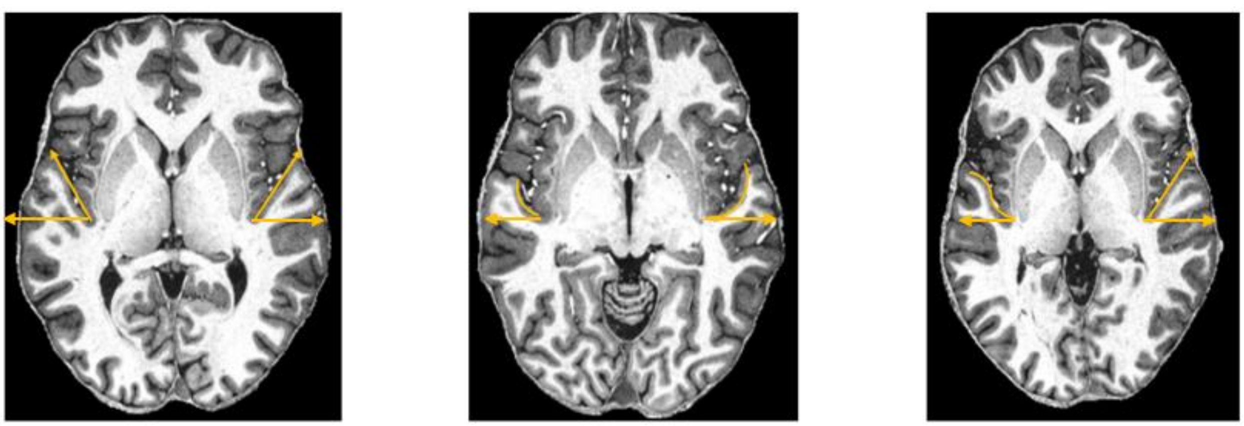


FIGURE 5

In the brain on the left, both hemispheres contain a HG with a straight angle. The middle brain has both HG presenting in a curvilinear configuration. The right brain has one of each – a curvilinear HG angle on the left hemisphere, and a straight angle on the right.

Ascending Ramus Type

The ascending ramus has been identified in previous literature as having an influence on the morphology of the superior temporal plane (St. George, 2017, Westbury et al., 1999). The ascending ramus can occur in several different morphological variations: straight, posterior ascending ramus (PAR), bifurcation, and trifurcation. A straight configuration is identified if the SF terminates without angling superiorly. A PAR configuration occurs when the SF terminates after progressing superiorly. If the ascending ramus branches into a straight and ascending ramus, this is called a bifurcation. A trifurcation occurs when the aforementioned two branches are present in addition to a false ascending ramus that arises before the final termination of the ascending ramus.

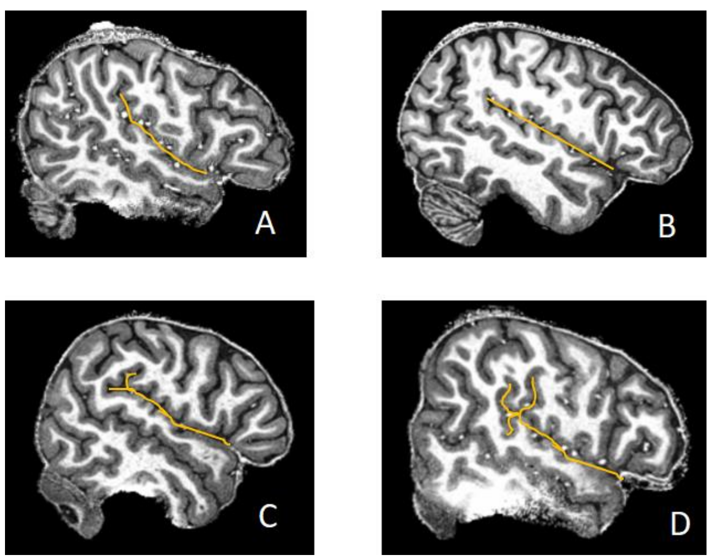


FIGURE 6

Sagittal view of four brains with different ascending rami. Brain A shows a posterior ascending ramus (PAR). Brain B shows a straight posterior ramus. Brain C shows a bifurcated PAR while D shows a trifurcated PAR.

A Note on Normalization

An important consideration on any anatomical study using MRI images is whether or not the brain images are "normalized." This is a process by which each brain image is altered in size to match a standardized map. This technique has certain advantages, in that it allows for functional areas to be visualized in an overlapping space. This allows researchers to make observations regarding what areas of the brain are activated by specific stimuli. Penhune et al. (1996) further discusses its limitations, stating that normalization limits the ability for researchers to make interhemispheric comparisons, and it standardizes all images to a single size of a single subject (Park et al., 2003). This makes it more difficult to observe variability between a large number of brains in the larger population.

Because of these limitations of normalization, the brains in this study are not normalized. The goal of this study is primarily to create a guideline for clinicians and students to identify where auditory structures are located. Clinicians observing MRI would not be observing a normalized brain, so this method will provide better real-world applicability. Lastly, the Two-Thirds Rule lends itself well to a discussion of anatomical structure in terms of what percentage of the length of the STP they exist upon. Discussing the location of an anatomical structure in terms of its location as a percent of the length of the brain is, in itself, a form of correction for size of the temporal lobe.

Statistical Analysis

Statistical analyses for this study were made using Microsoft Excel and an extended statistical package (Microsoft, 2019). The location of HG was obtained and then discussed in terms of its relation to hemisphere and gender. Paired t-tests were used to make comparisons between hemisphere and gender. Standard deviations for the location of HG were also obtained. A one-way ANOVA was utilized to make comparisons between groups when more than two factors were compared (such as the three types of HG), and post-hoc t-tests allowed for further examination on the difference between groups.

Results

Medial Vector Measurements

Superior Temporal Plane

The STP was measured along the medial vector for the left and right hemispheres. The left hemisphere had a mean STP length of 6.95 cm ($N = 28$, $\sigma = 0.56$), and the right hemisphere had a mean length of 6.26 cm ($N = 28$, $\sigma = 0.48$). There is a statistically-significant difference in STP length ($p = 0.00004$, d.f. = 27, $t = -5.77$).

Distance to Anterior Edge of Heschl's Gyrus

Raw Measurement

The mean distance from the anterior edge of the STP to the anterior edge of HG was found to be 4.75 cm ($\sigma = 0.42$) in the right hemisphere and 5.25 cm ($\sigma = 0.42$) in the left hemisphere. There is a statistically-significant hemispheric difference in distance to the anterior edge of HG ($p = 0.00005$, d.f. = 27, $t = -5.18$).

Percentage

The distance from the anterior edge of the STP to the anterior edge of HG was also calculated as a percentage of the total length of the STP. The anterior sulcus of HG was found at 75.84% (σ = 8.11%) of the length of the STP in the right hemisphere and 76.14% (σ = 8.11%) in the left hemisphere. There is no statistically-significant hemispheric difference in the percentage measurements for this vector ($p = 0.88$, d.f. = 27, $t = 0.14$).

Distance to Posterior Edge of Heschl's Gyrus

Raw Measurement

The mean distance from the anterior edge of the STP to the posterior edge of HG was found to be 5.36 cm (σ = 0.60) in the right hemisphere and 6.07 cm (σ = 0.67) in the left hemisphere. There is a statistically-significant hemispheric difference in distance to the anterior edge of HG ($p = 0.00006$, d.f. = 27, $t = -4.98$).

Percentage

The distance from the anterior edge of the STP to the posterior edge of HG was also calculated as a percentage of the total length of the STP. The anterior sulcus of HG was found at 86.58% (σ = 8.92%) of the length of the STP in the right hemisphere and 87.37% (σ = 5.54%) in the left hemisphere. There is no statistically-significant hemispheric difference in the percentage measurements for this vector ($p = 0.41$, d.f. = 27, $t = -0.89$).

Lateral Vector Measurements

Superior Temporal Plane

The STP was measured along the lateral vector for the left and right hemispheres. The left hemisphere had a mean STP length of 6.36 cm ($N = 28$, σ = 0.75), and the right hemisphere had a mean length of 5.54 cm (*N* = 28, σ = 0.64). There is a statistically-significant difference in STP length (p = 0.006, d.f. = 27, t = -4.66).

Distance to Anterior Edge of Heschl's Gyrus

Raw Measurement

The mean distance from the anterior edge of the STP to the anterior edge of HG was found to be 2.29 cm (σ = 0.69) in the right hemisphere and 2.84 cm (σ = 0.74) in the left hemisphere. There is a statistically-significant hemispheric difference in distance to the anterior edge of HG (p = 0.006, d.f. = 27, t = -3.13).

Percentage

The distance from the anterior edge of the STP to the anterior edge of HG was also calculated as a percentage of the total length of the STP. The anterior sulcus of HG was found at 41.50% (σ = 12.41%) of the length of the STP in the right hemisphere and 44.66% (σ = 10.37%) in the left hemisphere. There is a statistically-significant hemispheric difference in the percentage measurements for this vector (p = 0.04, d.f. = 27, t = -1.07).

Distance to Posterior Edge of Heschl's Gyrus

Raw Measurement

The mean distance from the anterior edge of the STP to the posterior edge of HG was found to be 4.08 cm (σ = 0.73) in the right hemisphere and 4.41 cm (σ = 0.81) in the left hemisphere. There is no statistically-significant hemispheric difference in distance to the posterior edge of HG (p = 0.121, d.f. = 27, t = -1.84).

Percentage

The distance from the anterior edge of the STP to the posterior edge of HG was also calculated as a percentage of the total length of the STP. The posterior sulcus of HG was found at 73.96% (σ = 12.22%) of the length of the STP in the right hemisphere and 69.37% (σ = 9.35%) in the left hemisphere. There is no statistically-significant hemispheric difference in the percentage measurements for this vector ($p = 0.13$, d.f. = 27, $t = 1.90$).

Mid-Way Vector Measurements

Superior Temporal Plane

The STP was measured along a line exactly in between the lateral and medial vectors for the left and right hemispheres. This measurement is called "mid-way." Along the mid-way vector, the left hemisphere had a mean STP length of 6.35 cm (*N*=28, σ = 0.69), and the right hemisphere had a mean length of 5.70 cm (*N*=28, σ = 0.55). There is a statistically-significant difference in STP length ($p = 0.0003$, d.f. = 27, $t = -4.05$).

Distance to Anterior Edge of Heschl's Gyrus

Raw Measurement

The mean distance from the anterior edge of the STP to the anterior edge of HG was found to be 2.99 cm (σ = 0.49) in the right hemisphere and 3.59 cm (σ = 0.65) in the left hemisphere. There is a statistically-significant hemispheric difference in distance to the anterior edge of HG ($p = 0.008$, d.f. = 27, $t = -3.73$).

Percentage

The distance from the anterior edge of the STP to the anterior edge of HG was also calculated as a percentage of the total length of the STP. The anterior sulcus of HG was found at 52.60% (σ = 8.06%) of the length of the STP in the right hemisphere and 56.69% (σ = 9.90%) in the left hemisphere. There is a statistically-significant hemispheric difference in the percentage measurements for this vector ($p = 0.03$, d.f. = 27, $t = -1.61$).

Distance to Posterior Edge of Heschl's Gyrus

Raw Measurement

The mean distance from the anterior edge of the STP to the posterior edge of HG was found to be 4.44 cm (σ = 0.67) in the right hemisphere and 4.92 cm (σ = 0.62) in the left hemisphere. There is a statistically-significant hemispheric difference in distance to the posterior edge of HG (p = 0.008, d.f. = 27, t = -3.24).

Percentage

The distance from the anterior edge of the STP to the posterior edge of HG was also calculated as a percentage of the total length of the STP. The posterior sulcus of HG was found at 77.87% (σ = 10.05%) of the length of the STP in the right hemisphere and 77.67% (σ = 7.71%) in the left hemisphere. There is no statistically-significant hemispheric difference in the percentage measurements for this vector (p = 0.93, d.f. = 27, t = 0.09).

Table 1 summarizes all of the aforementioned data.

	STP Length (cm)		Distance to Anterior HG (cm)		Distance to Anterior HG (%)		Distance to Posterior HG (cm)		Distance to Posterior HG (%)	
	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Medial	6.26	6.95	4.75	5.25	75.84	76.14	5.36	6.07	86.58	87.37
Lateral	5.54	6.36	2.29	2.84	41.50	44.66	4.08	4.41	73.96	69.37
Mid-Way	5.70	6.35	2.99	3.59	52.60	56.69	4.44	4.92	77.87	77.67

Table 1
The raw measurements and percentage measurements for the location of HG along the medial, lateral, and mid-way vectors

Gender Differences – Mid-Way Vector

Superior Temporal Plane

The STP length along the mid-way vector was compared between males and females. Female brains had a mean STP length of 6.01 cm (*N* =19, σ = 0.72), and the male brains had a mean length of 6.05 cm (*N* = 9, σ = 0.66). There is no statistically-significant difference in STP length (p = 0.85, d.f. = 54, t = 0.19).

Distance to Anterior Edge of Heschl's Gyrus

Raw Measurement

The mean distance along the mid-way vector from the anterior edge of the STP to the anterior edge of HG was found to be 3.35 cm (σ = 0.52) in males and 3.25 cm (σ = 0.69) in the females. There is no statistically-significant gender difference in distance to the anterior edge of HG (p = 0.62, d.f. = 54, t = 0.49).

Percentage

The distance from the anterior edge of the STP to the anterior edge of HG was also calculated as a percentage of the total length of the STP. The anterior sulcus of HG was found at 55.61% (σ = 7.67%) of the length of the STP in males and 54.19% (σ = 9.88%) in females. There is no statistically-significant hemispheric difference in the percentage measurements for gender (p = 0.60, d.f. = 54, t = 0.53).

Distance to Posterior Edge of Heschl's Gyrus

Raw Measurement

The mean distance from the anterior edge of the STP to the posterior edge of HG was found to be 4.70 cm (σ = 0.66) in males and 4.66 cm (σ = 0.70) in the females. There is no statistically-significant gender difference in distance to the anterior edge of HG (p = 0.86, d.f. = 54, t = 0.17).

Percentage

The distance from the anterior edge of the STP to the posterior edge of HG was also calculated as a percentage of the total length of the STP. The anterior sulcus of HG was found at

77.78% (σ = 8.70%) of the length of the STP in males and 77.77% (σ = 9.07%) in females. There is no statistically-significant hemispheric difference in the percentage measurements for gender (p = 0.99, d.f. = 54, t = 0.002).

Percent of Superior Temporal Plane Length vs. Heschl's Gyrus Number

The location of HG as a percentage of STP length was compared to the number of HG that were identified. The findings for this comparison are demonstrated in the figure 6. There was a statistically-significant difference between classification of HG in terms of the anterior sulcus of HG. Post-hoc t-tests revealed a significant difference between single gyri and common stems for the anterior sulcus and for common stems vs. complete duplications (p = 0.019 and p = 0.026 respectively, d.f. = 2/47 (between/within), F = 4.95). There was no statistically-significant difference between classifications regarding the distance to the posterior edge of HG (p = 0.28, d.f. = 2/53(between/within), F = 1.31).

Percent of STP Length vs. HG Number

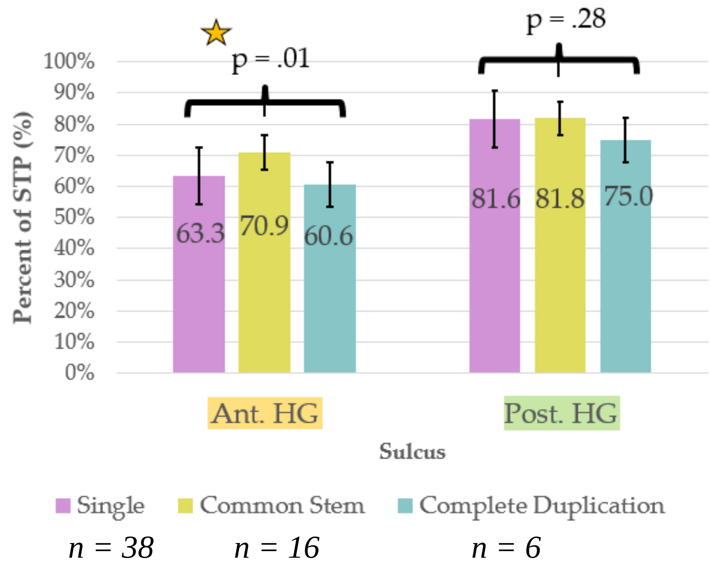


Figure 7
A comparison between the number of HG and the location along the STP that HG is located

Percent of Superior Temporal Plane Length vs. Heschl's Gyrus Angle Type

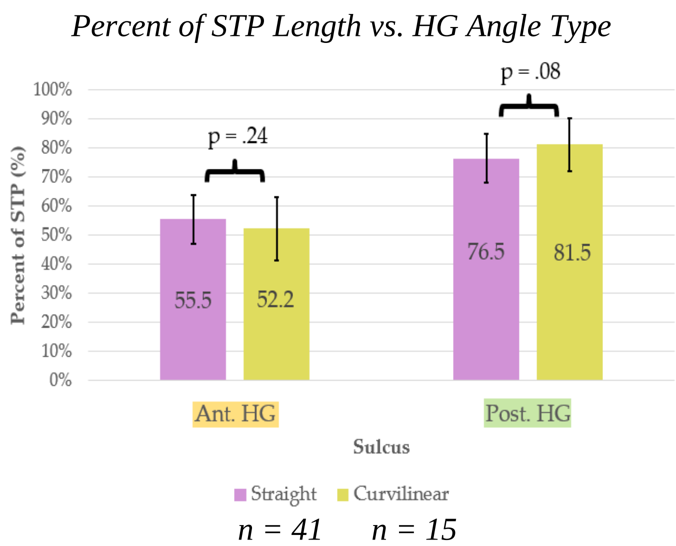


Figure 8

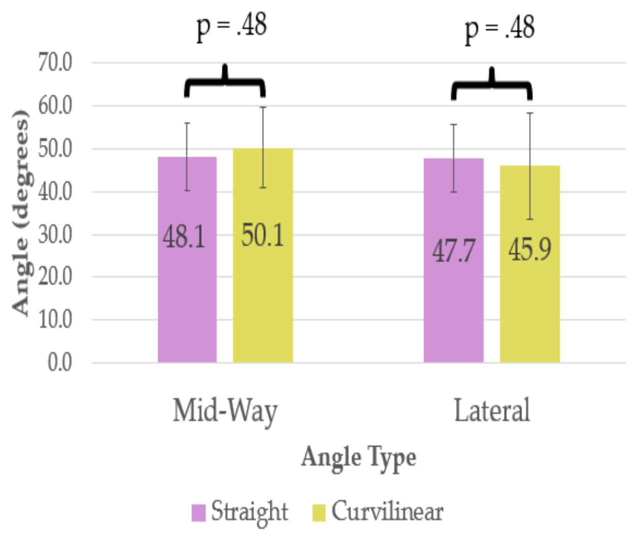
The curvature of HG is compared to the distance along the STP that HG is found.

The location of HG as a percentage of STP length was compared to the type of angle that HG took as it courses laterally towards the lateral edge of the STP. The findings for this comparison are demonstrated in the figure 7. There was no statistically-significant difference in the location of the anterior and posterior edge of HG between different angle types (anterior: $p = 0.24$, d.f. = 54, $t = -1.19$) (posterior: $p = 0.08$, d.f. = 54, $t = -.40$).

Angles of Heschl's Gyrus vs. Angle Type

The angle of HG was measured at two points – a mid-way and a lateral point. The angles of HG were found to be similar whether HG was classified as straight or curvilinear. The average angles at the two measurement points are shown below in figure 8.

Angles of HG vs. Angle Type



n = 41 *n = 15*

Figure 9
The curvature of HG measured at two different points – mid-way and lateral

Percent of Superior Temporal Plane Length vs. Ascending Ramus Type

The location of HG as a percentage of STP length was compared to the type of ascending ramus that terminated the STP. The findings for this comparison are demonstrated in the figure 9. Bifurcation and trifurcation were not included in statistical analyses due to a small number of these variations. There was no statistically-significant difference between classification of HG in terms of the anterior or posterior sulcus of HG (anterior: $p = 0.48$, d.f. = 48, $t = 0.71$) (posterior: $p = 0.28$, d.f. = 48, $t = -1.09$).

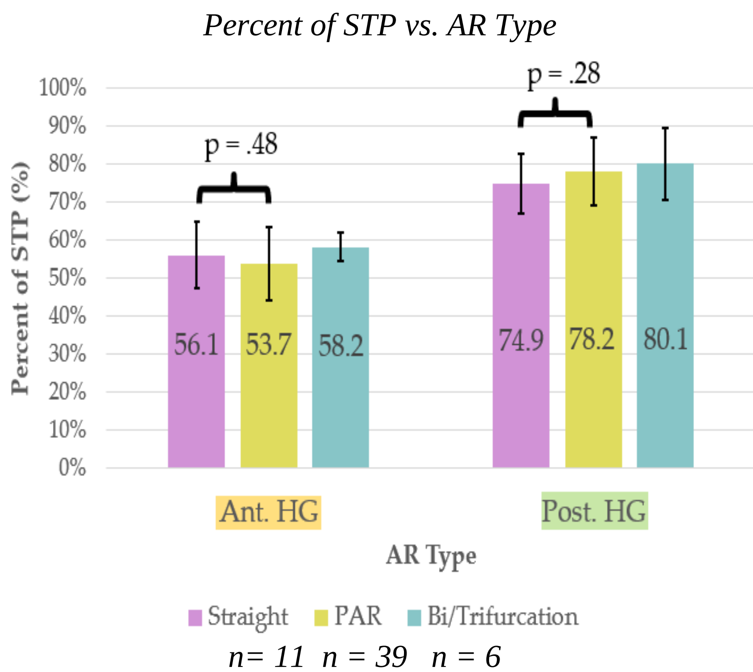


Figure 10

The type of AR is compared to the distance along the STP that HG is located

Discussion

The primary finding of this study is that the Two-Thirds Rule serves as a valuable guideline, or "rule of thumb" in quickly identifying HG. The Two-Thirds Rule is most accurate when utilizing the mid-way vector, and while the medial and lateral vectors also have value, their utility is not as pronounced as the mid-way measurement.

Prediction #1: The HG will be observed at an average location of the posterior third of the STP (two-thirds back on the STP).

The results of this study provide credibility to the Two-Thirds Rule. When observing the mid-way vector in particular, the Two-Thirds Rule works as a visual guideline for identifying the location of HG. Along this vector, the anterior edge of HG is found at approximately 52% and 57% of the distance back on the STP in the right and left hemispheres respectively. The posterior edge of HG appears at approximately 78% of the distance back on the STP in both the right and left hemispheres. Given the goal of clinical utility, the values of the “percent-back” measurements are rounded to 50% and 80% to the anterior and posterior edge of HG respectively. Stated as a percentage, the Two-Thirds Rule would indicate that HG can be found at 67% of the distance back on the STP. A percentage of 67% falls almost perfectly in between 50% and 80%, indicating that along the mid-way vector, the using the Two-Thirds Rule would have you observe almost the exact middle of HG. As a quick tool for clinicians and students, there is tremendous value in the Two-Thirds Rule. The mid-way vector is also preferred, as a sagittal MRI view of auditory structures would most closely fit our definition of this vector.

Prediction #2: The HG will appear at the same location regardless of hemisphere or gender.

For the mid-way vector, there was a statistically-significant difference between left and right hemispheres for the percent along the STP where the anterior edge of HG is found (52.60% in the right and 56.69% in the left, $p = 0.03$). However, there was no statistically-significant difference in the percent-measurement to the posterior sulcus of HG ($p = 0.93$). The approximate width of HG as a percentage of total STP length can be calculated by subtracting the percentage of the anterior sulcus from the posterior sulcus. Doing this would reveal a greater HG “width” on the left hemisphere, consistent with previous findings (Penhune et al., 1996).

Although a significant difference in percentage is only found for the distance to the anterior sulcus, raw measurements reveal significant differences or both sulci. Both the anterior and posterior sulcus occur a significantly greater distance back on the STP when measured in centimeters. This finding is seemingly associated with overall longer STP lengths in the left hemisphere, again consistent with findings from Penhune et al. (1996).

When looking for gender differences in the location of HG, none could be found for any measurement taken along the STP. Given that percentage measurements are a form of normalization, it is unsurprising that no differences were found between the location of HG in male or female brains. The degree of similarity was particularly notable for the distance to the posterior sulcus of HG ($p = 0.99$). This study finds itself in agreement with some previous research and in disagreement with others regarding gender differences in brain anatomy. Tang et al. (2013) found male brains to have significantly greater total brain volume (TBV) than female brains. Although our study does not directly measure TBV, there were no differences in the raw length of STP in males and females. Ruigrok et al. (2014) took volumetric measurements in different areas of the brain and found that males tend to have larger temporal pole volume while females have larger HG and PT volume. It is possible that some interaction of these differences cancelled out any gender differences in terms of total STP length, but this would not explain the lack of a significant difference in the raw distance measurement of HG. It is worth noting again that of the twenty-eight brains, only nine were males, presenting a limitation in the form of a skewed sample.

Prediction #3: The location of HG will be influenced by other factors such as the angle and number of HG and AR type.

Of all the extra variables considered in this study (HG number, HG angle, AR type), none demonstrated a convincingly-significant effect on the location of HG. The type of angle with which HG coursed anterio-medially did not seem to affect the location of HG along the STP. Although there is a visually-noticeable difference in the angles HG can take, it appears that this does not actually influence the location of HG. The type of AR also had no association with the location of HG. Although not directly measured in this study, it is fair to assume that the type of

AR likely has more influence on the surface area of PT than the location of HG, consistent with the findings from St. George (2017). Although there was a statistically-significant finding for the type of HG and the location of the anterior sulcus of HG, this finding must be discussed further. Of the fifty-six hemispheres in this study, only six demonstrated a completely duplicated HG. This severely limits any power a statistical comparison would have had.

From the standpoint of establishing a visual guideline, this actually works in the favor of a clinician trying to quickly find HG. Given that none of these extra variables had a truly significant impact on the location of HG, the clinician is more free to identify the approximate area of HG without worrying about these other factors.

Study Limitations and Future Goals:

In this section, limitations of this study are examined. First, the method used to measure the distance to HG diverges from methods used in other anatomical studies. Other studies regarding measurements of the brain have used more involved measurement techniques. Among these methods are ex-vivo MRI scans of brains (Kotrotsou et al., 2014) and physical measurements of cadaver brains (George, 1981). Cadaver brain measurement in particular allows for more accurate measurement of the location of structures along the superior temporal plane, as researchers are better able to account for curves and bumps along the brain. In this study, distances between two points on the brain were measured in an attempt to approximate this method as close as possible. The lateral, medial, and midway vectors were another way this study attempts to account for variation in measurement technique.

The number of participants included in this study is a limitation. Twenty-eight brains were included, totaling fifty-six hemispheres. While the total number of hemispheres is adequate, difficulties arose when making comparisons between uncommon types of categorical data. For example, the power of the comparison between HG location and HG type is limited because there were a small number of hemispheres that demonstrated a “complete duplication” configuration of HG. Had more brains been included, it is possible that there would be more power in this statistic.

Another limitation arises from the demographic information available. Given the fact that these brains were obtained from an open-access database, limited information was available for each patient. Information regarding gender, age, and handedness were available, but no information was provided regarding hearing status, language skills, or any other information in this realm. If this information were available, it is possible that a discussion could have existed regarding location of HG as it relates to hearing and language ability.

Conclusion

We found that HG can be located at approximately the beginning of the posterior third of the superior temporal plane. With limited comparative power, this finding seems unaffected by gender, hemisphere, and a variety of other factors. Although HG was found further back on the STP in the left hemisphere, this difference is accounted for using the percent measurements. The Two-Thirds rule is a valuable guideline for clinicians and students to quickly identify the approximate location of Heschl’s gyrus.

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