PROCEEDINGS
—— OF ——
THE ROYAL
SOCIETY

Wernicke's area homologue in chimpanzees (*Pan troglodytes*) and its relation to the appearance of modern human language

Muhammad A. Spocter[1], William D. Hopkins[2,3], Amy R. Garrison[1], Amy L. Bauernfeind[1], Cheryl D. Stimpson[1], Patrick R. Hof[4,5] and Chet C. Sherwood[1,*]

[1]*Department of Anthropology, The George Washington University, Washington, DC 20052, USA*
[2]*Department of Psychology, Agnes Scott College, Decatur, GA 30030, USA*
[3]*Division of Psychobiology, Yerkes National Primate Research Center, Atlanta, GA 30322, USA*
[4]*Department of Neuroscience, Mount Sinai School of Medicine, New York, NY 10029, USA*
[5]*New York Consortium in Evolutionary Primatology, New York, NY, USA*

Human language is distinctive compared with the communication systems of other species. Yet, several questions concerning its emergence and evolution remain unresolved. As a means of evaluating the neuroanatomical changes relevant to language that accompanied divergence from the last common ancestor of chimpanzees, bonobos and humans, we defined the cytoarchitectonic boundaries of area Tpt, a component of Wernicke's area, in 12 common chimpanzee brains and used design-based stereologic methods to estimate regional volumes, total neuron number and neuron density. In addition, we created a probabilistic map of the location of area Tpt in a template chimpanzee brain coordinate space. Our results show that chimpanzees display significant population-level leftward asymmetry of area Tpt in terms of neuron number, with volume asymmetry approaching significance. Furthermore, asymmetry in the number of neurons in area Tpt was positively correlated with asymmetry of neuron numbers in Brodmann's area 45, a component of Broca's frontal language region. Our findings support the conclusion that leftward asymmetry of Wernicke's area originated prior to the appearance of modern human language and before our divergence from the last common ancestor. Moreover, this study provides the first evidence of covariance between asymmetry of anterior and posterior cortical regions that in humans are important to language and other higher order cognitive functions.

Keywords: cytoarchitecture; chimpanzee; evolution; Wernicke's area; asymmetry

1. INTRODUCTION

Humans and chimpanzees share an indelible bond most strikingly manifest through our genetic similarity (Wildman *et al.* 2003). Nonetheless, the uniqueness of human speech and language remains a remarkable discontinuity between the two species (e.g. Chomsky 1980; Pinker & Jackendoff 2005). Understanding how our ability for language evolved requires a careful comparison with the cognitive capacities and communication systems of our closest living relatives, the great apes. Chimpanzees exhibit a sophisticated behavioural repertoire (Goodall 1971) and are known to engage in intricate communicative activities using facial expressions, manual gestures and vocalizations (Tomasello & Call 1997). Moreover, bonobos and chimpanzees can acquire and employ symbolic communication systems in laboratory settings (Savage-Rumbaugh 1986; Savage-Rumbaugh & Lewin 1994). In addition, chimpanzee vocalizations in captivity and the wild have been shown to demonstrate functional reference (Slocombe & Zuberbuhler 2005; Hopkins *et al.* 2007b), allowing individuals to relay information about the nature and location of food sources to conspecifics. Thus, exploring the homologues of human language in chimpanzees is relevant both to understanding the functional neuroanatomy underlying communication in this species and to revealing the evolutionary history of language circuits in the human brain.

The human brain is three times larger than that of chimpanzees, a change hypothesized to uniquely challenge the efficiency of cognitive processing due to constraints imposed upon interhemispheric transfer speed (Gilissen 2001). Hemispheric specialization is believed to have evolved as a solution to this problem by clustering processing elements in one hemisphere relative to another (Aboitiz *et al.* 1992; Ringo *et al.* 1994; Anderson 1999). Consequently, humans are expected to display a high degree of interhemipsheric asymmetry (e.g. Holloway & De La Coste-Lareymondie 1982; Beaton 1997; Shapleske *et al.* 1999). However, the uniqueness of human brain asymmetry (e.g. Corballis 1992) has been challenged by discoveries of behavioural and neuroanatomical asymmetries in other species (Rogers & Andrew 2002). In particular, gross structural asymmetries have been

* Author for correspondence (sherwood@gwu.edu).

observed in non-human primates, including chimpanzees, for homologues of areas implicated in human language and speech production (e.g. Gannon *et al.* 1998; Cantalupo & Hopkins 2001; Hopkins 2007).

Wernicke's area is located in the temporoparietal junction, encompassing the planum temporale of the posterior superior temporal lobe. Although a network of areas within the temporal cortex are important for the perception of speech and the comprehension of language, phonological processing, in particular, has been shown to recruit the cortex of the planum temporale and the inferior parietal lobe (e.g. Geschwind 1970; Wise *et al.* 1991; Karbe *et al.* 1998; Moffat *et al.* 1998; Nakada *et al.* 2001; Foundas *et al.* 2004; Campbell *et al.* 2008). In humans, the planum temporale is predominantly larger in the left hemisphere, especially among right-handed individuals (Galaburda *et al.* 1978; Hepper *et al.* 1991; Naidich *et al.* 2001), a pattern that mirrors the functional dominance of the left hemisphere for language. Notably, this leftward bias has also been observed for the cytoarchitectural area Tpt (corresponding to the posterior part of Brodmann's area 22 or von Economo and Koskinas' area TA_1), which comprises a substantial portion of the cortex underlying the planum temporale (Sweet *et al.* 2005) and, hence, has been suggested to be the major contributor towards leftward asymmetry of the planum temporale in humans (Galaburda *et al.* 1978).

Among non-human primates, area Tpt has been identified in chimpanzees (Bailey *et al.* 1950), macaque monkeys (von Bonin & Bailey 1947; Gannon *et al.* 2008) and galagos (Preuss & Goldman-Rakic 1991) suggesting a first appearance of this homologue at least 50–60 Ma in the primate lineage. The cytoarchitecture of area Tpt is characterized as a transitional type of cortex lying between the specialized parakoniocortical auditory region and the homotypical cortex of the inferior parietal lobule (Galaburda & Sanides 1980). Based on extensive work in macaques, area Tpt is known to have connections with multisensory and higher order areas of the somatosensory, auditory and visual cortex (Smiley *et al.* 2007; Ghazanfar in press). The thalamocortical afferents to area Tpt, arising from the medial geniculate complex, however, suggest that it is primarily associated with auditory processing (Hackett *et al.* 2007) and may play a role discriminating the spatial location of sounds (Leinonen *et al.* 1980). Accordingly, area Tpt of the left and right hemispheres has been demonstrated to be involved in the processing of species-specific vocalizations in Old World monkeys (Poremba *et al.* 2003, 2004; Gil-da-Costa *et al.* 2006) and chimpanzees (Taglialatela *et al.* 2009).

The present study examined whether population-level asymmetries were evident in area Tpt of chimpanzees using design-based stereologic data on regional volume, total neuron number and neuron density. We analysed these data in relation to gross morphological asymmetries of the planum temporale, handedness and asymmetries of Broca's area homologue obtained from previous studies of these same chimpanzee brain specimens. We also generated probabilistic maps of the location of area Tpt in a standard chimpanzee brain coordinate space. Here, we show that area Tpt is left hemisphere dominant in terms of neuron numbers and volume at the population level in chimpanzees, further supporting the conclusion that

hemispheric specialization of Wernicke's area evolved long before the emergence of modern human language. Furthermore, our data provide evidence for intra-individual covariance between asymmetry of anterior and posterior cortical regions implicated in human language.

2. MATERIAL AND METHODS

(a) *Subjects*
The study sample consisted of 12 chimpanzee subjects, including six females (mean age at death = 37.8 years, s.d. = 12.9, range = 13–48) and six males (mean age at death = 29.3 years, s.d. = 10.8, range = 17–41). These individuals formed part of an earlier study conducted by Schenker *et al.* (2010), which investigated Broca's area homologue in chimpanzees. For further details, see the electronic supplementary material.

(b) *Behavioural measurements*
All handedness data for these subjects have been previously reported (Hopkins 1995; Hopkins & Cantalupo 2004; Taglialatela *et al.* 2006). In accordance with these descriptions, two different tasks were used to evaluate handedness. The 'tube task' required the coordinated bimanual actions of the subject to remove peanut butter from the inside of a polyvinylchloride tube. Hand use was recorded for each event in which the subjects successfully reached into the tube with their finger, and extracted peanut butter and brought it to their mouth. Hand preference on the tube task remained stable across the lifespan of an individual (Hopkins 2007) adding credence to its inclusion for assessing handedness. Handedness data on the tube task were available for all subjects. The second task involved an assessment of the subject's hand preference during manual gesturing. Data on manual gesturing were available from 10 of the 12 subjects (see the electronic supplementary material).

(c) *Magnetic resonance imaging (MRI) collection*
Within 14 h of each subject's death, the brain was removed and immersed in 10 per cent formalin at necropsy. MRI scans of the post-mortem brain specimens were acquired on a commercial 1.5 T GE high-gradient MRI scanner equipped with 8.3 software (GE Medical Systems, Milwaukee, WI). Coronal T1-weighted MR images were acquired through the entire brain with TR = 666.7 ms and TE = 14.5 ms with an echo-train of 2. Slices were obtained as 1.5 mm thick contiguous sections with a matrix size of 256×256 and an field of view of 16×16 cm, resulting in a final voxel size of $0.625 \times 0.625 \times 1.5$ mm.

(d) *Tissue preparation and staining*
A block containing the temporal and parietal lobes was removed from each brain with a coronal cut at the level of the precentral gyrus rostrally and a further cut at the level of the angular gyrus caudally. Tissue blocks were cryoprotected by immersion in buffered sucrose solutions up to 30 per cent, embedded in tissue medium, frozen in a slur of dry ice and isopentane and sectioned at 40 μm with a sliding microtome in the coronal plane. Every 10th section (400 μm apart) was stained for Nissl substance with a solution of 0.5 per cent cresyl violet to visualize cytoarchitecture. Every 20th section was stained for myelin using the Gallyas (1971) method.

(e) *Area identification*
The boundaries of area Tpt were manually drawn for both hemispheres in serial sections using StereoInvestigator
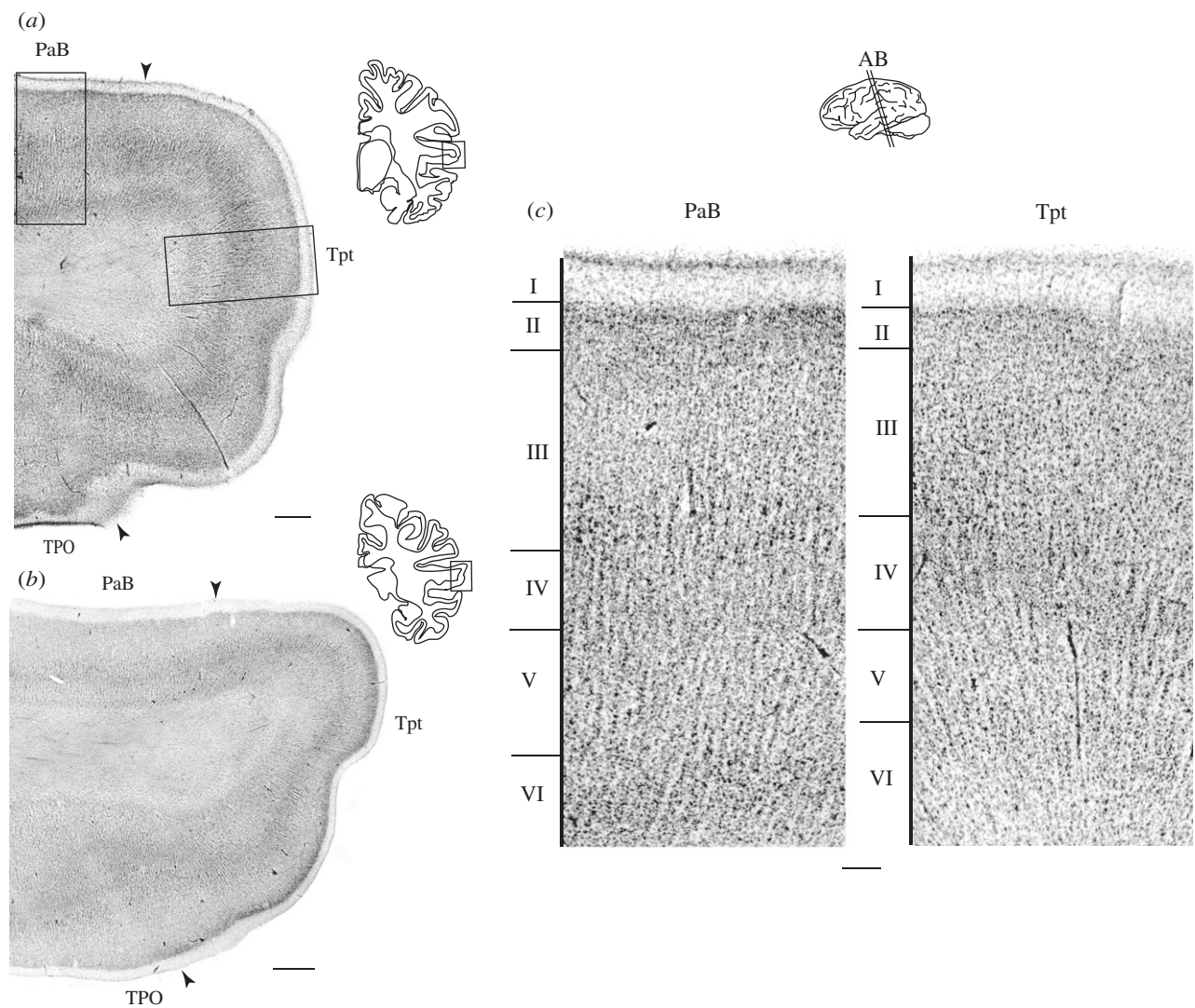
Figure 1. Cytoarchitectural organization of the superior temporal gyrus indicating the position and cytoarchitecture of area Tpt and the adjacent parabelt (PaB). (*a,b*) Adjacent coronal sections through the superior temporal gyrus of the chimpanzee. (*c*) High magnification views of the cytoarchitectural profiles of area Tpt and adjacent parabelt region within the superior temporal gyrus of the chimpanzee. Scale bar, (*a,b*) 1 mm; (*c*) 500 μm.

software (MBF Bioscience, Williston, VT) using a 2.5× objective (N.A. 0.075) on a Zeiss Axioplan 2 microscope. Regions of interest were identified using criteria from previous descriptions in humans (Galaburda & Pandya 1983; Sweet *et al.* 2005; Fullerton & Pandya 2007). In brief, area Tpt is characterized by a well-developed layer II and deeply stained medium sized pyramidal neurons in the lower tier of layer III (Fullerton & Pandya 2007). Layer IV is broad and has irregular outer and inner margins as a result of infiltrating pyramidal neurons from layers III and V (Galaburda & Pandya 1983; Sweet *et al.* 2005; Fullerton & Pandya 2007). For further details, see the electronic supplementary material.

(f) *Probabilistic mapping*

The exact boundaries of each cortical area, as observed under the microscope, were drawn on printouts of images produced from digital flatbed scans of the histological slides (figure 1). These boundaries were then used to manually delineate the borders of area Tpt on MRI scans of the brains, which had been collected prior to sectioning. Each MRI series was re-oriented to match the plane of sectioning

using prominent landmarks on each of the histological sections to the morphology of the MRI slices in order to facilitate the transfer of boundaries. Object maps were created using ANALYZE 7.0 software (AnalyzeDirect, Overland Park, KS) for each cortical area by manually drawing its extent on every MRI slice in which it occurred. After object maps of each cortical area were created for the MRI scans, the three-dimensional image of each brain was co-registered to a template chimpanzee brain (Rilling *et al.* 2007). Each individual MRI scan was re-aligned, spatially normalized into a standard coordinate space and then coregistered to the template using non-rigid registration (ANALYZE 7.0). The locations of the cortical areas were subsequently integrated across all subjects on a voxel-by-voxel basis to produce a probability map indicating the regions of overlap across all subjects as projected onto the template brain.

(g) *Cortical area volumes, neuron counts and shrinkage correction*

Volumetric data for area Tpt were collected from Nissl-stained histological sections using point counting and the Cavalieri method (Gundersen *et al.* 1999). Total neuron

numbers were estimated from Nissl-stained sections using the optical fractionator method (West *et al.* 1991). Histological processing invariably results in tissue shrinkage and other volumetric artefacts. To account for shrinkage, we calculated volumetric correction factors for each individual tissue block. Shrinkage correction, and parameters used for measuring cortical areas and obtaining neuron counts are described in the electronic supplementary material.

(h) *Validation and interobserver variability*

To validate our method of cortical area identification, measurement and alignment to MRIs, five specimens were randomly selected for comparison and the cytoarchitectural borders of each cortical area were independently delineated by a second observer (C.C.S.) blind to the results of the first (M.A.S.). High levels of congruency were observed between the borders and volumes delineated by each observer, suggesting that the subjective judgement of area boundaries between observers covaries in a systematic fashion and are reliable (see the electronic supplementary material).

(i) *Planum temporale measurements from MRI*

Measurements of planum temporale surface area asymmetry for the 12 chimpanzee subjects had previously been reported (Hopkins *et al.* 1998). In accordance with these descriptions, MRI scans from each individual were aligned in the coronal plane and the width of the planum temporale was measured on consecutive slices between Heschl's gyrus and the termination of the Sylvian fissure (Cantalupo *et al.* 2003). Grey matter volumes of the planum temporale were derived from segmented grey matter masks imported into Analyze software at a resolution of 1 mm and placed in the same stereotaxic space as the T1 MRI scan. The planum temporale was defined by drawing a line from the most lateral portion of the Sylvian fissure to the most medial point. The grey matter was traced to its most inferior, medial edge then towards the lateral edge of the brain. Individual grey matter areas were then summed across slices to create grey matter volumes for each hemisphere.

(j) *Data analysis*

To examine lateralization, an asymmetry quotient (AQ) was calculated using the equation $|(\text{right} - \text{left})/((\text{right} + \text{left})/2)|$. Positive values indicate a right greater than left asymmetry and negative values indicate a left greater than right asymmetry. Furthermore, population-level asymmetry in each parameter was examined using a one sample *t*-test to determine whether the means were significantly different from zero.

Non-parametric Spearman rank order correlations were used to evaluate the associations between volume and neuron number for area Tpt with asymmetry in volume and neuron number for Brodmann's areas 44 and 45 from these same chimpanzee brains reported by Schenker *et al.* (2010). Associations with planum temporale asymmetry and indices of handedness were also examined using Spearman rank order correlations. Finally, age was tested for possible effects on all variables; however, no significant effects were observed.

Statistical significance was considered at $\alpha = 0.05$. Detailed results from these analyses are provided in the electronic supplementary material, tables S1–S4.

3. RESULTS

(a) *Probabilistic mapping*

Area Tpt in chimpanzees was consistently located in the posterior one-third of the superior temporal gyrus, extending into the floor of the Sylvian fissure in some individuals (figures 2 and 3). This result was consistent with that reported for humans; however, in humans area Tpt also often extends onto the parietal convexity (Galaburda *et al.* 1978). We did not observe area Tpt within the parietal convexity of chimpanzees, suggesting that there may be a species difference in the extent and position of area Tpt relative to humans.

Figure 2 shows a probabilistic map of area Tpt registered to a template chimpanzee brain. On average, area Tpt was located ventral to the parietal operculum and along the lateral margin of the superior temporal gyrus. Despite interindividual variation in the location of area Tpt in the template space, it showed a considerable amount of consistency as indicated by the colour maps of overlapping voxels that contained area Tpt in the sample of 12 brains. To estimate the extent of spatial congruency in area Tpt across individuals, we calculated the volume where at least five of 12 subjects showed overlap. Notably, area Tpt in the right hemisphere demonstrated less variability in its location than in the left. These volumes and centroid coordinates are presented in table S4 in the electronic supplementary material.

(b) *Stereologic data*

Interindividual variability in area Tpt was also evident from stereologic measures of regional volume, total neuron number and neuron density. Coefficients of variation ranged from 26.1 to 59 per cent for volume, 34.7 to 79 per cent for total neuron number and 38.8 to 41.4 per cent for neuron density. This variation was substantially greater than for the whole brain volume (11.3%), but was within the range of coefficients of variation from these brains for Broca's area homologue (Schenker *et al.* 2010).

(c) *Asymmetry*

All stereologic data were examined for evidence of population-level asymmetry using the one sample *t*-test (figure 4). Results indicated a significant leftward asymmetry at the population level for total neuron number (mean $\text{AQ} = -0.40$, s.e.m. $= 0.14$, $t_{11} = -2.91$, $p = 0.01$) and leftward asymmetry for volume that approached significance (mean $\text{AQ} = -0.26$, s.e.m. $= 0.14$, $t_{11} = -1.89$, $p = 0.08$). In contrast, there was no significant asymmetry in neuron density (mean $\text{AQ} = -0.14$, s.e.m. $= 0.12$, $t_{11} = -1.17$, $p = 0.27$). The population-level asymmetry in total neuron number was consistent with that observed at the individual level, where 10 of the 12 individuals had more neurons in area Tpt of the left hemisphere. Similarly, nine of the 12 individuals showed a left hemisphere dominant asymmetry of area Tpt volume. There were no statistically significant sex differences in asymmetry of any variables.

(d) *Correlations between asymmetries in area Tpt, planum temporale and Broca's area*

We used Spearman's Rho correlation analyses to evaluate if there were significant associations between AQs in
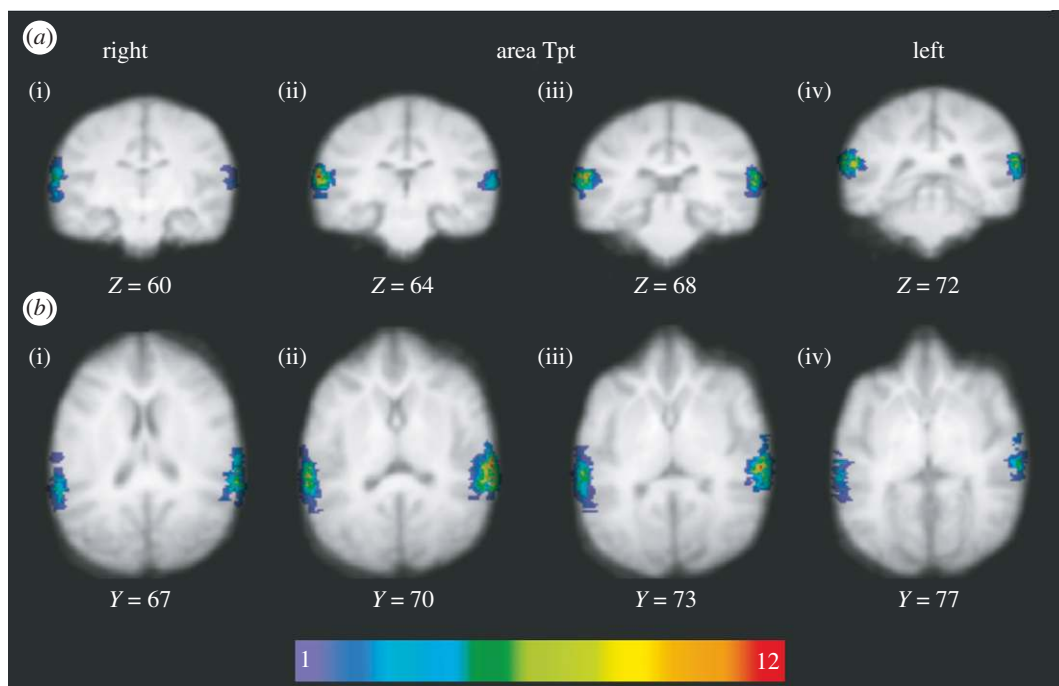
Figure 2. Probabilistic map of the location of area Tpt on a template of the chimpanzee brain. Colours indicate the number of individuals where the area is occupied by the region of interest. Warmer colours (more red) indicate greater number of individuals overlapping, cooler colours indicate fewer numbers of individuals overlapping.

stereologic measures for area Tpt and Brodmann's areas 44 and 45. Results indicated a significant positive correlation between neuron number AQ in area Tpt and neuron number AQ in area 45 ($r_S = 0.70$, $p = 0.01$). There were no other correlations between stereologic variables in area Tpt with area 44 or 45.

We also correlated the AQ values for area Tpt and planum temporale surface area and grey matter volume. No significant correlations were observed between asymmetry in the volume of area Tpt and the grey matter volume of the planum temporale ($r_S = 0.23$, $p = 0.47$), or in the surface area of the planum temporale ($r_S = -0.36$, $p = 0.26$).

(e) *Correlations with handedness*
We tested for correlations between the degree of asymmetry in stereologic measures of area Tpt and handedness derived from a bimanual coordinated task and a communicative gesturing task. Although no significant correlations were found between asymmetry of the stereologic measures of area Tpt and handedness in these individuals, the association between area Tpt neuron number and handedness for gesturing approached conventional levels of statistical significance ($r_S = -0.59$, $p = 0.07$). Right-handed chimpanzees tended to have a greater leftward asymmetry of area Tpt.

4. DISCUSSION
Our findings show that chimpanzees exhibit population-level asymmetries in neuron number and volume for area Tpt, an important cytoarchitectonic component of Wernicke's area. In addition, asymmetry of area Tpt neuron numbers was significantly associated with

asymmetries of neuron numbers in area 45 of the inferior frontal gyrus.

(a) *The topographic location of area Tpt in the chimpanzee*
An early description of the extent of area Tpt in humans reported its occurrence on the posterolateral aspect of the planum temporale surface (Galaburda *et al.* 1978). In humans, furthermore, area Tpt's borders are also found outside of the planum surface, on the lateral part of the superior temporal gyrus. Similarly, in macaque monkeys and galagos, area Tpt has been described on the superior surface of the posterior superior temporal gyrus (Galaburda & Pandya 1983; Preuss & Goldman-Rakic 1991; Gannon *et al.* 2008) and in macaques may often extend onto the inferolateral surface towards the superior temporal sulcus (Gannon *et al.* 2008). A further variation reported only in humans, however, also finds area Tpt extending onto the parietal convexity (Galaburda *et al.* 1978).

Our results indicated that in chimpanzees, area Tpt is consistently isolated to the posterior one-third of the superior temporal gyrus. Anteriorly, area Tpt progresses as a column-shaped region that hugs the medial surface of the superior temporal gyrus and in several individuals extends into the floor of the Sylvian fissure. In this respect, area Tpt of the chimpanzee shares several characteristics in common with galagos, macaques and humans (see figure 3 for a representation of the general pattern exhibited in humans, macaques and chimpanzees). But unlike the human brain, area Tpt in the chimpanzee was never observed in the parietal convexity. This suggests an expansion of the extent of area Tpt in modern humans and may represent a species-specific configuration indicative of greater connections with and
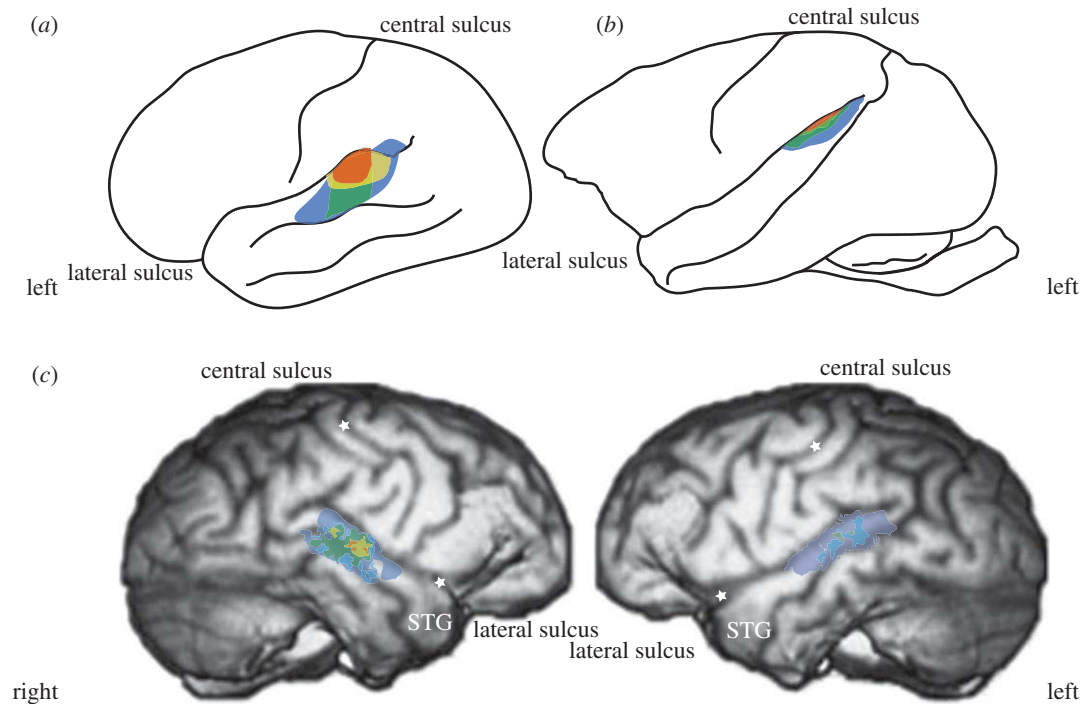
Figure 3. The extent of area Tpt in the (*a*) human (Galaburda *et al.* 1978), (*b*) macaque (Gannon *et al.* 2008) and (*c*) chimpanzee (current study). The human profile was derived from published sketches by Galaburda *et al.* (1978), which were aligned in two dimensions, warped and superimposed to create a two-dimensional probabilistic map. In a similar way, the extent of area Tpt in the macaque monkey is based on published lateral profiles from Gannon *et al.* (2008). The lateral view in the chimpanzee is the rendered probabilistic map obtained from the 12 individuals used in the present study. Note the parietal extension of area Tpt in the human brain, which differs from that observed in the macaque and chimpanzee.

extension into the parietal lobe association cortex. This region is the site of major cross-modality integration and, as argued by Geschwind (1965), is an important component for the foundation for human language.

This phyletic variation in parietotemporal cortex anatomy may also be linked to differences in cross-modal perception among monkeys, apes and humans. Though initially thought to be uniquely human, it has now been well documented that monkeys and apes are capable of integration between visual-to-tactile modalities (Savage-Rumbaugh *et al.* 1988). Yet, most apes and monkeys perform poorly on auditory–visual and auditory–tactile cross-modal matching tasks (Davenport 1977; Hashiya & Kojima 2001).

The hominin fossil record provides additional indirect evidence that area Tpt and adjacent posterior parietal areas might have been modified at an earlier stage in human ancestors. The placement of the lunate sulcus in Pliocene hominin endocasts suggests that there may have been a relative increase in the posterior parietal association cortex of small-brained taxa such as *Australopithecus afarensis* and *Australopithecus africanus*, concomitant with a reduction in the proportion of primary visual cortex (Holloway 1981; Holloway & Kimbel 1986). Hence, the increased parietal expansion of area Tpt might have participated in this reallocation of space in the cortical mantle of early hominins.

Probabilistic maps of area Tpt illustrated substantial interindividual variability in the position of area Tpt relative to sulci. A similarly high degree of interindividual variability has also been observed in areas 44 and 45 in chimpanzees (Schenker *et al.* 2010). Notably, however, there was considerably more overlap among individuals for area Tpt than that observed in either areas 44 or 45 (as indicated by the warmer colours in the colour bar in figure 2). This is probably reflective of the consistency with which area Tpt is found on the lateral surface of the planum temporale extending to the superolateral surface of the superior temporal gyrus and the relatively fewer neighbouring sulci in the superior temporal lobe as compared with the more complex and variable folding pattern of the inferior frontal gyrus. In particular, area Tpt is hemmed in by the Sylvian fissure and other regions which appear early in development, such as the auditory field, which may serve as important organizing centres during cortical growth (Kostovic & Vasung 2009).

(b) Evidence for population-level asymmetry

In humans, the majority of individuals display a larger planum temporale in the left than in the right hemisphere (e.g. Galaburda *et al.* 1978; for review, see Shapleske *et al.* 1999). This pattern is exemplified by the work of Geschwind & Levitsky (1968) who selected 100 human brains at random and found that 65 showed a larger left planum, 11 had a larger right planum, whereas 24 individuals had no bias to either direction. Interestingly, the degree of asymmetry in the planum temporale of humans was shown to correlate with volume asymmetry in area Tpt (Galaburda *et al.* 1978), as well as with the angular gyrus area PG (Eidelburg & Galaburda 1984) in small sample sizes. A tendency for a larger area Tpt in the posterior lateral region of the superior temporal gyrus was also purported to result in the asymmetric Sylvian fissure length observed in humans (Galaburda *et al.* 1978). These studies suggest the existence of associated
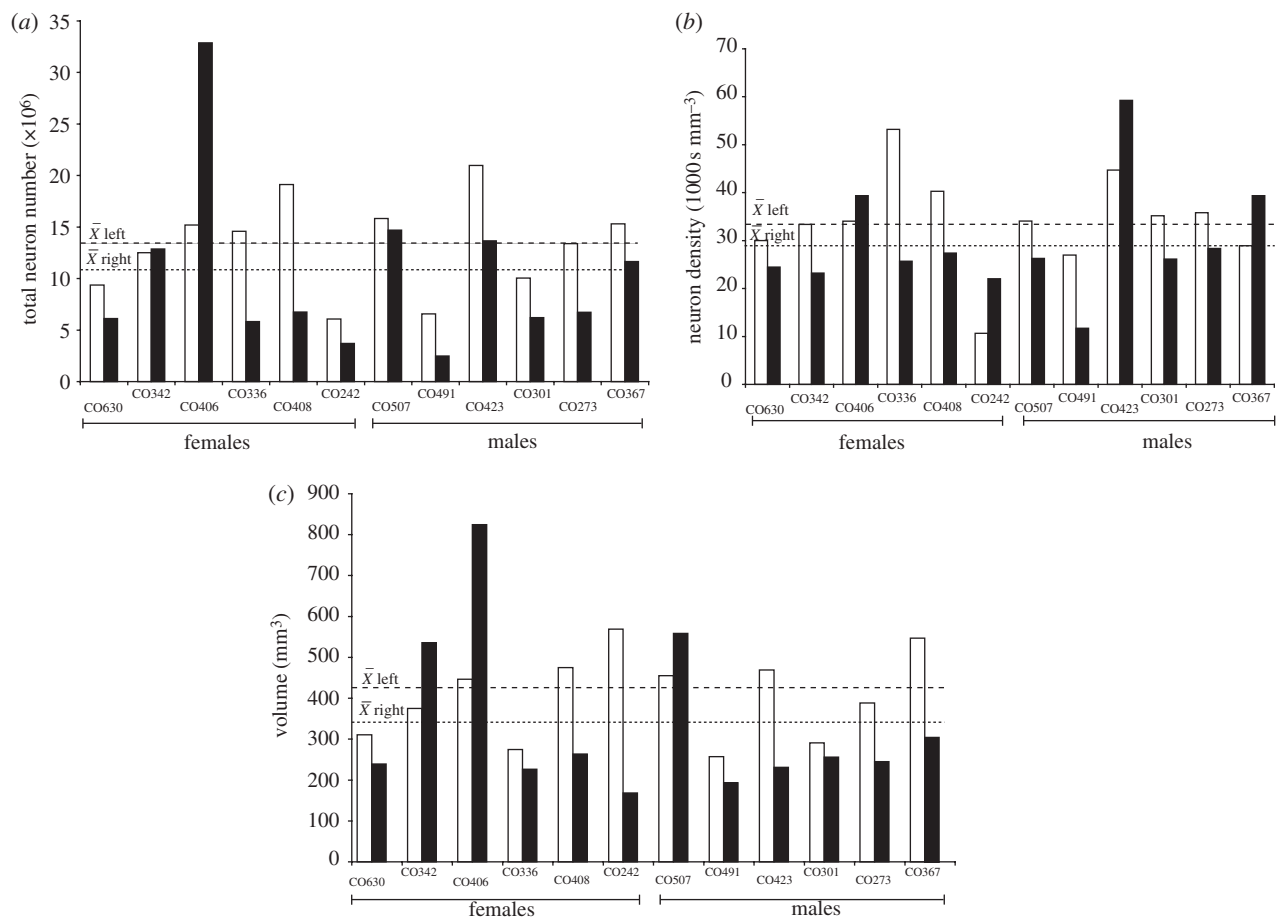
Figure 4. Bar graphs of (*a*) neuron number, (*b*) neuron density and (*c*) volume for left and right area Tpt. Unshaded box, left; shaded box, right.

asymmetries between parts of the posterior temporal and parietal regions involved in language.

Chimpanzees also display marked population-level left hemisphere dominance in the surface area of the planum temporale (Gannon *et al.* 1998; Hopkins *et al.* 1998), as well as significant correlations between planum temporale asymmetry and handedness for manual gestures and tool use (Hopkins *et al.* 2007*a*; Hopkins & Nir in press). Taken together with our results, these studies indicate that an asymmetric planum temporale, and underlying area Tpt, evolved prior to the emergence of modern humans, serving as a pre-adaptation to modern human language and speech (Hopkins *et al.* 2007*a*). The existence of an asymmetrical planum temporale and area Tpt in chimpanzees is consistent with the view that lateralization of complex auditory processing in this area may be important in the discrimination of species-specific vocalizations among primates in general, and later became recruited to participate in hemispheric specialization for human language functions.

In fact, anatomical and functional asymmetries of the temporal cortex appear to be basal in the Old World primate lineage. Recently, Gannon *et al.* (2008) demonstrated asymmetry of area Tpt volume in macaque monkeys, with five of six macaque brains displaying a leftward bias. Congruent with these anatomical findings, several studies of non-human primates have revealed a right ear orienting bias when subjects are presented with species-specific vocal calls (Petersen *et al.* 1978; Beecher

et al. 1979; Hauser & Anderson 1994; Hauser *et al.* 1998; Ghazanfar *et al.* 2001), suggesting left hemisphere specialization for processing communication signals. Similarly, experimental lesion of the left superior temporal cortex in Japanese macaques results in transient disruption of the ability to discriminate conspecific vocalizations, whereas there is no such deficit with right hemisphere lesion (Heffner & Heffner 1984). Functional imaging studies in non-human primates also indicate the existence of asymmetric hemispheric activation of auditory areas in the superior temporal gyrus, including area Tpt (Poremba *et al.* 2003, 2004). In particular, the posterior portion of the right superior temporal gyrus processes a wide variety of auditory stimuli in macaques (Poremba *et al.* 2003, 2004), whereas the left hemisphere is specifically involved in the analysis of species-specific vocalizations, which activates the dorsal temporal pole (Poremba *et al.* 2004). In addition, vocal calls have been demonstrated to elicit increased activity in area Tpt of macaques (Gil-da-Costa *et al.* 2006) with seemingly greater intensity in the left hemisphere, although this pattern appeared variable among the three subjects studied. A recent positron emission tomography study of chimpanzees found activation of the right posterior superior temporal lobe in response to rough grunts, which are typically given in close proximity to a social partner, to the exclusion of longer range broadcast calls and other acoustic stimuli (Taglialatela *et al.* 2009). As evident from these neuroimaging results, it appears that the extent that area

Tpt in each hemisphere is involved in the processing of species-specific vocal calls may be influenced by the semantic, emotive or temporal characteristic of primate vocal signals. At this point, considerably more research is needed to address this issue.

In the present study, chimpanzees displayed a consistent leftward directional asymmetry in neuron number and volume for area Tpt, whereas no significant population-level asymmetry was detectable for neuron density. Furthermore, neuron number asymmetry in area Tpt was associated with individual lateralization in handedness for communicative gesturing ($p = 0.07$). In contrast, a recent study of these same chimpanzee brains (Schenker et al. 2010) did not find anatomical asymmetry of Brodmann's areas 44 and 45. Although subtle population-level asymmetries of Broca's area homologue might be difficult to detect with our relatively small sample size, it is notable that Wernicke's area homologue clearly exhibited more robust anatomical lateralization. We propose that the manifestation and persistence of asymmetry in area Tpt is reflective of its ancient origin, as suggested by the occurrence of its homologue in galagos and as evidenced from asymmetry in macaques. This potentially suggests an early specialization common among primates for left hemisphere auditory discrimination of conspecific vocalizations, stretching back at least to the common ancestor of humans and macaques.

It is of note that the inconsistencies between patterns of asymmetry in area Tpt and areas 44 and 45 as revealed at the microstructural level in chimpanzees and humans are in many ways mirrored by the findings of gross anatomical asymmetries measured from MRI. In humans, the leftward asymmetry in the planum temporale has been one of the most consistent asymmetries reported in the human brain (Beaton 1997; Shapleske et al. 1999), whereas reports of population-level asymmetries in the frontal operculum have been far less consistent across studies (Keller et al. 2007, 2009). Similarly, in chimpanzees, post-mortem and *in vivo* analysis of the planum temporale have revealed significant leftward asymmetries (Hopkins & Nir in press) but this is less clear for the inferior frontal gyrus (Cantalupo & Hopkins 2001; Hopkins et al. 2008; Keller et al. 2009; Schenker et al. 2010) and appears to depend on the landmarks used to define the region-of-interest as well as other factors.

In the current study, we observed a significant correlation between asymmetry of neuron numbers in area Tpt and area 45, suggesting a close link between these cortical regions. In light of the underlying anatomy, covariance in asymmetry between these regions seems hardly surprising. Indeed, others have reported projections from auditory regions of the temporal cortex to the ventral frontal cortex in macaques (e.g. Deacon 1992) and a more recent detailed study of the inputs to Broca's area homologue in the macaque demonstrated the existence of a number of fibre pathways that link the superior temporal cortex with areas 44 and 45 (Petrides & Pandya 2009). In particular, a dorsal stream of fibres that originate from various cortical areas in the inferior parietal lobule and the adjacent caudal superior temporal sulcus were found to specifically target areas 44 and 45 (Petrides & Pandya 2009) and it is likely that covariance in asymmetry in these regions could be mediated by these or similar inputs. The existence of these circuits in the macaque along with the collaborative evidence of covariance in asymmetry between these regions in the chimpanzees suggests that these pathways along with the pattern of asymmetry were not uniquely designed for language. We may speculate that they served some pre-adaptive function in non-human primates by conveying information about conspecific communication to the action planning system, which was later co-opted in human evolution to subserve language.

In conclusion, the present study provides an important step towards defining the anatomical characteristics of Wernicke's area homologue for one of our closest living relatives. Further comparative studies that examine asymmetry in language-associated areas would benefit from an investigation of asymmetry at different levels of organization and the potential for covariance between regions.

REFERENCES

Aboitiz, F., Scheibel, A. B., Fisher, R. S. & Zaidel, E. 1992 Individual differences in brain asymmetries and fiber composition in the human corpus callosum. *Brain Res.* **58**, 154–161. (doi:10.1016/0006-8993(92)90179-D)

Anderson, B. 1999 Commentary—Ringo, Doty, Demeter and Simard, Cereb. Cortex 49, 331–343: a proof of the need for the spatial clustering of interneuronal connections to enhance cortical computation. *Cereb. Cortex* **9**, 2–3. (doi:10.1093/cercor/9.1.2)

Bailey, P., von Bonin, G. & McCulloch, W. S. 1950 *The isocortex of the chimpanzee*. Urbana-Champaign, IL: University of Illinois Press.

Beaton, A. A. 1997 The relation of planum temporale asymmetry and morphology of the corpus callosum to handedness, gender and dyslexia: a review of the evidence. *Brain Lang.* **60**, 255–322. (doi:10.1006/brln.1997.1825)

Beecher, M., Petersen, M., Zoloth, S., Moody, D. & Stebbins, W. 1979 Perception of conspecific vocalizations by Japanese macaques: evidence for selective attention and neural lateralization. *Brain Behav. Evol.* **16**, 443–460. (doi:10.1159/000121881)

Campbell, R., MacSweeney, M. & Waters, D. 2008 Sign language and the brain: a review. *J. Deaf Stud. Deaf Educ.* **13**, 3–20. (doi:10.1093/deafed/enm035)

Cantalupo, C. & Hopkins, W. D. 2001 Asymmetric Broca's area in great apes. *Nature* **414**, 505. (doi:10.1038/35107134)

Cantalupo, C., Pilcher, D. & Hopkins, W. D. 2003 Are planum temporale and sylvian fissure asymmetries directly related? A MRI study in great apes. *Neuropsychologia* **41**, 1975–1981. (doi:10.1016/S0028-3932(02)00288-9)

Chomsky, N. 1980 *Rules and representations*. New York, NY: Columbia University Press.

Corballis, M. C. 1992 *The lopsided brain: evolution of the generative mind*. New York, NY: Oxford University Press.

Davenport, R. K. 1977 Cross-modal perception: a basis for language? In *Language learning by a chimpanzee: the LANA project* (ed. D. M. Rumbaugh). New York, NY: Academic Press.

Deacon, T. W. 1992 Cortical connections of the inferior arcuate sulcus cortex in the macaque brain. *Brain Res.* **573**, 8–26. (doi:10.1016/0006-8993(92)90109-M)

Eidelburg, D. & Galaburda, A. M. 1984 Inferior parietal lobule. Divergent architectonic asymmetries determined with 3D MR technology. *J. Neurosci. Meth.* **39**, 185–191.

Foundas, A. L., Bollich, A. M., Feldman, J., Corey, D. M., Hurley, M., Lemen, L. C. & Heilman, K. M. 2004 Aberrant auditory processing and atypical planum temporale in developmental stuttering. *Neurology* **63**, 1640–1646.

Fullerton, B. C. & Pandya, D. N. 2007 Architectonic analysis of the auitory related areas of the superior temporal region in the human brain. *J. Comp. Neurol.* **504**, 470–498. (doi:10.1002/cne.21432)

Galaburda, A. & Pandya, D. 1983 The intrinsic architechtonic and connectional organization of the superior temporal region of the rhesus monkey. *J. Comp. Neurol.* **221**, 169–184. (doi:10.1002/cne.902210206)

Galaburda, A. & Sanides, F. 1980 Cytoarchitectonic organization of the human auditory cortex. *J. Comp. Neurol.* **190**, 597–610. (doi:10.1002/cne.901900312)

Galaburda, A. M., Sanides, F. & Geschwind, N. 1978 Human brain. Cytoarchitectonic left–right asymmetries in the temporal speech region. *Arch. Neurol.* **35**, 812–817.

Gallyas, F. 1971 A principle for silver staining of tissue elements by physical development. *Acta Morphol. Acad. Sci. Hung.* **19**, 57–71.

Gannon, P. J., Holloway, R. L., Broadfield, D. C. & Braun, A. R. 1998 Asymmetry of chimpanzee planum temporale: humanlike pattern of Wernicke's brain language area homolog. *Science* **279**, 220–222. (doi:10.1126/science.279.5348.220)

Gannon, P. J., Kheck, N. & Hof, P. R. 2008 Leftward interhemispheric asymmetry of macaque monkey temporal lobe language area homolog is evident at the cytoarchitectural, but not gross anatomic level. *Brain Res.* **1199**, 62–73.

Geschwind, N. 1965 Disconnexion syndromes in animals and man. I. *Brain* **88**, 585–644. (doi:10.1093/brain/88.3.585)

Geschwind, N. 1970 The organization of language and the brain. *Science* **170**, 940–944. (doi:10.1126/science.170.3961.940)

Geschwind, N. & Levitsky, W. 1968 Human brain: left–right asymmetries in the temporal speech region. *Science* **151**, 186–187. (doi:10.1126/science.161.3837.186)

Ghazanfar, A. 2009 Multisensory roles for auditory cortex in primate vocal communication. *Hearing Res.* **258**, 113–120. (doi:10.1016/j.heares.2009.04.003)

Ghazanfar, A. A., Smith-Rohrberg, D. & Hauser, M. D. 2001 The role of temporal cues in rhesus monkey vocal recognition: orienting asymmetries to reversed calls. *Brain Behav. Evol.* **58**, 163–172. (doi:10.1159/000047270)

Gil-da-Costa, R., Martin, A., Lopes, M. A., Munoz, M., Fritz, J. B. & Braun, A. R. 2006 Species-specific calls activate homologs of Broca's and Wernicke's areas in the macaque. *Nat. Neurosci.* **9**, 1064–1070. (doi:10.1038/nn1741)

Gilissen, E. 2001 Structural symmetries and asymmetries in the human and chimpanzee brain. In *Evolutionary anatomy of primate cerebral cortex* (eds D. Falk & K. R. Gibson), pp. 187–216. Cambridge, UK: Cambridge University Press.

Goodall, J. 1971 *In the shadow of man*. Boston, MA: Houghton Mifflin Publishing.

Gundersen, H. J. G., Jensen, E. B., Kieû, K. & Nielsen, J. 1999 The efficiency of systematic sampling in stereology-reconsidered. *J. Microsc.* **193**, 199–211. (doi:10.1046/j.1365-2818.1999.00457.x)

Hackett, T. A., De La Mothe, L. A., Ulbert, I., Karmos, G., Smiley, J. & Schroeder, C. E. 2007 Multisensory convergence in auditory cortex, II. Thalamocortical connections of the caudal superior temporal plane. *J. Comp. Neurol.* **502**, 924–952. (doi:10.1002/cne.21326)

Hashiya, K. & Kojima, S. 2001 Acquisition of auditory–visual intermodal matching-to-sample by a chimpanzee (*Pan troglodytes*): comparison with visual–visual intramodal matching. *Anim. Cognit.* **4**, 231–239. (doi:10.1007/s10071-001-0118-3)

Hauser, M. D. & Anderson, K. 1994 Left hemisphere dominace for processing vocalizations in adult, but not infant, rhesus monkeys: field experiments. *Proc. Natl Acad. Sci. USA* **91**, 3946–3948. (doi:10.1073/pnas.91.9.3946)

Hauser, M. D., Agnetta, B. & Perez, C. 1998 Orienting asymmetries in rhesus monkey vocalizations: the effect of time-domain changes on acoustic perception. *Anim. Behav.* **56**, 41–47. (doi:10.1006/anbe.1998.0738)

Heffner, H. E. & Heffner, R. S. 1984 Temporal lobe lesions and perception of species-specific vocalizations by macaques. *Science* **226**, 75–76. (doi:10.1126/science.6474192)

Hepper, P. G., Shahidullah, B. S. & White, R. 1991 Handedness in the human fetus. *Neuropsychologia* **29**, 1107–1111. (doi:10.1016/0028-3932(91)90080-R)

Holloway, R. L. 1981 Culture, symbols, and human brain evolution: a synthesis. *Dial. Anthropol.* **3**, 215–232.

Holloway, R. L. & De La Coste-Lareymondie, M. C. 1982 Brain endocast asymmetry in pongids and hominids: some preliminary findings on the paleontology of cerebral dominance. *Am. J. Phys. Anthropol.* **58**, 101–110. (doi:10.1002/ajpa.1330580111)

Holloway, R. L. & Kimbel, W. H. 1986 Endocast morphology of Hadar hominid AL 162-28. *Nature* **321**, 536. (doi:10.1038/321536a0)

Hopkins, W. D. 1995 Hand preference for a coordinated bimanual task in 110 chimpanzees (*Pan troglodytes*): cross-sectional analysis. *J. Comp. Psychol.* **109**, 291–297. (doi:10.1037/0735-7036.109.3.291)

Hopkins, W. D. 2007 Hemispheric specialization in chimpanzees evolution of hand and brain. In *Evolutionary cognitive neuroscience* (eds T. Shackelford, J. P. Keenan & S. M. Platek), pp. 95–120. Boston, MA: MIT Press.

Hopkins, W. D. & Cantalupo, C. 2004 Handedness in chimpanzees (*Pan troglodytes*) is associated with homologous language areas. *Behav. Neurosci.* **118**, 1176–1183. (doi:10.1037/0735-7044.118.6.1176)

Hopkins, W. D. & Nir, T. 2009 Planum temporale surface area and grey matter asymmetries in chimpanzees (*Pan troglodytes*): the effect of handedness and comparison within findings in humans. *Behav. Brain Res.* (doi:10.1016/j.bbr.2009.12.012)

Hopkins, W. D., Marino, L., Rilling, J. K. & MacGregor, L. A. 1998 Planum temporale asymmetries in great apes as revealed by magnetic resonance imaging (MRI). *NeuroReport* **9**, 2913–2918.

Hopkins, W. D., Russell, J. L. & Cantalupo, C. 2007a Neuroanatomical correlates of handedness for tool use in chimpanzees (*Pan troglodytes*): implication for theories on the evolution of language. *Psychol. Sci.* **18**, 971–977. (doi:10.1111/j.1467-9280.2007.02011.x)

Hopkins, W. D., Taglialatela, J. P. & Leavens, D. A. 2007b Chimpanzees differentially produce novel vocalizations to capture the attention of a human. *Anim. Behav.* **73**, 281–286. (doi:10.1016/j.anbehav.2006.08.004)

Hopkins, W. D., Taglialatela, J. P., Meguerditchian, A., Nir, T., Schenker, N. M. & Sherwood, C. C. 2008 Gray matter asymmetries in chimpanzees as revealed by voxel-based morphometry. *NeuroImage* **42**, 491–497. (doi:10.1016/j.neuroimage.2008.05.014)

Karbe, H., Herholz, K., Weber-Luxemburger, G., Ghaemi, M. & Heiss, W. D. 1998 Cerebral networks and functional brain asymmetry: evidence from regional metabolic changes during word repetition. *Brain Lang.* **63**, 108–121. (doi:10.1006/brln.1997.1937)

Keller, S. S., Highley, J. R., Garcia-Finana, M., Sluming, V., Rezaie, R. & Roberts, N. 2007 Sulcal variability, stereological measurement and asymmetry of Broca's area on MR images. *J. Anat.* **211**, 534–555.

Keller, S. S., Roberts, N. & Hopkins, W. D. 2009 A comparative MRI study of the anatomy, variability and asymmetry of Broca's area in the human and chimpanzee brain. *J. Neurosci.* **29**, 14 607–14 616. (doi:10.1523/JNEUROSCI.2892-09.2009)

Kostovic, I. & Vasung, L. 2009 Insights from *in vitro* fetal magnetic resonance imaging of cerebral development. *Semin. Perinatol.* **33**, 220–233. (doi:10.1053/j.semperi.2009.04.003)

Leinonen, L., Hyvärinen, J. & Sovijärvi, A. R. A. 1980 Functional properties of neurons in the temporo-parietal association cortex of awake monkey. *Exp. Brain Res.* **39**, 203–215. (doi:10.1007/BF00237551)

Moffat, S. D., Hampson, E. & Lee, D. H. 1998 Morphology of the planum temporale and corpus callosum in left handers with evidence of left and right hemisphere speech representation. *Brain* **121**, 2369–2379. (doi:10.1093/brain/121.12.2369)

Naidich, T. P., Hof, P. R., Gannon, P. J., Yousry, T. A. & Yousry, I. 2001 Anatomical substrates of language: emphasizing speech. *Neuroimag. Clin. N. Am.* **11**, 305–341.

Nakada, T, Fujii, Y., Yoneoka, Y. & Kwee, I. L. 2001 Planum temporale: where spoken and written language meet. *Eur. Neurol.* **46**, 121–125. (doi:10.1159/000050784)

Petersen, M. R., Beecher, M. D., Zoloth, S. R., Moody, D. B. & Stebbins, W. C. 1978 Neural lateralization of species-specific vocalizations by Japanese Macaques. *Science* **202**, 324–327. (doi:10.1126/science.99817)

Petrides, M. & Pandya, D. 2009 Distinct parietal and temporal pathways to the homologues of Broca's area in the monkey. *PLOS Biol.* **7**, e1000170. (doi:10.1371/journal.pbio.1000170)

Preuss, T. M. & Goldman-Rakic, P. S. 1991 Architectonics of the parietal and temporal association cortex in the strepsirhine primate *Galago* compared to the anthropoid primate Macaca. *J. Comp. Neurol.* **310**, 475–506. (doi:10.1002/cne.903100403)

Pinker, S. & Jackendoff, R. 2005 The faculty of language: what's special about it? *Cognition* **95**, 201–236. (doi:10.1016/j.cognition.2004.08.004)

Poremba, A., Saunders, R. C., Crane, A. M., Cook, M., Sokoloff, L. & Mishkin, M. 2003 Functional mapping of the primate auditory cortex. *Science* **299**, 568–572. (doi:10.1126/science.1078900)

Poremba, A., Malloy, M., Saunders, R. C., Carson, R. E., Herscovitch, P. & Mishkin, M. 2004 Species-specific calls evoke asymmetric activity in the monkey's temporal poles. *Nature* **427**, 448–451. (doi:10.1038/nature02268)

Rilling, J. K., Barks, S. K., Parr, L. A., Preuss, T. M., Faber, T. L., Pagnoni, G., Bremner, J. D. & Votaw, J. R. 2007 A comparison of resting-state brain activity in humans and chimpanzees. *Proc. Natl Acad. Sci. USA* **104**, 17 146–17 151. (doi:10.1073/pnas.0705132104)

Ringo, J. L., Doty, R. W., Demeter, S. & Simard, P. Y. 1994 Time is of the essence: a conjecture that hemispheric specialisation arises from interhemispheric conduction delay. *Cereb. Cortex* **4**, 331–343. (doi:10.1093/cercor/4.4.331)

Rogers, L. J. & Andrew, J. R. 2002 *Comparative vertebrate lateralization*. Cambridge, MA: Cambridge University Press.

Savage-Rumbaugh, E. S. 1986 *Ape language: from conditioned response to symbol*. New York, NY: Columbia University Press.

Savage-Rumbaugh, E. S. & Lewin, R. 1994 *Kanzi: the ape at the brink of the human mind*. New York, NY: John Wiley.

Savage-Rumbaugh, E. S., Sevcik, R. A. & Hopkins, W. D. 1988 Symbolic cross-modal transfer in two species of chimpanzees. *Child Dev.* **59**, 617–625. (doi:10.2307/1130561)

Schenker, N. M., Hopkins, W. D., Spocter, M. A., Garrison, A. R., Stimpson, C. D., Erwin, J. M., Hof, P. R. & Sherwood, C. C. 2010 Broca's area homologue in chimpanzees (*Pan troglodytes*): probabilistic mapping, asymmetry, and comparison to humans. *Cereb. Cortex* **20**, 730–742. (doi:10.1093/cercor/bhp138)

Shapleske, J., Rossell, S. L., Woodruff, P. W. & David, A. S. 1999 The planum temporale: a systematic, quantitative review of its structural, functional and clinical significance. *Brain Res. Rev.* **29**, 26–49. (doi:10.1016/S0165-0173(98)00047-2)

Slocombe, K. E. & Zuberbuhler, K. 2005 Functionally referential communication in a chimpanzee. *Curr. Biol.* **15**, 1779–1784. (doi:10.1016/j.cub.2005.08.068)

Smiley, J. F., Hackett, T. A., Ulbert, I., Karmas, G., Lakatos, P., Javitt, D. C. & Schroeder, C. E. 2007 Multisensory convergence in auditory cortex, I. Cortical connections of the caudal superior temporal plane in macaque monkeys. *J. Comp. Neurol.* **502**, 893–923. (doi:10.1002/cne.21325)

Sweet, R. A., Dorph-Petersen, K. & Lewis, D. A. 2005 Mapping auditory core, lateral belt, and parabelt cortices in the human superior temporal gyrus. *J. Comp. Neurol.* **491**, 270–289. (doi:10.1002/cne.20702)

Taglialatela, J. P., Cantalupo, C. & Hopkins, W. D. 2006 Gesture handedness predicts asymmetry in the chimpanzee inferior frontal gyrus. *NeuroReport* **17**, 923–927. (doi:10.1097/01.wnr.0000221835.26093.5e)

Taglialatela, J. P., Russell, J. L., Schaeffer, J. A. & Hopkins, W. D. 2009 Visualizing vocal perception in the chimpanzee brain. *Cereb. Cortex* **19**, 1151–1157. (doi:10.1093/cercor/bhn157)

Tomasello, M. & Call, J. 1997 *Primate cognition*. Oxford, UK: Oxford University Press.

Von Bonin, G. & Bailey, P. 1947 *The neocortex of Macaca mulatta*. Urbana, IL: University of Illinois.

West, M. J., Slomianka, L. & Gundersen, H. J. G. 1991 Unbiased stereological estimation of the total number of neurons in the subdivisions of the rat hippocampus using the optical fractionator. *Anat. Rec.* **231**, 482–497. (doi:10.1002/ar.1092310411)

Wildman, D. E., Uddin, M., Liu, G., Grossman, L. I. & Goodman, M. 2003 Implications of natural selection in shaping 99.4% nonsynonymous DNA identity between humans and chimpanzees: enlarging genus. *Homo. Proc. Natl Acad. Sci. USA* **100**, 7181–7188. (doi:10.1073/pnas.1232172100)

Wise, R., Chollet, F., Hadar, U., Friston, K., Hoffner, E. & Frackowiak, R. 1991 Distribution of cortical neuronal networks involved in word comprehension and word retrieval. *Brain* **114**, 1803–1817. (doi:10.1093/brain/114.4.1803)