

Dual streams of auditory afferents target multiple domains in the primate prefrontal cortex

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'What' and 'where' visual streams define ventrolateral object and dorsolateral spatial processing domains in the prefrontal cortex of nonhuman primates. We looked for similar streams for auditory–prefrontal connections in rhesus macaques by combining microelectrode recording with anatomical tract-tracing. Injection of multiple tracers into physiologically mapped regions AL, ML and CL of the auditory belt cortex revealed that anterior belt cortex was reciprocally connected with the frontal pole (area 10), rostral principal sulcus (area 46) and ventral prefrontal regions (areas 12 and 45), whereas the caudal belt was mainly connected with the caudal principal sulcus (area 46) and frontal eye fields (area 8a). Thus separate auditory streams originate in caudal and rostral auditory cortex and target spatial and non-spatial domains of the frontal lobe, respectively.

Anatomical, physiological and neuropsychological evidence suggests that visual information is transmitted as distinct 'what' and 'where' processing streams that ultimately terminate within the frontal lobes^{1–3}. In contrast, attempts to understand higher auditory processing have not yielded as complete a picture as that of the visual system. Frontal as well as temporal lobe regions have been associated with language processing since the discoveries of Broca and Wernicke. Localization of language function to frontal regions has been confirmed and extended by fMRI and PET imaging during the performance of a wide range of auditory and language tasks including auditory working memory, verbal recall, phonological processing, comprehension and semantic judgement^{4–7}. Although anatomical connections exist between the superior temporal gyrus and frontal lobes^{8–14}, functional characterization of the auditory pathways terminating within the prefrontal cortex, including those involved in speech and language processing, remains incomplete.

The primate cortical auditory system in the temporal lobe has a concentric organization¹⁵. The central core region, including primary auditory cortex, is located on the supratemporal plane and is encircled by secondary auditory cortices, the belt areas, which are bordered laterally by a parabelt region^{16–21} (Fig. 1a and b). The lateral belt areas can be distinguished from primary auditory cortex by the presence of neurons with increased responsiveness to complex acoustic stimuli, including band-passed noise and species-specific vocalizations¹⁷, as opposed to pure tones. Indeed, three cochleotopically organized fields separated by frequency reversals, termed anterolateral (AL), middle-lateral (ML) and caudolateral (CL) areas, are mapped within the lateral belt¹⁷. Electrophysiological studies of the superior temporal region in nonhuman primates suggests that its anterior and posterior aspects may differ functionally^{22,23}. Furthermore, differences also

exist between anterior and posterior belt/parabelt connectivity with nearby cortical and thalamic targets^{18–21,24}. These findings raise the possibility that separate thalamocortical and cortico-cortical streams exist in the auditory system just as they do in the visual system^{14,18,25}.

We combined electrophysiological recording and anatomical tract tracing in Old World monkeys (*Macaca mulatta*) to characterize more precisely the pathways by which acoustic information emanating from defined fields of the auditory association cortex may reach higher cognitive processing areas of the frontal lobes. We provide evidence that separate cochleotopic fields in non-primary auditory cortex are connected with distinct spatial and non-spatial domains of the prefrontal cortex in pathways analogous to visual cortical streams.

RESULTS

We recorded from the lateral auditory belt and parabelt cortices in the superior temporal region of four rhesus macaques and determined the best center frequency along each electrode penetration through lateral belt areas AL, ML and CL. The presence of frequency reversals along the anterior-posterior extent of the superior temporal gyrus identified the cochleotopic boundaries of these fields (Fig. 1). The most anterior field, AL, had neuronal responses that ranged from 12.5 kHz at its most anterior edge down to 0.5 kHz where a frequency reversal occurred at its caudal edge, the point where area ML began. The best center frequencies in ML ranged from 0.5 kHz at its rostral edge to 20 kHz caudally just before the frequency reversal that marked the beginning of the caudal field, CL. The best frequencies in CL ranged from 20 kHz to 1 kHz. At the conclusion of the electrophysiological recordings, four to six distinguishable anatomical tracers were distributed among AL, ML and CL. For two of four cases

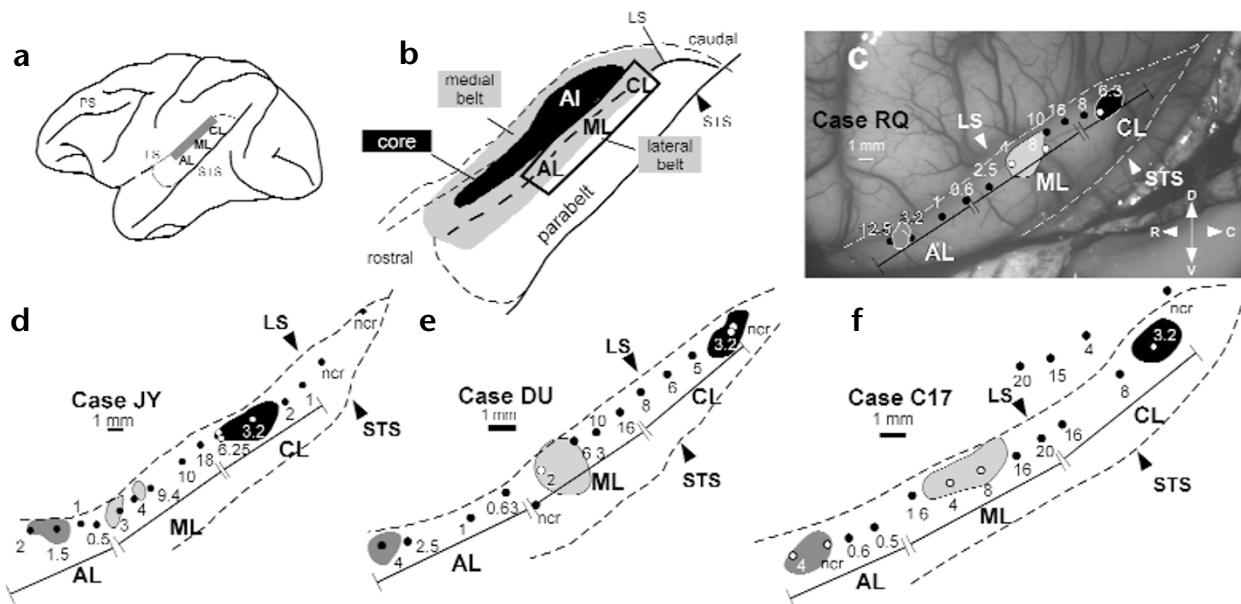


Fig. 1. Tonotopic maps of the lateral belt region recorded in four monkeys. (a) Lateral belt region (shaded in gray) overlies the superior temporal plane and dorsal aspect of the superior temporal gyrus. (b) The same region, enlarged to show the locations of the medial and lateral belt (shaded in gray), primary auditory cortex (AI, black) and the parabelt cortex on the superior temporal gyrus. The portion of the lateral belt recorded from is outlined. (c–f) Physiological maps of the lateral belt recordings from each of the four monkeys in a schematic of the superior temporal region. (c) Photomicrograph taken during the electrophysiological recordings of the lateral belt in case RQ. (d–f) Mappings from the other three cases. The best center frequency for each electrode penetration (black or white dots) is labeled in kHz. Injections of different anterograde and retrograde tracers (shaded regions) for each case are shown with respect to these recordings (for details of tracers in each case see Methods). The boundaries of AL, ML and CL are delineated by a bounded line and are derived from the frequency reversal points. Abbreviations: ncr, no clear response for this electrode penetration; LS, lateral sulcus; PS, principal sulcus; STS, superior temporal sulcus; D, dorsal; V, ventral; R, rostral; C, caudal.

(Fig. 1e and f), a different tracer was injected into the identical frequency region of all three fields, allowing us to determine the possible interactions of region and frequency within the prefrontal cortex. The tracers included both anterograde and retrograde tracers that permitted visualization of whole axonal arbors as they entered different laminae in cortical targets.

In all four experiments, five specific regions of the frontal lobes had labeled retrograde cells and anterograde fibers. These

frontal lobe targets included the frontal pole (Fig. 2a), the principal sulcus, the lateral inferior convexity (Fig. 2b and c), the lateral orbital cortex (Fig. 2b and d) and the dorsal periarculate region. Moreover, these connections were topographically organized such that projections from AL typically involved the frontal pole (area 10), the rostral principal sulcus (area 46), the inferior convexity (areas 12 vl and 45) and the lateral orbital cortex (areas 11, 12o; Fig. 3a, b and e). In contrast, **projections from area CL targeted the dorsal periarculate cortex (area 8a, frontal eye fields) and the caudal principal sulcus (area 46) as well as the caudal inferior convexity (areas 12 vl and 45; Fig. 3b, c and e) and, in two cases, premotor cortex (area 6d)**. The frontal pole (area 10)

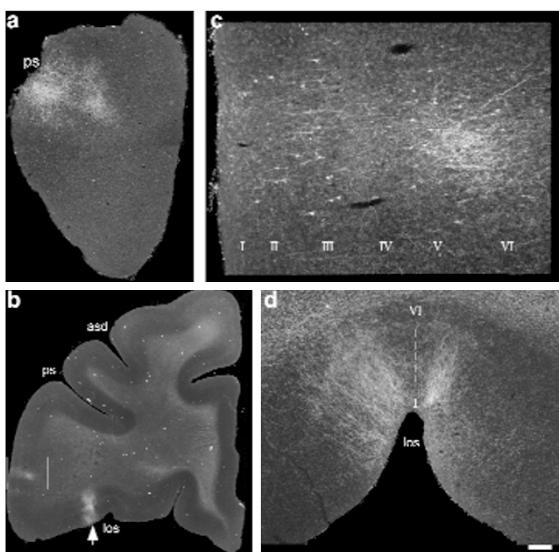
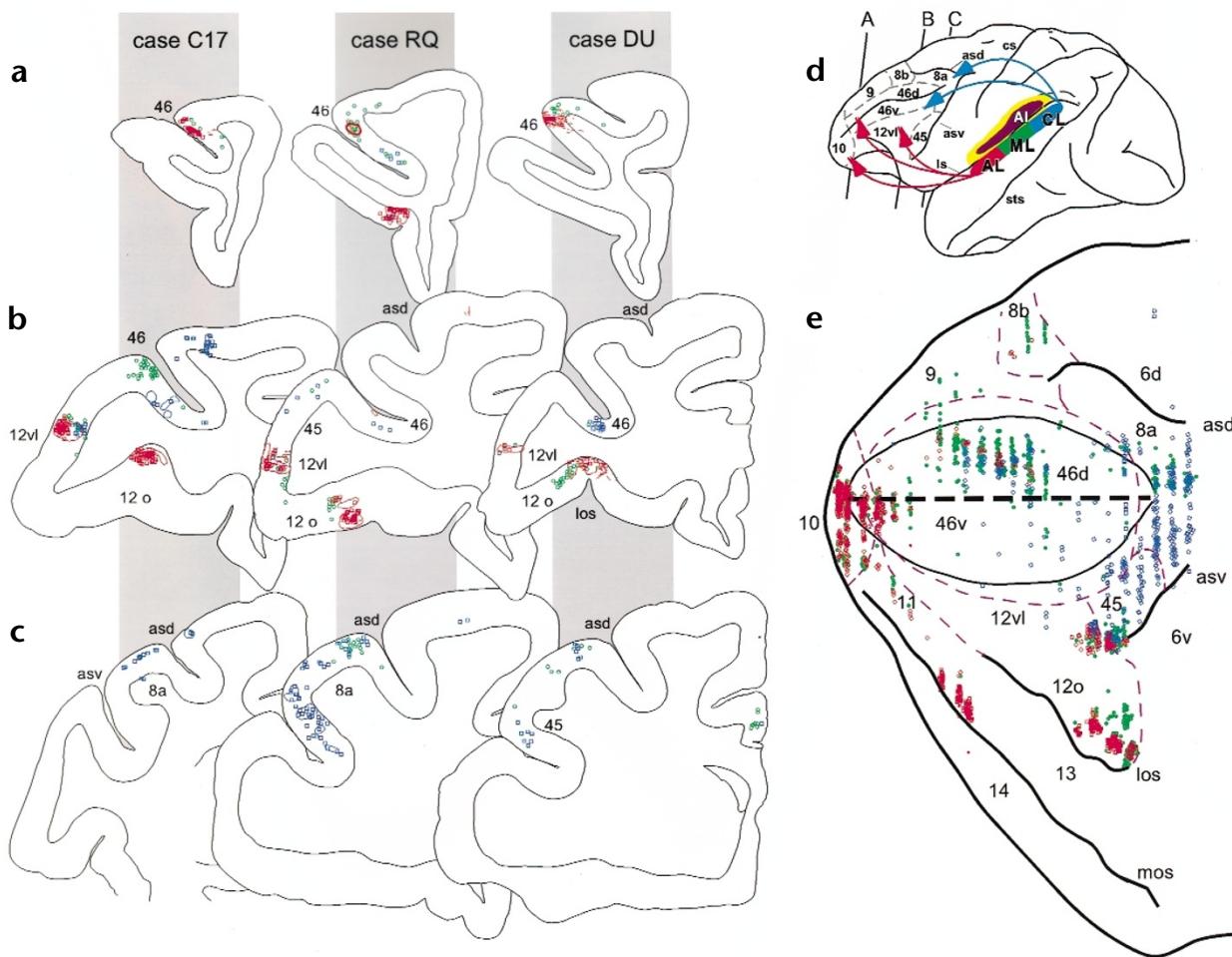


Fig. 2. Photomicrographs of anterograde and retrograde labeling in the rostral and ventral regions of the prefrontal cortex after injections of Fluoro-ruby (a, d; case DU) or Fluoro-Emerald (b, c; case RQ) into area AL. (a) Low-power photomicrograph of anterogradely labeled fibers in a coronal section through the frontal pole region, just anterior to the beginning of the principal sulcus. (b) Low-power photomicrograph from a coronal section with labeling in the lateral inferior convexity (boxed region) and the lateral orbital cortex (arrow). (c) The boxed region at higher power. Cells in layers III and V were retrogradely labeled, whereas anterogradely labeled fibers were seen in layers II, III, V and VI. (d) Photomicrograph of the same lateral orbital region (b; arrow) from a different case (DU), detailing the lateral orbital projections at higher magnification in a coronal section in which they were densest. Labeled axons made columnar terminations spanning all layers (I–VI) at the junction of the lateral orbital sulcus. Scale bar (a) 600 µm; (b) 2250 µm; (c) 250 µm; (d) 425 µm. Abbreviations: asd, dorsal arcuate sulcus; los, lateral orbital sulcus; ps, principal sulcus.



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previous findings^{16,18–20}. Projections from areas AL and ML were densest within the rostral parabelt and rostral temporal lobe, including the rostral supratemporal plane. In contrast, the posterior parietal cortex areas 7a and 7ip were labeled from injections only in CL. In addition, the medial belt regions and the caudal half of the dorsal bank of the superior temporal sulcus received dense projections from areas ML and CL but only light projections from AL.

DISCUSSION

Combining electrophysiological recording and anatomical tracing, we demonstrated two pathways originating in separate, non-primary, cochleotopic auditory fields of the superior temporal region and terminating in distinct regions of the frontal lobes (Fig. 3d). One pathway, originating in CL, targets caudal dorsolateral prefrontal cortex (DLPFC); the other pathway, originating in AL, targets rostral and ventral prefrontal areas. Because these dorsal and ventral prefrontal regions are respectively characterized as spatial and non-spatial functional domains^{2,27–29}, a possible interpretation is that these separate streams originating from posterior and anterior auditory belt and parabelt cortices are analogous to the 'where' and 'what' streams of the visual system. Although topographic connections between the auditory belt and parabelt cortex and the prefrontal cortex are demonstrated^{13,14}, these purely anatomical studies are less compelling than the present study in that, without physiology, they could not identify the separate origins of possible auditory streams. We combined the physiological identification of separate auditory cortical fields with multiple injections of anterograde and retrograde anatomical tracers in a nonhuman primate.

The DLPFC is essential in visuospatial working memory, as demonstrated by electrophysiological recording and lesions in primates^{27–29} and by imaging in humans^{30,31}. Here we showed that the DLPFC also receives auditory afferents from the caudal auditory belt region, suggesting its involvement in auditory processing as well. This is supported by previous studies in nonhuman primates demonstrating that neurons in DLPFC respond to acoustic stimuli and that lesions of the periarcuate and dorsolateral cortex impair auditory conditional responses^{32–35}. Specifically, electrophysiological recordings show that the responsiveness of acoustic neurons in the DLPFC depends on sound-source location³³ and that auditory neurons in the periarcuate region are more active during auditory localization than during passive listening³⁴. Furthermore, neuroimaging studies demonstrate involvement of the DLPFC in sound localization in humans³⁶.

Evidence suggests that neurons in the caudal superior temporal region are sensitive to sound-source location^{22,23,25} in the same way as their target region, the DLPFC. Neurons in CL and AL have been directly compared for their sensitivity to sound location and for their selectivity for monkey vocalizations (J.P.R., A. Durham, A. Kustov, A. Lord & B. T., *Soc. Neurosci. Abstr.* 25, 157.2, 1999). Neurons in AL of anesthetized monkeys presented with acoustic stimuli (consisting of vocalizations and band-passed noise from a variety of different azimuth locations in free field) show better selectivity for particular monkey calls, whereas neurons in CL had significantly narrower spatial tuning. These results confirm previous studies^{22,23} and support the notion of an auditory spatial stream originating in the caudal belt and parabelt region and targeting the DLPFC. The caudal belt and parabelt are also connected to the DLPFC via the posterior parietal cortex, which is itself involved in the localization of both visual and auditory signals^{36–39}.

In addition to this dorsal (and potentially 'spatial') auditory pathway, we present evidence for a second auditory stream originating in the anterior belt and parabelt region and terminating in the rostral and ventral frontal lobe. Neuroimaging studies demonstrate involvement of the frontal pole (area 10) of the rostral frontal lobe in verb generation, auditory working memory and musical consonance^{4,7,40}.

Neuropsychological research and imaging studies firmly establish involvement of the ventral frontal lobe, including Broca's area and the inferior frontal gyrus, in non-spatial, higher auditory and language processing^{4–7,41}. Our results substantiate findings of a connection between the ventral prefrontal cortex and anterior auditory cortical regions^{10,14,42}. Ventrolateral frontal lobe regions 12 and 45, which make up the inferior convexity in the nonhuman primate, are situated just anterior to area 6, the premotor cortex⁴³; it is suggested, on the basis of anatomical location and connections, that they represent the macaque homolog of Broca's area⁴². Disruption of auditory discrimination performance by lesions of the ventrolateral prefrontal cortex that include the prefrontal inferior convexity or ventral arcuate region^{44–46} implies a link between the nonhuman primate ventral frontal lobe and higher auditory processing. Electrophysiological studies also provide some evidence of auditory-responsive neurons in the ventrolateral prefrontal cortex^{47–49}. Prefrontal auditory neurons are generally observed as sparsely distributed over a widespread region of the lateral frontal lobe, although in one study, responses of anesthetized monkeys to simple auditory and visual stimuli were localized to the lateral orbital cortex⁴⁹. In contrast, there is substantial evidence of a visual object domain physiologically localized to the inferior convexity region, which has neurons that robustly respond to pictures of objects, patterns and faces^{2,50}. Visual physiology together with earlier lesion studies and our present anatomical evidence suggest that the ventrolateral prefrontal cortex may also be devoted to auditory 'pattern' or 'object' processing in the nonhuman primate. Further physiological analysis of ventral prefrontal cortex is needed to examine this possibility.

Our findings also relate to general theories of frontal lobe organization. The observation that both auditory and visual modalities are represented in similar regions of the frontal lobe supports the functional domain hypothesis, which stresses that the frontal lobe is organized into separate dorsolateral spatial- and ventrolateral object-processing regions^{27,29}. These domains, specified by distinct afferent inputs, including those presented here, are functionally distinct but extend across modalities.

METHODS

Surgery and electrophysiological recordings. Four rhesus macaques (*Macaca mulatta*) were used. All methods were in accordance with NIH Guidelines for the Care and Use of Laboratory Animals. Surgical and recording methods were as described previously^{17,19}. Electrophysiological recordings were made in macaques anesthetized with isoflurane (1–2%) in a nitrous oxide/oxygen mixture (50:50). The bone overlying the superior temporal gyrus was removed under aseptic surgical conditions and lacquer-insulated tungsten microelectrodes were placed into the belt cortex of the superior temporal region. Auditory stimuli, including pure tones and band-passed noise (BPN) bursts, were produced using the program SIGNAL (Engineering Design, Belmont, Massachusetts) and presented to the anesthetized monkey. The auditory stimuli were delivered through a power amplifier to a single loudspeaker (Infinity Kappa 5) placed 1.14 m. in front of the monkey. The sound pressure level of the stimuli (measured with a Brüel & Kjaer half-inch condenser microphone and a B & K precision sound level meter) measured at the monkey's head, varied between 60 and 85 dB SPL. The position of each

electrode track was digitally acquired (NIH Image) and aligned using blood vessels as reference landmarks (Fig. 1c). Neuronal spike activity was collected, stored and analyzed on a personal computer (Pentium, IBM-compatible). Raster displays and peristimulus time histograms were generated and evaluated in response to the various auditory stimuli. Stimuli were repeated 10–20 times in blocks of 7 different stimuli. An average of 14 electrode tracks per monkey were distributed across the lateral belt cortex of the superior temporal region. At least three responses from single and multiple units were sampled along each electrode track along a depth of approximately 2 mm. A best center frequency (BF_c) was calculated for each penetration by averaging the responses to pure tone and BPN stimuli. Maps of the BF_c for each experiment are shown in Fig. 1.

Injects of both anterograde and retrograde anatomical tracers were made in each of the four monkeys at the end of the electrophysiological recordings. One or two different tracers were placed into AL, ML and CL, respectively (Fig. 1c–f). The fluorescent tracers Fast Blue (FB), Diamidino Yellow (DY), Fluoro-Ruby (FR) and Fluoro-Emerald (FE) and the tracer BDA (biotinylated dextran amine) were pressure-injected via a Hamilton syringe (200–300 nl per injection, 2 injections per site) or via a glass cannula with a tip diameter of 30 μ m (150–300 nanoliters per injection, 2 injections per site). Phaseolus leucoagglutinin (Pha-L; Sigma) was iontophoresed for 20 min at 7.2 μ A. The tracers and areas injected in each case were as follows. In case RQ, DY and FE were placed between the 12.5 and 3.2 kHz regions of AL; FB and Pha-L in the 4 kHz region of ML; FR in the 6.3 kHz region of CL. In case JY, FB was placed in the 1.5 kHz region of AL, FR and BDA in the 3 and 8 kHz region of ML and DY in the 3 kHz region of CL. In case DU, FR was placed in the 4 kHz region of AL, DY and BDA in the 4 kHz region of ML and FB in the 4 kHz region of CL. In case C17, FE was placed in the 4 kHz region of AL, FB in the 4 kHz region of ML and FR in the 4 kHz region of CL.

Histology and tissue processing. Monkeys were perfused with 4% paraformaldehyde 10–21 days after recording. Brains were blocked, sunk in increasing sucrose gradients, snap frozen in isopentane and cut at 40 μ m on a cryostat. Seven of every ten sections were immediately processed and three sections were saved in freezing medium at 4°C. In a series of ten sections, two or three were immediately mounted onto slides, stored at 4°C and examined for fluorescent labeling. Additional series of sections were processed as follows: one was stained with cresyl violet or thionin, one was stained with parvalbumin (antibody from Sigma, 1:7500 concentration), one was immunohistochemically processed with an antibody to fluoro-ruby and one was immunohistochemically processed with an antibody to fluoro-emerald (cases RQ and C17) or stained for BDA (case JY). In case RQ, one series was immunohistochemically processed for Pha-L. Described cytoarchitectonic borders⁴³ were estimated from adjacent Nissl sections and sulcal landmarks.

Charting and analysis. Fluorescent labeling in frontal and temporal lobes was examined in coronal sections spaced at 200 μ m. Immunohistochemistry for tracers was more sensitive than fluorescence and rendered labeled cells, particularly the anterograde fibers, less susceptible to fading and photo-bleaching. Therefore, anterograde and retrograde labeling with tracers FR and FE were charted from immunohistochemically processed sections; labeling was confirmed by fluorescence in unprocessed sections. Labeled sections were charted every 400 μ m with the Neurolucida plotting system on a Zeiss Axiophot coupled to an LEP stage.

Some temporal sections were also digitally captured with a Spot 2 (Medical Instruments, Germany) video camera. Analysis of the injection sites (Fig. 1) verified that the tracer injections were located on and confined to the dorsal aspect of the superior temporal gyrus and superior temporal plane from which the recordings were made. Tracer injections that spread into the ventral superior temporal gyrus or the superior temporal sulcus were not included in our analysis. Coronal sections were aligned to standard atlas drawings converted to lateral brain schematics of the superior temporal region (Fig. 1). We designated the region recorded and subsequently injected as the lateral belt region based on physiological classification of this non-primary auditory region demonstrated previously¹⁷. However, some injections may have included portions of the parabelt, whose boundaries are not yet physiologically defined in detail.

The flat map in Fig. 3e is based on the method of Barbas¹². After mapping anterograde fibers and retrograde cells from coronal sections using the Neurolucida Digital plotting system, a line was drawn through the midpoint of the cortex, approximating layer IV throughout the entire perimeter of the digitized coronal section. This line was then extrapolated to the vertical. Labeled cells and fibers, as well as cytoarchitectonic boundary lines were maintained in appropriate spatial location during this translation. Each coronal section was then aligned along the fundus of the principal sulcus and other sulcal landmarks. Using the drawing program Canvas (ver. 5.0, Deneba), vertical section lines were removed and sulcal boundaries were smoothed, leaving behind retrograde and anterograde plots. Because the anterograde and retrograde labeling were localized to the same regions, lines depicting anterograde labeling were removed for clarity.

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