Literature Review
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# Anatomical Variations of the Auditory Cortex and their Clinical Significance, Prevalence and a Review of the Literature

Konstantinos Papantzikos, Spyridon Kantartzis, Dimosthenis Chrysikos, Amir Shihada, Dimitrios Filippou, Maria Piagkou, Theodore Troupis

Department of Anatomy, Medical School, National and Kapodistrian University of Athens, Athens, Greece

**Correspondence:** *ttroupis@gmail.com*; *ttroupis@med.uoa.gr*; Tel.: +302107462388

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**Abstract**

**Objective.** This literature review aims to present anatomical variations in the primary and secondary auditory cortex, and an analysis of the categories (or classifications) of variation. **Background.** Many types of variation of the auditory cortex have been described, but there is a need to classify these variations and reveal their clinical implications. **Methods.** A detailed search in PubMed medical database was conducted, from October 2023 to November 2024 using the terms« ("anatomical") AND ("variations" OR "categories" OR "types" OR "differences") AND ("human" OR "man") AND ("auditory cortex" OR "auditory cortex" [MeSH]) and 44 articles were found. Applying the inclusion and exclusion criteria, 29 articles were finally selected. **Results.** A number of asymmetries have been recorded related to the size of the cortex between the two hemispheres, the number of Heschl's gyri and Heschl's gyrus surface variations, the distribution of gray and white matter, and the surface and size of the secondary auditory cortex. Reviews, and all prospective and retrospective studies, as well as case reports, were eligible for this review. **Discussion.** Variations werefound amongst patients of reduced auditory ability and the non-hearing impaired, musicians, amateur musicians, and non-musicians, right and left-handed people, men and women, and people with high and low pitch perception ability. Furthermore,variations were detected in people with dyslexia and learning disabilities. **Conclusion.** Asignificant number of anatomical variations of the auditory cortex have been recorded, andcloser research will contribute to our comprehension of the origin of some discrepancies in everyday clinical practice.

**Key Words:** Auditory Corte ▪ Heschl's Gyrus ▪ Planum Temporale ▪ Anatomical Variation.

## Introduction

The auditory cortex consists of the primary and secondary auditory cortex. The Heschl's gyrus (HG) is foundon the superior surface of the temporal lobe, and demarcated anteriorly by the first transverse sulcus and posteriorly by Heschl's sulcus, containing the primary auditory cortex (medial 2/3 of the gyrus) (1). In addition, the HG is bounded laterally by the fissure of Sylvius, and includes 1-3 gyri per hemisphere. The Planum Temporale (PT) is located posterior to the HG, hosting the secondary auditory cortex (2). More specifically, the posterior 2/3 of the HG belongs to the primary auditory cortex, while the anterolateral part is associated with auditory stimuli perception ability and pitch pattern perception ability (3). Therefore, the HG is a brain structure involved in the processing of speech, and is adjacent to the Wernicke area (2).

The PT is detected on the medial surface of the superior temporal gyrus, posterior to the HG, and it contains the Wernicke area, which is involved in the processing of speech (4). Regarding the anatomical interaction of HG and PT, since there are 1-3 gyri per hemisphere, the HG (Primary Auditory Cortex) is considered to be H1, while H2 and H3 are considered to appertain to the PT. This distinction (H1, H2, H3) is due to the anatomical position of Heschl's sulcus which separates the HG from the PT. The PT is defined posteriorly by the posterior branch of the fissure of Sylvius (5). To sum up, the HG houses the primary auditory cortex (PAC) and receives stimuli from the medial geniculatenucleus of the thalamus. These stimuli are expedited to the adjacent PT. In the PT, auditory stimuli are correlated with the visual stimuli coming from the occipital lobe (6).

As a general rule, the volume of theleft HG seems to be positively related to the ability to process sound, while an increase in the left PT is associated with increased activity during language comprehension (2). In addition, as far as the functionality of the auditory cortex in relation to the cerebral hemisphere (right or left) is concerned, the left PAC is mainly related to speech processing, while the right PAC to processing of extra linguistic elements (7). Also, the left hemisphere is specialized in processing auditory stimuli which occur in a short temporal integration window, while the right hemisphere is specialized in auditory processing for a longer temporal integration window (8). The neurons of the right auditory cortex are more strongly synchronized at specific frequencies compared to the neurons of the left cortex in a homologous area. Moreover, the processing of spectral information takes place in the right hemisphere, while the processing of temporal information occurs in the left hemisphere (9). Finally, voicing and aspiration differences between stop consonants are processed differently between the two hemispheres (10), and an asymmetry in tonotopic organization was observed (9). This might implicate hemispherical specialization.

Consequently, the aim of our project was the complete presentation of anatomical variations in the primary and secondary auditory cortex, and an analysis of categories of people who display variations (for instance according to occupation, handwriting, possible learning disabilities, etc.).

## Materials and Methods

The topic of our narrative project focuses on anatomical variation of the auditory cortex. Database PubMed was the source of our investigation. We conducted an advanced search of the PubMedblockchain.The search strategy included the following keywords:("anatomical") AND ("variations" OR "categories" OR "types" OR "differences") AND ("human" OR "man") AND ("auditory cortex" OR "auditory cortex" [MeSH]). Initially, 44 articles were found, while afterusing a date filter for the period 2000-2024, 38articles remained. Of these primary38 articles, five were related to the topic of our paper. From a secondarysearch ofthereferences of these fivearticles, 29 more were added, of which four articles were duplicates. However, one main search article was not used, as a reference article. Consequently, for the composition of our paper, 29 articles were used (34-5=29). The main search articles were 18, 22, 24, and 28. Eligible articles were identified by a search for the period from October 2023 to November 2024.

Language restrictions were not applied (only articles in English were found in the database).Two investigators (KP and DC), working independently, searched the literature and extracted data from each eligible study. Manuscripts that did not state the names of the authors were excluded. In addition, we checked all the references of relevant reviews and eligible articles that our search retrieved, so as to identify potentially eligible conference abstracts. Titles of interest were further reviewed by the abstract. Finally, reference lists of eligible studies were manually assessed in order to detect any potentially relevant article ("snowball" procedure).

The inclusion criteria encompassed: (a) clinical trials, comparative studies, and anatomical reviews, (b) articles published in the English language, (c)research involving human-only studies, (d) reviews of variationassociated with the auditory cortex, (e) a limitation regarding the year of the publication.

## Results

### *Article Selection and Study Demographics*

The search strategy retrieved 38 articles for full-text evaluation.All of the articles from the search in database were in English.Twenty-nine studies were deemed eligible and were included in the

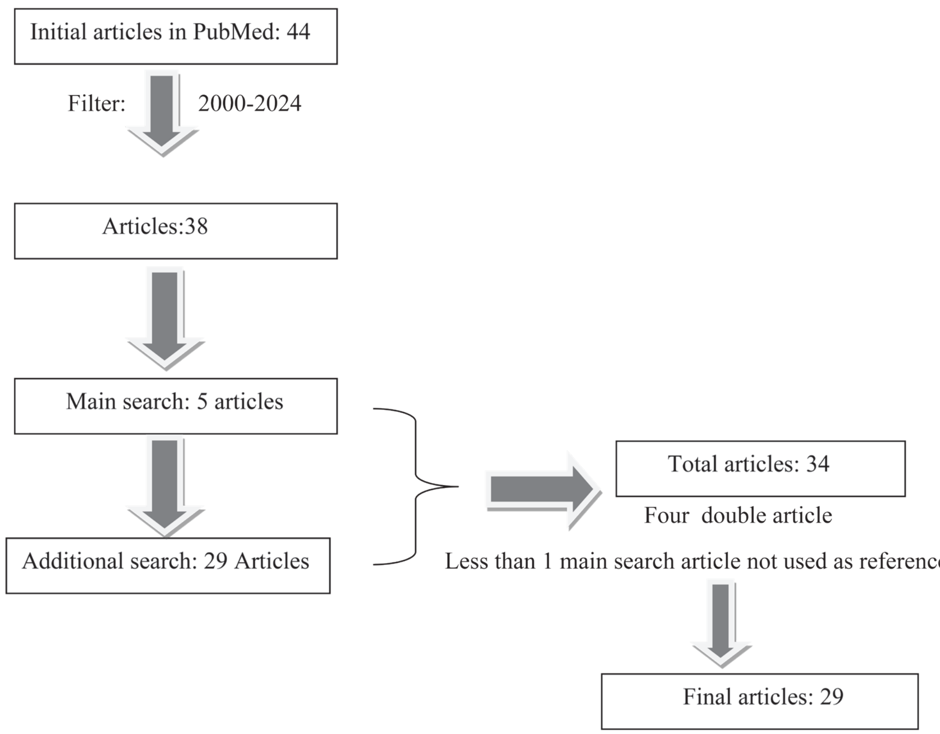


Figure 1. Search strategy.

analytic cohort. According to our literature review, variations included the size of the cortex between the two hemispheres, the numberand the surface area of the HG, the distribution of gray and white matter, and the surface and size of the secondary auditory cortex.

Furthermore, the narrative study focused on the correlation betweenvariations and specific categories of people, for example, patients with reduced auditory ability and the non-hearing impaired, musicians/amateur musicians/non-musicians, right and left-handed people, and men and women. Also, variationsweredetected in people with high and low pitch perception ability, and in people with dyslexia and learning disabilities.

The search strategy is depicted in Figure 1.

## Discussion

### *Variation of the Auditory Cortex*

HG, which house the PAC, may exist as single, as partially duplicated (CSD: common stem duplication), as completely posteriorly duplicated (CPD), and as multiply duplicated (MD) HG,according to a study about the gyrification patterns and surface areas of HG in 430 healthy volunteers mapped with magnetic resonance imaging (2). Also, there are variations in the HG as far as the volume is concerned, the surface at specific parts, the distribution of white and gray matter, and the distance from the midline. As far as HG duplication is concerned, one study referred to the developmental trajectory of its morphology and the function of the superior temporal cortex in children, adolescents, and young adults. It showed that, morphologically, the superior temporal cortex shows cross-sectional variability in the number of HG, including the absence and complete duplication of the HG in both hemispheres (11). In fact, the frequency of duplications ranges from 20% to 60%, depending on the distance from the midline, according to a study reporting variations in frequency and location of the sulcal boundaries of HG in volumetric magnetic resonance imaging scans of 105 normal controls aged 5-65years(12). Finally, CSD is more frequent than CPD, especially in the right hemisphere (12). As for the PT, the variations found were related to asymmetries in volume, the angle of the PT, its surface, the number of minicolumnstructures, and the length of the PT. In addition, variationsweredetected in the quantity of gray matter, in the ratio of white/gray matter, and in the distance fromthe midline.

### *Classification of Variations*

Significant variations were observed in both the primary and secondary auditory cortices between the two hemispheres. First of all, a comparative study involving 42 infants, 8–19 months of age, 26 with normal hearing (NH) and 16 with sensorineural hearing impairment, using high-resolution 3D magnetic resonance imaging, showed that the left auditory cortex was larger than the right auditory cortex (13). The study's measurements of the volume of the PT and HG on the MRI scans of epilepsy patients indicated that there was more gray matter in the right hemisphere, while there was more white matter in the left hemisphere in the area of the auditory cortex(14). Generally, according to a study in 17 neurologically normal adults, surface asymmetry was found in the HGs as they were larger in the left hemisphere ($P<0.01$). The study concerns minicolumn spacing and number, and regional cortical volume and surface area measurements in the primary auditory region (HG) and the posterior auditory association region (PT) (15). Two experiments in a study, one regarding magnetic resonance (MR) scans of normal healthy volunteers, and the other MR data on normal, right-handed volunteers, showed that the PAC volume was larger in the left hemisphere compared to the right onedue to the larger volume of white matter ($P<0.0005$). The left PAC was found to be on average further forward and towards the midline. This fluctuation was about 5-8 mm (16). Nevertheless, regarding the surface of the HG, in a study conducted of 430 healthy brains, in the right hemisphere a medial decrease in the cortical surface area (CSA) and a lateral increase in the CSA in the CSD compared to a single HG were found (17).

The PT was observed to have significant asymmetry between the two hemispheres. More specifically, the left PT was larger in the left hemisphere than in the right by 0.9 cm ($P<0.001$) (left hemisphere 3.6 cm, right hemisphere 2.7cm), on the basis of a study involving 100 adult human brains, obtained postmortem and free of significant pathology (4). In fact, a study of the brains of 21 individuals free of known neurological and neuropathological abnormalities showed that the left PT was thin and elongated, while the right PT was short and thick, with a significant difference. This means that the left and the right PTs have approximately the same volume, although their surface area varies due to this morphology (18). Nevertheless, according to a comparative study of 76 young,nativeEnglish-speaking adults, the women's PT was symmetrical in both hemispheres, while men's PT was observed to be larger in the left hemisphere (19). In addition, as far as the surface area was concerned, there was a reduction in the CSA on the PT in instances of duplication in the left hemisphere (17). The right PT showed a greater inclination than the left ($P<0.01$) (14), i.e., the angle created by the gyrus was more acute. The left PT was larger than the right in 65% of brains, with greater frequency in right-handed people, according to a review study (20), while the right PT was larger than the left in only 11% of brains (4). As far as microanatomy is concerned, a greater distance between minicolumn structures was observed in the left PT ($P<0.03$) (15). Some authors argue that a greater quantity of gray matter is found in the left PT, compared to the right PT ($P<0.05$) (14). However, there was a greater amount of white matter in the total left auditory cortex, compared to the right.

Individuals with congenital deafness have a lower amount of white matter associated with HG and PT than those with NH, according to a study comparing 53 prelinguallyhearing-impairedsubjects with 51 non–hearing-impaired control subjects (21, 22). Thus, the auditory cortex ofhearing-impaired individuals had significantly less white matter than that of hearing individuals. Since the amount of gray matter is the same in-people with impaired hearing and with NH, the white-to-graymatter ratio was lower in the auditory cortex ofhearing-impaired people than in those with NH(2). Also, in general, the left superior temporal gyrus white matter was lower in thehearing-impaired people than inthose with NH(13). In non-hearing-impaired human beings, the PT shows volume asymmetry,which it does not in thehearing-impaired, to a statistically significant degree (P<0.0002).Furthermore, the angle in the PT is more acute in the right than in the left hemisphere in thehearing-impaired (P<0.07), but there is no differentiation in those with NH (P>0.05), as indicated by a clinical trial involving 12 right-handedhearing-impaired adults and 10 right-handed hearing adults (22) (23). Moreover, 42 infants aged 8-19 months, 26 with normal hearing (NH), and 16 with impaired hearing (IH) were involved in a relative study. SixteenIHinfants had increased gray matter and decreased white matter in the anterior HG (aHG) compared to the NH infants, while the typical pattern of asymmetry between the right and left hemispheres (L>R) was absent (13). These differences might cause auditory deprivation (13).

Professional musicians and musically trained children were reported to have increased gray matter volume in the HG and its repetitions, according to a study of 41 experienced musicians (24). More specifically, professional musicians showed 130% more gray matter (in volume) on the anterior and medial surface of the HG (amHG) than non-musicians (P<0.0001). Professional musicians showed 37% more gray matter in the HG overall compared to non-musicians, and 67% more gray matter in the aHG (P<0.001) (1). In general, a study comparing 20 professional male musicians and 20 amateur male musicians with a matched control group of 40 male non-musicians showed that more gray matter was observed in the musicians, particularly in the left HG (25). The activity in the PAC of musicians was 102% greater, compared to non-musicians, according to a clinical trial involving 37 right-handed adults with NH, 12 of whom were non-musicians, 12 were professional musicians, and 13 were amateur musicians (1). In addition, professional musicians showed 30% more white matter overall in the HG compared to non-musicians (P<0.05) (1). Regarding HG repetitions, the vast majority of musicians (90%) showed HG repetitions (CSD, CPD, MD) either in one (39%), with higher frequency in the left hemisphere, or both (51%) hemispheres. In 27% of musicians, multiple duplications of up to four curves of helices were found (24). When it comes to amateur musicians, they showed 60% more gray matter in the anteromedial and anterior sections of the HG (amHG and aHG) than non-musicians (P<0.01). Furthermore, there was no statistically-significant variation in the white matter volume between amateur musicians and non-musicians (1). Finally, no significant changes in the PT were observed in any of the comparisons (25).

In the right-handers, the right hemisphere had a higherprevalenceof CPD than CSD by 10%, while the left hemisphere had a higher prevalenceof CSD than CPD by 200% (2). Concerning both hemispheres, a duplication of HG appeared in 37% (approximately) of the left hemispheres and 49% (approximately) of the right hemispheres (24). Specifically: L1/R1: 36.2%, L1/R2: 27.2%, L2/R1:15.1%, L2/R2:21.5%. Moreover, in right-handed individuals, in the case of duplication, the aHG showed a significant reduction of 22% in the left hemisphere and 11% in the right hemisphere, regardless of the type of duplication (P<0.001). However, if there was duplication, the total area of the HG increased significantly in both hemispheres by 46% in the right hemisphere and 79% in the left hemisphere, to a statistically significant degree. Furthermore, in right-handed people, the posterior HG (postHG) surface area of the left hemisphere increased by 64% in the CSD compared to CPD.The surface of the right hemisphere increased by 42% (P<0.001), and the aHG surface area was greater in the left hemisphere in individuals with L1/R1 and L1/R2, while in individuals with L2/R1 and L2/R2, it was greater in the right hemisphere. Regarding overall HG surface area (totHG), L2/R1 and L1/R1 showed greater surface area in the left hemisphere and L1/R2 in the right hemisphere, whereas L2/R2 showed no statistically significant variation between the two hemispheres (2).In left-handed people, the rates of variation in HG repetitions were: L1/R1: 49%, L2/R2: 19.2%, L1/R2: 39.4%, L2/R1: 30.8%. The L1/R1 variant was more frequent than L2/R2 (49% and 19.2% respectively). In addition, there were more individuals with duplication in the right hemisphere than those with duplication in the left (2). When the right-handed and the left-handed people were compared, it was observed that L1/R1 was more frequent in left-handed people than in right-handed people (49% and 36.2% respectively), to a statistically significant degree. L1/R2 was more frequent in the right-handers (48.7%) than in the left-handers (39.4%). L2/R2 and L2/R1 showed no statistically significant difference between the two hands used for writing. To a statistically significant degree, it appears that the percentage of left-handers who had the same number of HG helical structures in both hemispheres was higher than that of the right-handers (68.2% and 57.7% respectively) (P<0.001). Additionally, both aHG and totHG in the right hemisphere had a significantly larger surface area, by 28 mm2 and 20 mm2, respectively, in the left-handed compared to the right-handed subjects, with P<0.05. In fact, the right aHGwas larger in the left-handers regardless of the existence of duplications in the right HG. In the left aHG and totHG, there was no statistically significant difference in the surface section depending on the dominant writing hand. The aHG showed less asymmetry between the two hemispheres in the left-handers compared to the right-handers, while the total HG showed a significant increase in the right hemisphere in the left-handers, with P<0.05 (2). Finally, the PT showed statistically significantly less asymmetry between the two hemispheres in the left-handers compared to the right-handers according to a study examining 52 healthy volunteers (26).

Given that the female brain is smaller in volume than the male brain, in women the superior temporal gyrus has 17.8% more volume than in men, to a statistically significant degree (P<0.04), while the PT has 29.8% more volume in women than in men (P<0.04). These data relate to the overall volume of these brain zones. The HG in both men and women occupies the same volume in each of the two hemispheres [avg 2mL and 1.7 (men) 1.8 (women) in the left and right hemispheres, respectively] as demonstrated by a study involving 10 males and 11 females free from neurological or neuropathological abnormalities (27). However reverse asymmetry towards the right side (larger right hemisphere than left), compared to the known asymmetries towards the left side, was more frequent in women according to a study using an observer-independent cytoarchitectonic method (28). Finally, in terms of microanatomy, the PT minicolumn number showed greater asymmetry in men than in women, although the mean PT volume as a function of brain weight was greater in women (15).

Anatomical differences in the HG and PT were also observed in other categories of individuals. For example, in individuals with dyslexia, two HGs were observed at the inner level. The more aHG branched at some of the convolutions, while the more posterior HG remained as it was. In contrast, in individuals without dyslexia, one HG was observed in the internal plane, which moved anterolaterally and branched at some convolutions and therefore producedmore than one helix (anteriorly, not medially), according to a study of individuals with dyslexia from professional families and unaffected first- and second-degree relatives (6). In addition, while in women the PT is more symmetrical in both hemispheres and in men it shows increased size in the left hemisphere, in men with dyslexia there may be opposite asymmetry or an absence of asymmetry (19). The HG duplications (CSD, CPD, MD) increased in families with learning disabilities, while children with reduced comprehension-attention had smaller HGs and enlarged PTs, as indicated by a study investigating 111 children without developmental disorders and 21 children with attention deficit (hyperactivity) disorder AD(H)D (29). Furthermore, anatomical differences were also observed according to the ability to intonate syllables. The results presented were for native English speakers learning a foreign language and trying to render the language with correct pitchpatterns. Thus, the gray matter of the left HG of those with slightly better intonation ability had a larger volume compared to that of those with greater difficulty in voice coloration (P<0. 05), while there was a small increase in the white matter that needs further research (P=0.047). Indeed, a study involving 17 young adult native speakers of American English who reported having no audiological, cognitive, neurological, or linguistic deficits, showed that the gray matter of the left HG shrank in volume in people who did not practice voice intonation, but increased in people with increased intonation ability (3). Finally, young children with poor vocal skills had significantly lower asymmetry than their peers with better vocal performance (12). In terms of age, the number of HG duplications in the right hemisphere was consistent across all age groups (11). Therefore, age does not affect the presence of HG duplications. Moreover, it seems that there are more HG duplications in boys with genetic resistance to thyroid hormones(12). As for deviation from the midline of the brain, an average deviation of 3 cm was found in the position of the auditory cortex grooves from their normal position. However, despite the variety of asymmetries, they showed firmness in both the right and left hemispheres: the frequency of duplication increases as the distance from the midline increases. Age, gender, and handedness are not strong enough factors to influence the diversity of asymmetries in terms of distance from the midline (12). Finally, in terms of microanatomy, more minicolumnswere found in HG than in the PT (P<0.01) (15).

## Conclusions

There are several types of variations in both the primary auditory cortex (HG) and the PT, and they occur in different categories of people. Variationseven occur between the two hemispheres, with the left auditory cortex being overall larger than the right (13). Variations in the auditory cortexareseen betweenhearing-impaired and hearing people, while in musicians there is an increase in the gray matter volume of the HG (1). Variationsin the HG in individuals with good and reduced intonation ability suggest that the HG play an important role in intonation ability. In addition, reduced asymmetry was observed in females, left-handed people, and children with reduced language manipulation skills in some areas of the auditory cortex, while excessive asymmetry was linked to early musical ability (12). Moreover, variation associated with HG duplication may be related to the functions processed jointly within each hemisphere: temporal processing and speech processing on the left, and spectral and musical processing on the right (17). Finally, asymmetry is also related to the volume of cortical fibers carrying information to and from the auditory cortex (16), and this in turn affects hemispheric specialization.

**What Is Already Known on This Topic:**
*The auditory cortex consists of the primary and secondary auditory cortex. According to the literature, many types of variation have been described which are correlated to certain categories of individuals and cognitive functions. Variations should be acknowledged because they can define and explain some crucial clinical issues.*

**What This Study Adds:**
*The study records anatomical variations of auditory cortex and categories those variations in correlation with their clinical significance. It is of paramount importance to understand how the plurality of anatomical variationsof the auditory cortex contributes to our comprehension of the origin of pathologies in the auditory cortex found in clinical practice in the field of neuroanatomy and neurosciences. The study focuses on the difference betweenhearing-impaired and normal hearing people.*

**Conflict of Interest:** The authors declare that they have no conflict of interest.

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