Interpersonal communication via the auditory modality is fundamental to normal human development. One of the prominent anatomical specializations supporting this communication is the transverse gyrus of Heschl on the superior surface of the temporal lobe. This gyrus frequently appears duplicated, either by a sulcus indenting the crown of an initially single gyrus (common stem), or by a complete posterior duplication. The frequency of these duplications has been reported to be elevated in populations with learning disabilities and genetic anomalies. The significance of this observation is unclear, however, due to conflicting reports of the base rate of duplication and the location of relevant sulcal landmarks. In this study we report the variation in frequency and location of the sulcal boundaries of Heschl’s gyrus in volumetric magnetic resonance imaging scans of 105 normal controls aged 5–65. The major results were as follows: (i) duplications were unstable – the frequency of duplication ranged from 20 to 60% depending on distance from the midline; (ii) common stem duplications were more frequent than posterior duplications, particularly in the right hemisphere. Intra- and interindividual instability in sulcal landmarks pose serious obstacles to the attempt to map behavioral function onto the brain. Novel methods for dealing with structural variation are needed to facilitate the development of valid mapping techniques.

Introduction
One of the most prominent landmarks in the human brain is the bulge in the lower bank of the sylvian fissure that is formed by auditory cortex on the transverse gyrus of Heschl (H, see Fig. 1). Posterior to this bulge is a prominent sulcus [Heschl’s sulcus (H1S)] and the planum temporale (P), the only structure that is reliably larger in the left hemisphere than the right (Geschwind and Levitsky, 1968; Witelson, 1982; Steinmetz, 1989). As the anterior boundary is affected by duplication of H, the anterior and the posterior boundary of the planum can be difficult to identify, due to anatomical variation. The location of the anterior boundary is affected by duplication of H. Two types of duplication have been described: in one case, a sulcus intermedius (SI) indents the crown, forming a common stem (CS) duplication (see Fig. 2); in the other, depicted in Figure 3, there is a complete posterior duplication (PD) of H that is bounded by a second Heschl’s sulcus (H2S) (Rademacher et al., 1993).

A recent cytoarchitectonic study of a small number of brains (Rademacher et al., 1993) has reported that the granular koniocortex characteristic of primary cortex is limited to the first H in both types of duplication. This suggests that if the planum temporale is to be defined as the cortical zone caudal to primary auditory cortex, its anterior boundary should always be the most anterior sulcus associated with H, i.e. the SI if it exists, or H1S, in the case of a PD. This rule has rarely been followed in the past. Geschwind and Levitsky (1968) chose H1S on the left and H2S on the right as anterior boundaries, due to their belief that duplications were standard on the right. Subsequent authors have tended to follow Witelson and chosen H1S on both sides (Witelson, 1982). Steinmetz et al. (1989) were the first modern authors to call attention to SI, although they did not consider it to be the anterior boundary of the planum. In the most recent study, Penhune et al. (1996) accepted SI as an anterior border if it indented more than half the lateral extent of H. The frequency of duplications reported in the literature ranges from 15 to 83% on the right and from 10 to 40% on the left (Von Economo and Horn, 1950; Campain and Minckler, 1976; Musick and Reeves, 1990; Penhune et al., 1996). Inconsistency in reported frequencies could reflect real differences between the populations sampled or be an artifactual result of technical differences in the definition of sulcal landmarks.

Although it is conventional to refer to the first transverse gyrus of Heschl as the site of primary auditory cortex, recording experiments in a small number of humans undergoing surgery for epilepsy have revealed that primary auditory cortex (as defined by response latency) is actually restricted to the caudomedial region of the gyrus (Liegeois-Chauvel et al., 1991). Thus measurements of Heschl’s gyrus which include its entire length overestimate the extent of primary auditory cortex. Nonprimary areas of H1G, H2G and the remaining superior temporal gyrus are thought to contain duplicated auditory maps specialized in the processing of particular auditory features (Merzenich and Brugge, 1973; Rauschecker et al., 1995), analogous to those found in the visual system (Allman and Kaas, 1971; Allman, 1987; Felleman and Van Essen, 1991; Sereno et al., 1995). In animals as diverse as canaries and bats (Hauser, 1996), it is known that distinctive features of critically important species-specific signals are amplified in topographically organized maps. By analogy, it seems reasonable to suppose that the size and diversity of auditory maps on Heschl’s gyrus and the planum could be related to the efficiency of auditory and language processing in the human. For this reason, it is important to obtain information on the sampling distribution of auditory cortex landmarks, as variation in these anatomical characteristics might serve as a visible indicator of individual variation in physiology and behavior.

In postmortem studies, it is rarely possible to relate variation in anatomy to behavioral characteristics during life [although Witelson and Kigar’s (1992) prospective study of terminal cancer patients is a notable exception]. The introduction of high-resolution magnetic resonance technology has allowed the establishment of a new field: in vivo human cognitive neuroanatomy – the use of magnetic resonance imaging (MRI) scans for the identification of the anatomical substrate of human behavioral variation (Bookstein, 1996). A number of studies have focused on Heschl’s gyrus and the planum temporale, due to the pioneering work of Galaburda (1989). Studies using qualitative
A quantitative study found that young children with poor phonemic awareness had significantly less planar asymmetry than their same-aged peers with good phonemic skills (Leonard et al., 1996). Reduced planar asymmetry has also been reported in women and left-handers (Witelson and Kigar, 1992; Steinmetz et al., 1991; Foundas et al., 1995) and in children with language impairment (Gauger et al., 1997), while exaggerated planar asymmetry is associated with absolute pitch and early musical ability (Schlaug et al., 1995).

In view of the conflicting data on the frequency of duplication and its importance for the calculation of planar asymmetry, we decided to investigate the incidence of duplication in a large set of normal controls. Our objectives were to determine (i) the anterior and posterior borders of Heschl’s gyrus and the planum temporale in Talairach space; (ii) the frequency of the two types of duplication of Heschl’s gyrus in the left and right hemispheres; and (iv) the contribution of age, sex and handedness to variation in the location of these sulcal landmarks.

### Materials and Methods

#### Subjects

The data were acquired from archived scans of individuals who participated as controls in funded studies. The scans of 52 children aged 5–12 (29 boys, 23 girls) and 53 adults aged 18–65 (40 men, 13 women) were used. All subjects had signed informed consent forms after the purpose and risks of the studies were explained.

#### Test Battery

Subjects received a handedness preference questionnaire (Briggs et al., 1976) from which a quantitative handedness score was calculated (–1 = completely left; 0 = no preference; 1 = completely right; 0.75 = cutoff between dextral and adextral). They also received the Lindamood test of Auditory Conceptualization (LAC) (Lindamood and Lindamood, 1979). The LAC assesses the metalinguistic ability to conceptualize the phonemic structure of language by the manipulation of colored blocks that symbolize phonemes. Performance is scored on a scale of 0–100. Scaled or normalized scores are not calculated but norms are provided. Children in the sixth grade (11 years old) are expected to score 100%. In addition, most of the children received a neurolinguistic battery (Gauger et al., 1997) and a test of nonverbal intelligence (TONI) (Brown et al., 1982). An attempt was made to obtain children with a range of socioeconomic status (SES) (Hollingshead, 1975). Most adults were recruited to match the parental education of a sample of male patients with schizophrenia and received the Wechsler Adult Intelligence Scale (Wechsler, 1987). The remainder of the adult sample were college students. Some demographic characteristics of the sample are given in Table 1. The samples are well matched on nonverbal IQ but the children are more right-handed (P < 0.05) than the adults. Reanalysis of the data after matching the two groups on handedness did not change any of the findings reported here.

Table 1

<table>
<thead>
<tr>
<th>Children</th>
<th>Adults</th>
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<tbody>
<tr>
<td>n</td>
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<tr>
<td>Handedness index</td>
<td>52</td>
</tr>
<tr>
<td>Nonverbal intelligencea</td>
<td>40</td>
</tr>
<tr>
<td>Phonemic awarenessb</td>
<td>50</td>
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</tbody>
</table>

*The children were given the Test of Nonverbal Intelligence (Brown et al., 1982), the adults were given the Wechsler Scale of Adult Intelligence. The mean performance IQ score is given here.

b Phonemic awareness was measured with the Lindamood Test of Auditory Conceptualization (Lindamood and Lindamood, 1979).
**MRI Scan**
The scans were performed in a Siemens 1 or 1.5T Magnetom (quadrature head coil) with a three-dimensional MPRage ‘Turboflash’ technique. Scan parameters: repetition time (TR), 10 ms; echo time (TE), 4 ms; flip angle, 10°; field of view (FOV), 25 cm; matrix = 130 × 256. The series were gapless sequences of 1.25 or 1.4 mm slices. The images were transferred to a computer workstation where they were rotated into the Talairach plane (horizontal anterior commissure–posterior commissure axis) and reformatted into 1.00 mm sagittal images using programs written in PVWave (Visual Numerics, Boulder CO) (Leonard et al., 1993, 1996).

**Localization in Talairach Space**
Parameter files were created for each scan that contained the distance between the anterior commissure and the edges of the brain in all three Talairach planes. The Talairach procedure was used to normalize the identified locations (Talairach and Tournoux, 1988). This procedure involves dividing the actual location in millimeters by Talairach distances obtained from the brain measurements in the Talairach atlas. This procedure corrects for differences in brain size, without warping or distorting individual brain anatomy.

**Landmark Identification**
For each hemisphere, 12 images 2 Talairach mm apart between 34 and 56 lateral to the midsagittal plane (x-coordinate) were displayed simultaneously. A cursor was used to mark the depth of five sulcal locations in each image where they could be identified. The y (horizontal) and z (vertical) position of the cursor in each image were converted into Talairach units and stored in an ASCII file for later analysis.

**Major Landmarks**
Figure 1c depicts the sulcal locations that were located in all hemispheres: (1) HA, the anterior border of the transverse gyrus of Heschl; (2) H1S, the posterior border of Heschl’s gyrus; and (3) PHRP, the termination of the posterior horizontal ramus (PHR) that forms the posterior border of the planum temporale. In cases where there was a terminal posterior ascending ramus, PHRP was located at the origin of this ramus. When

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**Figure 2.** A common stem duplication caused by a sulcus intermedius (SI) in sagittal and axial planes of section at x = 38 in the left hemisphere. Grey hairlines indicate planes of intersection. (a) SI does not extend to the base of H. (b) Arrowheads indicate medial and lateral extent of SI. (c) Magnification of (b). (d) Magnification of (a).
there was no ascending ramus. PHRP was marked at the most posterior extent of PHR on all sections where the fissure extended posteriorly to H1S.

**Landmarks Associated with Heschl Duplications**

Two additional sulci were marked when they appeared: (i) SI — the sulcus that forms a CS duplication by indenting the crown of H, causing it to develop a heart-shaped appearance (Fig. 2). SI varies considerably in lateral location and extent. (ii) H2S, the posterior border of a second H associated with a complete PD. This sulcus was identified when a separate gyrus emerged lateral to the insula, just caudal to H1S (see Fig. 3). Distinguishing between a CS duplication and a PD in the sagittal plane is sometimes difficult, especially when an SI is found at medial positions. A CS duplication can generally be seen in sagittal and coronal planes, but is sometimes not deep enough to be visible in the axial plane. By contrast, a complete PD can be identified in sagittal and axial planes but cannot be visualized in the coronal plane because the second Heschl’s gyrus occurs completely posterior to the first (compare Figs 2 and 3). The morphology of the two formations is also typically different. Initially, SI does not extend to the base of H and the two divisions remain connected with a heart-shaped or bow-tie appearance. A PD, by contrast, forms a fully separate structure shaped like a rectangle or a square.

**Figure 3.** A posterior duplication (PD) in coronal, sagittal and axial planes of section. Grey hairlines indicate planes of intersection. (a) H and H2 cannot be seen simultaneously in coronal plane. (b) In the sagittal plane there is a clear separation between H1 and H2. Arrowhead indicates position of H2S. (c) Axial plane. Arrowhead indicates medial border of H2S.
Two operators marked the landmarks in all 105 brains. The means for most landmarks differed by \(<2\) mm between the two raters. Initial intraclass reliability coefficients ranged from 0.93 for HA to 0.5 for medial positions of SI. In cases of disagreement discussions were held in order to develop a system of rules and landmarks were then reassessed.

Data Analysis

The files with Talairach locations were analyzed with analysis of variance and regression methods using PC SAS. Means and standard deviations were calculated as well as medial-lateral differences in all coordinates. Distributions of each statistic were plotted by age, sex and handedness and regression methods using PC SAS. Means and standard deviations as well as medial–lateral differences in all coordinates.

Results

This study had three objectives: to measure (i) variation in the location and frequency of the anterior and posterior borders of Heschl’s gyrus and the planum temporale in Talairach space; (ii) the frequency of the two types of duplications of Heschl’s gyrus; and (ii) the influence of age, sex and handedness on the position and frequency of these landmarks.

Location in Talairach Space

The major auditory landmarks all move anteriorly (Fig. 4) and shift slightly inferior (Table 2) as distance from the midline increases. Some landmarks disappear while others remain constant for at least 2 cm. Figure 5 shows the proportion of hemispheres in which each landmark was present for each sagittal position. Since there were few differences between adults and children, the general features of each sulcus will first be described in adults.

The Sulcus Anterior to the First Transverse Gyrus of Heschl (HA)

This sulcus is the first of the five to appear at the posterolateral corner of the insula (x = 34). In all 105 hemispheres examined it continued anterolaterally for at least 1 cm (Fig. 4). It disappeared more rapidly in the right hemisphere than the left. At x = 56 HA remained in 40% of the left and 20% of the right hemispheres (Fig. 5). The HA shifted 20 mm anteriorly and dropped 4 mm during its course anteriorly on both left and right. From x = 34 to x = 54, HA was found more anteriorly on the right (paired t-tests, \(P < 0.0001\); effect sizes ranging from 0.9 to 1.5).

The Sulcus Posterior to the First Transverse Gyrus of Heschl (H1S)

A prominent sulcus marking the posterior border of H1S was found in all hemispheres by x = 38. There was a slight but significant lateral asymmetry in the position (left more posterior). The sulcus coursed anteriorly at about a 45° angle in both hemispheres and was still present at x = 56 in 92% of the left and 72% of the right hemispheres (Fig. 5). It shifted 8 mm inferiorly during its anterior course. From x = 34 to x = 54, H1S was found more anteriorly on the right (paired t-tests, \(P < 0.0001\); x = 48, \(P < 0.001\); x = 50, \(P < 0.01\); x = 52 to x = 54, \(P < 0.05\); effect sizes = 2.1 to 0.9 from x = 34 to x = 42; effect sizes <0.6 lateral to x = 44).

The Posterior Termination of the Sylvian Fissure (PHRP)

This landmark was visible in all hemispheres by x = +4. It was the only landmark that diverged during its lateral course in the two hemispheres (Fig. 4). It moved posteriorly by 5 mm in the left and anteriorly by 6 mm in the right. Thus a modest lateral asymmetry at medial positions increased substantially between x = 34 and x = 56. This asymmetry was significant at all lateral positions (paired t-test, \(P < 0.0001\); effect sizes = 0.7–1.7). Between x = 48 and x = 50 this landmark was further posterior on the left in 50/53 adults. In contrast, there was no lateral asymmetry in the dorsoventral coordinates at any lateral position.

Landmarks Associated with Heschl’s Duplications: Sulcus Intermedius

The average AP position of SI moved anteriorly ~15 mm between x = 34 and 56 and there was no lateral asymmetry in average position or anterior course (Fig. 6). The frequency of an SI rose and then dropped with distance from the midline (Fig. 7). In fact the frequency quadrupled between x = 34 and x = 42 in each hemisphere. A SI was found between x = 43 and x = 51 in 40% of the left and 50% of the right hemispheres. By x = 56, SI was only visible in 21% of the left and 32% of the right hemispheres.

Complete Posterior Duplications: H2S

A separate gyrus caudal to the first transverse gyrus was found in seven (13%) of the left and eight (15%) of the right hemispheres. In five of the left and six of the right hemispheres this gyrus was still visible at x = 56. In contrast to the sulci described above, H2S

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Comparison with previous work. As can be seen from the bottom complete PDs, we combined the two types for the purposes of gyrus have varied widely (Table 3). Since previous studies did the right hemisphere in adults. As noted in the Introduction, each hemisphere in children but were slightly more frequent in midline (Fig. 7). Duplications caused by a SI indenting the crown the frequency of duplication depended on distance from the hemisphere and did not take an anterolateral course (Fig. 6). 

**Duplication of Heschl’s Gyrus**

The frequency of duplication depended on distance from the midline (Fig. 7). Duplications caused by a SI indenting the crown were more frequent than those caused by a complete PD. Duplications occurred with approximately equal frequency in each hemisphere in children but were slightly more frequent in the right hemisphere in adults. As noted in the Introduction, previous reports of the frequency of duplication of Heschl’s gyrus have varied widely (Table 3). Since previous studies did not distinguish between the incidence of CS duplications and complete PDs, we combined the two types for the purposes of comparison with previous work. As can be seen from the bottom half of Table 3, the incidence of duplications increased with distance from the midsagittal plane. At x = 34, 73% of the brains had single gyri bilaterally, but by x = 46, only 17% of the brains had single gyri bilaterally. [The incidence of duplications was not tabulated more laterally because of landmark instability (see Fig. 4). At each lateral position the distribution of frequencies agrees with one of the previous studies. The fact that the number of sulci associated with Heschl’s gyri varies with lateral position could explain the wide range of Heschl duplications reported in the literature. Different groups of investigators may have used different subjective criteria for the identification of a second Heschl’s gyrus.

At lateral positions, the incidence of CS duplications was much greater than that of complete PDs. An attempt was made to determine whether the frequency of different combinations was different from that expected from random assortment of the different types. This analysis suggested that a left CS/right PD might occur less often than expected by chance while a right PD/left CS might occur more often. The difference between expected and observed frequencies was not significant, however, because of the large number of cells with low expected values.

**Effect of Demographic Variables**

Although only two-thirds of the group fell within 1 cm of the average position of any sulcus, little of this variance could be attributed to sex or handedness. None of the sulcal positions correlated significantly with the handedness quotient. When handedness was treated as a categorical variable, either as writing hand or by use of the arbitrary cutoff score of 0.75, group means were always within a few millimeters of each other with similar standard deviations and no significant differences. There were also no significant differences with regard to sex. The sample size was not large enough to test for interactions between handedness and sex.

**Age**

Figures 4–8 and Table 2 demonstrate remarkably few developmental differences in the coordinates of the major sulci. The most striking difference between the children and adults was in the anterior trajectory of PDs on the left. In adults, there was no mean AP shift in H2S while in children, the mean position of the sulcus moved forward 5 mm. In children, duplications occurred with approximately equal frequencies in the two hemispheres, while in adults, CS duplications were more frequent in the right hemisphere. This lateral asymmetry in duplication in adults was only significant at x = 44, however. A longitudinal investigation will be necessary to determine whether the absence of significant developmental differences is real or due to the variance inherent in a cross-sectional design.

**Discussion**

The identification of sulcal landmarks is not straightforward (Ono et al., 1990; Paus et al., 1996). Although the general trajectories of major sulci such as the cingulate sulcus, central sulcus and superior temporal sulcus are easily recognized, interruptions and branches complicate the identification of comparable locations in different brains. The instability of sulcal landmarks poses difficulties for the measurement of cortical volumes with parcellation methods (Caviness et al., 1996). Novel methods for visualization of human cortical structure may require novel approaches to quantification. One novel method that has been successfully applied to volumetric MRIs is the brain averaging technique (Evans et al., 1992). In a variant of that approach Penhune et al. (1996) and Paus et al. (1996) have described the location of Heschl’s gyrus and the cingulate sulcus in probability space. As an extension and partial replication of the Penhune study, we have used a slightly different technique to describe normal variation in the location and frequency of the major and minor sulci associated with Heschl’s gyrus.

The study had three objectives: to determine (i) the variability in standardized three-dimensional space of the major auditory cortex landmarks; (ii) the incidence of Heschl duplications in the left and right hemispheres; and (iii) the influence of demo-
graphic and cognitive factors such as age, sex and handedness on landmark frequency, location and asymmetry. The major results were that (i) there was a 3 cm range in the normalized location of each sulcal landmark; (ii) in spite of this variability, there were consistent left–right asymmetries in landmark position; (iii) the incidence of duplication increased with distance from the midline; and (iv) the effects of age, sex and handedness were not powerful enough to contribute significantly to variance in sulcal frequency, position or asymmetry.

In a pioneering but smaller study of 40 brains, Penhune et al. (1996) also found a 3 cm variation in the boundaries of Heschl’s gyrus accompanied by a leftward asymmetry in the volume of the white matter. The average minimum and maximum AP coordinates reported in their paper correspond remarkably well with those reported here, given the differences in sample characteristics, scan parameters and image-processing techniques between the two studies. This agreement provides confidence that in future investigations, it will be possible to characterize individual Heschl’s gyri in terms of their position with respect to a population rather than their deviance from an atlas mean.

What Is the Significance of Individual Variation in Landmark Position?

Although individual variability in sulcal landmarks is sometimes interpreted as anatomical noise, it is equally possible that variation in gyral size and position is a consequence of differences in neural connectivity (Van Essen, 1997). In support of the functional significance of gyral size, previous studies have found that women and left-handers have less planar asymmetry (Steinmetz et al., 1991; Witelson and Kigar, 1992; Foundas, et al., 1995). In the present study, neither sex nor handedness accounted for significant variance in either the anterior or posterior boundary of the planum. Methodological or sampling differences may account for our failure to find sex and handedness effects.

It is remarkable how much effort has been devoted to the search for anatomical differences due to sex and handedness in contrast to those underlying cognitive and sensory processing differences. Behaviors based on auditory input — verbal and nonverbal communication, music and sound localization — have been of critical importance in the evolution of our species (Hauser, 1996). In order for a behavior to evolve through natural selection, it must vary. Auditory and language function do indeed vary markedly among individuals (Bates et al., 1995). Dysregulated variation in the neurobiological substrates for these functions has been hypothesized as the cause of behavioral disorders as different as dyslexia (Liberman et al., 1974; Liberman and Shankweiler, 1985), specific language impairment (Elliot et al., 1989; Merzenich et al., 1996; Tallal et al., 1996) and schizophrenia (Crow, 1990). When functional variation has arisen through natural selection, anatomical substrates for this variation can generally be identified in animals. Classic examples of form reflecting function are found in the cortical barrel fields (Woolsey and Van der Loos, 1970) and the ocular dominance columns in cat and monkeys (Hubel et al., 1977). The size and arrangement of these arrays are dictated genetically but can be altered by manipulations of sensory experience.
example of a genetically programmed anatomical substrate whose development is epigenetically regulated by auditory input is the vocal control network of the songbird (Nottebohm et al., 1976; Bottjer and Johnson, 1992). A network of nuclei ‘visible to the naked eye’ is found in the sex and species that learn their song and is reduced in size or absent in females and species with stereotyped song. Manipulation of experience and hormonal environment can shrink or expand nuclei in the network with dramatic functional effects.

These animal model systems provide the scientific foundation for speculating that variation in anatomical size and shape of human brain structures can have functional significance. The parallel to the animal work is clear. Somatosensory information provided by the whiskers dominates the world of the mouse. Humans, on the other hand, depend on oral language to interpret experience. The sensory system necessary for the normal development of oral language is audition. Instead of barrel fields, humans have a prominent bulge in the lower bank of the sylvian fissure: Heschl’s gyrus. This suggests the testable hypothesis that variation in the size, shape and asymmetry of Heschl’s gyrus and the planum reflects variation in the size of auditory receptive fields, their underlying connectivity and accompanying auditory detection performance.

In a recent article, Gannon et al. (1998) suggest that human planar asymmetry may be an ‘epiphenomenon’ (p. 221) because chimpanzees also have planar asymmetry but do not depend on oral language for communication. They suggest that planar asymmetry could underlie diverse abilities in the two species. Tallal et al. (1996) have proposed that the left hemisphere in a variety of mammals is specialized for discrimination of very short sounds. In some animals this ability might be used for prey location, in others for mate recognition, while in humans it might facilitate the discrimination of consonants. In any species, individual differences in the ability to perform this type of discrimination might correlate with epigenetically regulated differences in size and shape.

### What Is the Base Rate of Heschl Duplications?

The incidence of Heschl’s duplications has been reported to be elevated in individuals with dyslexia (Leonard et al., 1993) and resistance to thyroid hormone (Leonard et al., 1995). In both of these studies the identification of Heschl duplications was restricted to sections just medial to the insula. At medial positions, the incidence of such duplications is low in the normal adults studied here. The fact that the incidence of medial duplications is higher in the children than in the adults is difficult to interpret in this cross-sectional study. It is possible that there are developmental changes in Heschl morphology, but it seems more reasonable to suppose that there are sampling differences in our child and adult population. We are presently engaged in a longitudinal study to distinguish between these two interpretations.

This study provides a possible resolution to one question that has occasioned considerable debate — the prevalence of Heschl duplications in normal adults. Because postmortem studies have reported a high incidence of duplications, the significance of an elevation in clinical populations has been difficult to evaluate. A recent quantitative MRI study of normal subjects (Penhune et al., 1996), however, found the incidence to be only ∼20%. Our study suggests that range of frequencies in previous reports may reflect a range of criteria for duplication. It turns out that the landmarks that define the duplications are not constant but emerge and disappear at varying lateral positions. The frequency of duplication rises and falls with distance from the midline.

It is time to recognize the arbitrary nature of landmark identification and the relatively abstract, derived and evanescent nature of concepts such as Heschl’s gyrus and Heschl’s duplications. The subtitle of this paper is a paraphrase of Bogen and Bogen (1976). Their paper was a scholarly rumination on the lack of overlap between depictions of Wernicke’s area found in...
various sources. Since Wernicke’s area is a concept, it should not be so surprising that it would have many cortical instantiations. Anatomical landmarks, however, are supposed to be objects, not concepts. They should exist in a particular location. On medial sections, this expectation was fulfilled for Heschl’s gyrus. It was easily visualized in all 105 brains. Laterally, however, the boundary landmarks faded out gradually. Caviness and his colleagues have solved the problem of landmark instability with canonical planes and landmark boundaries in the hope that other laboratories will adopt a common set of criteria for cortical parcellation (Rademacher et al., 1993; Caviness et al., 1996). But the location of these canonical planes and sulci has been investigated in a relatively small number of brains. The validity of these parcellation techniques is compromised when brains are encountered which vary so far from the canonical type that the rules become difficult, if not impossible, to apply (Steinmetz et al., 1990a; Witelson and Kigar, 1992; Ide et al., 1996). Our studies have adopted an alternate strategy and established boundary rules that exaggerate the difference between normal and patient populations (e.g. by restricting the definition of Heschl’s duplications to medial slices where the frequency is low in normal adults). Ideally, of course, structure boundaries should be defined by function (King et al., 1997). Appropriately designed functional imaging experiments that map signal elevations onto sulcal banks in single subjects (Crosson et al., 1998; Gokcay et al., 1998) may reveal less arbitrary signposts to the construction of a functionally valid anatomy.

Notes
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Address correspondence to Christiana M. Leonard, PO Box 100244, Department of Neuroscience, University of Florida Brain Institute, Gainesville, FL 32610, USA. Email: leonard@ufbi.ufl.edu.

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