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Distinct core thalamocortical pathways to central and dorsal primary auditory cortex

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Abstract

The cat primary auditory cortex (AI) is usually assumed to form one continuous functional region. However, the dorsal and central parts of the AI iso-frequency domain contain neurons that have distinct response properties to acoustic stimuli. In this study, we asked whether neurons projecting to dorsal versus central regions of AI originate in different parts of the medial geniculate body (MGB). Spike rate responses to variations in the sound level and frequency of pure tones were used to measure characteristic frequency (CF) and frequency resolution. These were mapped with high spatial density in order to place retrograde tracers into matching frequency regions of the central narrow-band region (cNB) and dorsal AI. Labeled neurons projecting to these two parts of AI were concentrated in the middle and rostral thirds of the MGB, respectively. There was little evidence that differences in dorsal and central AI function could be due to convergent input from cells outside the ventral division of the MGB (MGBv). Instead, inputs arising from different locations along the caudal-to-rostral dimension of MGBv represent potential sources of response differences between central and dorsal sub-regions of AI.

1. Introduction

Core auditory cortices are an essential first level of cortical processing of sound location, context and pattern and yet their functional organization has not been fully elucidated (Griffiths and Warren, 2004; King and Nelken, 2009; Rauschecker et al., 1997; Schreiner and Winer, 2007). All core auditory cortices receive thalamic input primarily from the ventral division of the medial geniculate body (MGBv) and have a topographic or cochleotopic organization of short latency characteristic frequency (CF) responses reflecting response topography of the sensory epithelium of the ear (Hackett, 2010). Though core regions share common features, such as a global cochleotopic organization and relatively short response latencies, they are also functionally specialized. Three core regions have been defined in several smaller mammals (i.e., primary (AI), anterior (AAF) and ventral (VAF) auditory fields (Hackett, 2010)) and in primate auditory cortex (AI, rostral (R) and rostral

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temporal (RT) fields (Hackett et al., 2001)). The cochleotopic gradient direction, and cortical area representing one octave can differ across neighboring core regions. For example, the direction, magnitude and frequency composition of cochleotopy, the spectral resolution and temporal response properties are different in AI versus AAF (Bizley et al., 2005; Imaizumi et al., 2004; Polley et al., 2007; Schreiner and Winer, 2007). On its ventral border, AI shares one continuous cochleotopy with VAF in cat and rat and its possible homologue, the posterior suprasylvian field (PSF), in ferret (Bizley et al., 2005; Kalatsky et al., 2005; Reale and Imig, 1980). Neighboring ventral core regions in small mammals have distinct and complementary response latencies, spectral resolutions, sound level tuning, and sensitivities to sound position cues without pronounced differences in cochleotopy (Bizley et al., 2005; Higgins et al., submitted for publication; Polley et al., 2007; Storace et al., 2010b). Primate core regions also have distinct and complementary sound sensitivities with or without marked differences in cochleotopy (Bendor and Wang, 2008; Recanzone et al., 2000).

Functional specializations can exist within sub-regions of a single core area. In the cat, AI is defined by a single cochleotopic organization, and yet sound frequency, level and binaural sensitivities vary systematically along its dorso-ventral or “iso-frequency” axis (Ehret and Schreiner, 1997; Mendelson et al., 1993; Middlebrooks and Zook, 1983; Nakamoto et al., 2004; Phillips et al., 1994; Read et al., 2001; Schreiner and Mendelson, 1990; Semple and Kitzes, 1993a). Dense multi-unit mapping studies find AI is divided into central and dorsal parts that can be further subdivided into smaller regions with distinct spectral bandwidths and corresponding spectral resolutions including: the central narrow (cNB) and broad (cBB) bandwidth regions and dorsal narrow (dNB) and broad (dBB) bandwidth regions (Schreiner et al., 2000). The cNB region has the highest spectral resolution (Q factor) measured with sound level at 40 decibels above threshold (Q_{40}). A small dNB region has higher spectral resolution than adjacent cBB and dBB regions but lower median spectral resolution than the cNB region (Imaizumi and Schreiner, 2007; Read et al., 2001; Schreiner et al., 2000). The cNB region covers a larger dorso-ventral cortical area than the frequency-matched dNB region creating a magnified representation of narrow bandwidths in central AI, as quantified with two-dimensional autocorrelations and linear cortical magnification factors (Imaizumi and Schreiner, 2007; Read et al., 2001). The dNB region has higher spatial variation or “scatter” of CF and a lower median tuning resolution (i.e., lower Q_{40}) than the cNB region (Ehret and Schreiner, 1997; Schreiner et al., 2000). Each narrow and broad bandwidth region is associated with a corresponding local maxima or minima in the topographic Q_{40} map of AI, quantified with two-dimensional autocorrelation (Read et al., 2001). This spatial organization allows for multiple representations of high and low spectral resolution in central and dorsal AI (Imaizumi and Schreiner, 2007) without marked differences in cochleotopy.

Differences in frequency tuning for central versus dorsal AI could, in principle, stem from differences in feed-forward projections from the thalamus (de la Rocha et al., 2008; Liu et al., 2007; Miller et al., 2001; Series et al., 2004; Wu et al., 2008). The present study investigates MGBv and non-MGBv pathway connections as possible sources of response property differences between cNB and dorsal AI. Response differences could arise from MGBv connections, as frequency response resolution and frequency laminar organization have been shown to vary along the caudal-to-rostral dimension of MGBv in several mammals (Calford, 1983; Cant and Benson, 2007; Rodrigues-Dageaef et al., 1989; Rouiller et al., 1989; Storace et al., 2010a, b). Alternatively, response differences in dorsal AI could be due to connections with non-MGBv nuclei that are characteristic of the neighboring dorsal zone (DZ) belt region in the cat (He and Hashikawa, 1998; Lee and Winer, 2008). Here we present evidence that response differences across central and dorsal AI predominately stem from differences in MGBv source location.

2. Methods

2.1. Surgery and recording

Cats were housed and handled according to approved guidelines by the Institutional Animal Care and Use Committee (University of California at San Francisco). Data examined here were obtained from four adult cats purchased from an approved vendor.

Previously, we described the corticocortical and thalamocortical connections to the cNB region for five animals (Read et al., 2008, 2001). The aim of the present study was to characterize thalamocortical connections to dorsal AI in three of these previously described cases (Read et al., 2008, 2001). We also review the areal patterns of cNB-projecting neurons for a fourth cat, case 591, that has been quantified previously (Read et al., 2008). Single- and multi-unit responses to a five-octave range of pure tone stimuli were recorded in layers IIIb and IV of AI in ketamine-anesthetized adult cats. Transient (100 ms duration, 3 ms rise time) pure tones were presented with identical sound pressure level and frequency to both ears and varied pseudo-randomly over a 70 dB and five-octave range, respectively. Single and multi-unit spike rate responses within the 100 ms tone presentation window were averaged across repeat sound conditions to generate a tone frequency response area (FRA). Parameters measured from the FRA include the sound frequency eliciting a response at the lowest threshold of all tested frequencies (i.e., CF), linear bandwidth, and tuning resolution (i.e., Q factor). Linear bandwidth was estimated as the difference between upper and lower frequency limits of the FRA at 40 dB above threshold and its inverse normalized to CF was computed as a metric of tuning resolution ($Q_{40} = \text{CF}/\text{band-width}$). Maps of CF and Q_{40} measured at each recording position were plotted, tessellated and spatially smoothed. The location and size of cNB and dNB and surrounding regions for three hemispheres of AI described here have been reported previously (Read et al., 2008, 2001). The Q_{40} map obtained in the fourth hemisphere for injection of cNB region is not illustrated.

2.2. Tracers and histology

Surgical and histological methods have been described in detail previously (Read et al., 2008, 2001). Retrograde tracers were wheat-germ agglutinin apo-horseradish peroxidase conjugated to colloidal gold (WAHG) (Basbaum and Menetrey, 1987), cholera toxin B subunit (CTB, List Biological Laboratories, Campbell, CA), and cholera toxin B subunit conjugated to gold particles (CTBG, List Biological Laboratories, Campbell, CA) (Luppi, Fort et al., 1990). Single WAHG or CTB injections were made in physiologically mapped cNB and dorsal AI in the right cerebral hemispheres of three cats. cNB and dorsal AI injections were made into regions with matched CF (± 0.5 octaves) and matched Q_{40} (> 1). In a fourth cat (case 591), CTB and CTBG were deposited into 4 and 12 kHz iso-frequency contours within the confines of cNB in a single hemisphere. Post-tracer survival in all cases was 3.5 (± 1) days.

Following transcardial saline and formalin perfusion, brains were removed and the cortex was flattened and separated from thalamus. Fixed tissue was cut into 40 μm coronal sections. An adjacent series of sections was Nissl-stained with cresyl violet and examined microscopically to determine medial, ventral, dorsal and supragenulate (SG) divisions of the MGB thalamic nuclei corresponding to prior cytoarchitectonic studies (Morest, 1964). Anatomic features used to delineate borders included fiber bundles, laminar pattern, somatic cell size, and orientation. Nuclear borders corresponded well with similar studies (Middlebrooks and Zook, 1983; Winer, 1985) and standard references (Berman, 1982). Histological processing methods are detailed elsewhere (Read et al., 2008, 2001). WAHG and CTBG labeling were intensified with silver for light microscopy. Alternating adjacent sections were processed for single and dual tracers and compared confirming matched cell

distribution patterns under both processing conditions. Tracer deposit measures and thalamic cell position plots were taken from dual reacted tissue. Cortical injection deposit measurements were made from photomicrographs of the flat sections of cortex ~960 μm from the flat mount surface. Circles were fit to the deposit alone and to the dense halo of label perimeter. The diameter and radius were used as metrics of injection size and area; the shortest distance between the deposit centers was used to estimate injection separations. A photomicrograph documents deposit and halo perimeters in case 591 (see Read et al., 2008). In this case, the radii of CTB (low CF) and CTBG (high CF) deposit halos were both 350 μm (diameters = 700 μm); centers were separated by 1.25 μm , and deposit perimeters were separated by 550 μm . Area and separation between all deposit perimeters and halo perimeters were estimated from the 40 μm sections of flattened cortex.

2.3. Data analysis

Cell distributions were examined across caudal-to-rostral dimension and nuclear divisions of the thalamus. Neuron cell body positions were plotted with high spatial precision utilizing a mechanically driven stage while viewing the histology with a light microscope and a 40–60 $\times$ objective lens. Horizontal mediolateral (x) and inferior–superior (y) thalamic position coordinates were measured and mapped in an xy coordinate frame-work for each cell body with the NeuroLucida software package (MicroBrightField, Colchester, VT). A fiduciary mark, fiber bundles, blood vessel artifacts and the perimeters of each section were outlined. Adjacent sections of Nissl-stain and histochemically treated tissue were overlaid and scaled to align blood vessel artifacts and thalamic section outlines. In this way, nuclear divisions determined from Nissl-stained section could be aligned with labeled cell position plots to analyze corresponding nuclear distributions. Data were imported into custom MATLAB (Math-works, Inc) programs to quantify cell numbers and distributions within each cytoarchitectonic division and section. The average total number of cells labeled in seven sections was 570 (± 167) and 1466 (± 566) in cNB and dorsal AI, respectively.

3. Results

3.1. Organization of tone response properties in central and dorsal AI

Cortical spike rate responses to pure tones are organized into topographically orthogonal gradients for CF and frequency resolution in AI of the cat (Imaizumi and Schreiner, 2007; Read et al., 2008, 2001). An exemplar map illustrates a single gradient increase from low-to-high (blue-to-red) CFs observed with caudal-to-rostral shifts in AI recording position (Fig. 1A). CF does not change greatly in the dorso-ventral dimension resulting in continuous “iso-frequency” or “iso-CF” contours (Fig. 1A, see black overlaid contours) and similar CF gradient directions for central and dorsal AI (Imaizumi and Schreiner, 2007). In contrast, frequency bandwidth and tuning resolution (Q_{40}) change along the iso-CF dimension. Central (cNB, $Q_{40} \geq 1$) and dorsal (dNB) narrow bandwidth regions are flanked by two broader band-width regions ($Q_{40} < 1$, Fig. 1B, blue regions). This spatial pattern of frequency resolution results in separate high-to-low directed Q_{40} gradients in central and dorsal AI, as quantified in a separate set of densely mapped hemispheres (Imaizumi and Schreiner, 2007) and evident in the alternating pattern of NB and BB regions in four mapped hemispheres considered here (e.g. Fig. 1B).

3.2. Frequency organization of thalamic cells projecting to cNB region

Before describing the character of thalamic connections with dorsal AI, we will review previous findings about the basic frequency organization of thalamic cells projecting to physiologically defined cNB region of AI (Read et al., 2008). Thalamic cells that project to the cNB region predominately are located in MGBv and have a heterogeneous frequency organization and size distribution within MGBv. Retrograde tracer deposits in the cNB

region label neurons in inferior (iMGBv) and superior (sMGBv) halves of the MGBv (Read et al., 2008) as illustrated in an example case where CTB and CTBG were injected into low (4 kHz) and high (12 kHz) iso-CF contours of the cNB region, respectively, in one hemisphere (Fig. 2). A high magnification image illustrates the label pattern in the iMGBv region (Fig. 3). Soma sizes of labeled neurons in iMGBv are, on average, larger than those located in the sMGBv (Read et al., 2008). These large somas iMGBv cells typically have “tufted spindle” and stellate morphologies (Fig. 4). Unlike the magnocellular neurons in the medial nucleus of the MGB, projection neurons in sMGBv and iMGBv are frequency organized (Figs. 2 and 3) (Read et al., 2008): Cells projecting to low (4 kHz) and high (12 kHz) iso-CF contours are located in lateral and medial parts of the MGBv, respectively, revealing a frequency organization of projection neurons very closely resembling that of single unit CF responses recorded in the MGBv (Calford, 1983; Imig and Morel, 1985). Some differences exist for the frequency organization in iMGBv and sMGBv. Cells projecting to low and high iso-CF contours in the cNB formed “frequency lamina” that abut one another in iMGBv but were separated in sMGBv by a gap containing unlabeled cells (Fig. 2A, double-headed arrow) and persisting in several neighboring sections along the caudal-to-rostral axis (Fig. 2A–C, arrows). Presumably these gap neurons project to intermediate iso-CF contours in cNB region and do not provide input to either injected region. Poor separation between frequency lamina in iMGBv (Fig. 3A) could stem from increased thalamic axon arborization within cortex or decreased frequency lamina order within MGBv. In either case, it suggests a coarser frequency organization of iMGBv projection neurons. Some double-labeled neurons were observed in iMGBv that presumably sent branched projections to both 4 and 12 kHz iso-CF contours of the cNB region (Fig. 3B, arrow). These differences in frequency lamina separation for sMGBv and iMGBv are compatible with properties of CF maps for this caudal-rostral position of MGBv (Escabi and Read, 2005; Imig and Morel, 1985).

3.3. Tracer injections into cNB and dorsal AI

In the present study, we injected two different retrograde tracers into cNB and dorsal AI to determine whether the same nuclear divisions and caudal-rostral sections of MGB project to these two cortical sub-regions. The boundaries of cNB and dorsal AI for injection were determined by mapping CF and Q_{40} , as described above (Fig. 1A, B). In the example Q_{40} map, the spatial separation between cNB and dNB regions (and therefore central and dorsal AI) was 1.7 mm (e.g. Fig. 1B). For three injected animals, the average diameters of cNB and dorsal AI deposits were $467 (\pm 24) \mu\text{m}$ and $450 (\pm 71) \mu\text{m}$, respectively (e.g., Fig. 1C, dotted circle). The corresponding halos were $758 (\pm 120) \mu\text{m}$ and $752 (\pm 214) \mu\text{m}$, respectively. The deposit centers were on average separated by $1.31 (\pm 0.365) \text{mm}$. Deposit position and area markers from histological sections of flattened cortex were scaled, aligned and overlaid with physiological maps using blood vessels and electrolytic lesions (e.g. Fig. 1A, B). All deposits in central AI were confined within the boundaries of the cNB region (e.g. Fig. 1B, cNB). Though injections in dorsal AI were primarily within the dNB compartment in all cases, the perimeter of label deposit (dotted circle) extended into neighboring broad bandwidth regions (blue regions, Fig. 1B) as evident in this example map due to the small dorso-ventral extent of the dorsal narrowband regions (dNB).

3.4. Areal patterns and rostrocaudal positions of MGB cells

Cells projecting to cNB and dorsal AI had overlapping spatial distributions at the rostrocaudal level (Fig. 5) where cells were densely packed into a single “frequency lamina” spanning superior and inferior halves of MGBv. This coronal section of MGB contained the majority of cNB-projecting neurons but fewer dorsal AI-projecting neurons in all cases. Most double-labeled neurons were located in this section (Fig. 5, arrows).

The cat MGB extends approximately 4 mm in the caudal-to-rostral dimension. Here, only the rostral 3 mm of thalamus were examined as all but a few labeled neurons were within this range. The majority of cNB-projecting neurons (black filled circles) were located caudal to the majority of dorsal AI-projecting neurons (red filled circles) (Fig. 6). Dorsal AI-projecting cells in rostral MGBv were distributed in both pars ovoidalis and pars lateralis (Fig. 6, section 4, double arrows) over an area where thalamic neuron CF responses are known to range from 4 to 32 kHz in the cat (Calford, 1983; Imig and Morel, 1985). Twelve dorsal AI-projecting cells (red filled circles) also were located in the rostral pole (RP; Fig. 6, section 7) of MGB where most AAF projecting neurons are found (Lee et al., 2004a; Lee and Winer, 2008; Morel and Imig, 1987).

For all three injected cortices, most cells projecting to cNB region were located in the middle third of MGB corresponding to sections 1–3 in the series examined (Fig. 7A–C, black bars). The distribution of cells projecting to dorsal AI was overlapping but shifted about 480 μ m in the rostral direction (Fig. 7A–C, gray bars). Only 4% of cells were double-labeled.

3.5. Distribution of cells in MGB divisions

The DZ auditory cortex on the dorsal border of AI in the cat is considered a belt cortex and receives its primary feed-forward thalamic input from MGBd and RP (He and Hashikawa, 1998; Lee and Winer, 2008). Here we compared the distribution of labeled cells in the different divisions of MGB to determine whether the thalamic connections of dorsal AI resemble DZ or cNB projections. MGB divisions were determined with cytoarchitectonic assessment of adjacent Nissl-stained sections and reconstructed (see Fig. 6 and Read et al., 2008). Cell counts were compared, for each label type within each division, for 7 sections in three dual injection cases. Less than 5% of cNB or dorsal AI-projecting neurons were found in the SG, MGBm, or RP nuclear divisions of MGB (Fig. 7D). Significantly more (~73%) of cNB and dorsal AI-projecting cells were located in MGBv than any other division (Fig. 7D, $p < 0.001$). This pattern of thalamocortical divisions projecting to dorsal AI more closely resembles that of the cNB core region than of the DZ belt region (see He and Hashikawa, 1998; Lee and Winer, 2008), underscoring its distinction from DZ.

4. Discussion

The present study supports an organizational scheme where feed-forward thalamocortical pathway distinctions contribute to cortical area and sub-area formation and specializations (Hackett, 2010; Lee and Winer, 2005; Middlebrooks and Zook, 1983; Schreiner and Winer, 2007). We investigated whether distinctions in sound frequency sensitivities of central and dorsal AI could stem from differences in MGBv or non-MGBv pathway connections. The majority of neurons projecting to both regions were found to be located in MGBv, supporting the view that both parts of AI are core auditory regions and that dorsal AI is distinct from DZ belt cortex. Less than twenty percent of neurons projecting to either cortical region were located in non-MGBv nuclei (Fig. 7D). Most MGBv neurons projecting to cNB and dorsal AI were located within the middle and rostral thirds of MGBv, respectively (Fig. 7A–C). The majority (96%) of neurons were labeled with only one tracer, indicating a nearly complete segregation of these ascending thalamocortical pathways. The medial-to-lateral spread of neurons projecting to dorsal AI was spatially more confined in middle MGBv as compared to that of rostral MGBv. If the medial-to-lateral spread in MGBv projection neurons reflects the frequency convergence to cortex, then the majority of input to dorsal AI is highly convergent; whereas thalamic input to the cNB region is more frequency-specific. This suggests that differences in frequency resolution and CF scatter between dorsal AI and the cNB region could stem from corresponding pathway differences in organization along the caudal-to-rostral dimension of MGBv.

A portion of the dorsal AI-projecting neurons was located in central MGBv where coarse (iMGBv) and fine (sMGBv) frequency organized laminae converge their inputs onto the cNB region. In a prior study (Read et al., 2008), we suggested that convergence of iMGBv and sMGBv onto the cNB region could account for the variety of binaural response properties observed in this region including those with excitatory (EE type) or facilitatory binaural interaction (Middlebrooks and Zook, 1983; Nakamoto et al., 2004; Phillips et al., 1994; Semple and Kitzes, 1993a, b). A similar convergence could contribute to narrow tuning properties found within the dNB region of dorsal AI. A computational model finds that sharp frequency and intensity tuning of cortical neurons can be created by convergent feed-forward excitatory and inhibitory input that is CF-matched but not bandwidth matched (de la Rocha et al., 2008). This intracortical circuit model is consistent with matched feed-forward excitatory and inhibitory response properties in auditory, somatosensory and visual cortices (Ben-Yishai et al., 1995; Inoue and Imoto, 2006; Tan et al., 2004; Wehr and Zador, 2003). According to this model, convergence of iMGBv and sMGBv onto single cNB pyramidal and neighboring cortical inhibitory neurons could, in principle, create the sharp frequency- and intensity-tuning characteristic of many neurons in the NB regions. Thalamocortical convergence patterns described here are also consistent with an alternate scheme where neurons within iMGBv and sMGBv have spatially limited axon arborization and non-overlapping terminal fields that impart a continuous range of frequency convergences in parallel onto their cortical targets and never converge onto a single common cortical neuron. The alignment of CF and spectrotemporal receptive field similarities between pairs of single neurons in AI and MGBv also are consistent with both models of convergence (Miller et al., 2001). Ultimately, a different approach than taken here is needed in order to determine the convergence of iMGBv and sMGBv inputs onto cNB and dorsal AI neurons.

Frequency lamina organization changes along the caudal-to-rostral dimension of MGB in several mammals (Cant and Benson, 2007; Cetas et al., 2001; Imig and Morel, 1985; Redies et al., 1989; Rodrigues-Dageaff et al., 1989; Rouiller et al., 1989), as suggested in the present study and summarized in Fig. 8. Here, injections into cNB or dorsal AI (Fig. 8A) resulted in minimal label in the caudal third of thalamus that is predominantly occupied by the caudal dorsal division (MGBcd) of MGB (Fig. 8B). As discussed above, the highest frequency resolution and magnification of cochleotopy in cortex is within the cNB region of AI (Fig. 8A). Likewise, the highest frequency resolution and magnification of cochleotopy (i.e., mm/octaves) in thalamus are found in the middle third of MGBv (Rodrigues-Dageaff et al., 1989). Correspondingly, we find that most neurons projecting to the cNB region are located in the middle third of MGBv (Fig. 8C). Neurons that project to frequency-matched regions in cNB and dorsal AI are distributed in a complementary spatial pattern in this region of MGB (Fig. 6, section 3) suggesting dorsal AI receives a proportion of its input from the middle third of MGBv (Fig. 8C, dotted lines). Few studies have examined the physiologic or anatomic organization of the rostral third of MGBv, the site of the majority of dorsal AI (Fig. 8D) and AAF projecting neurons (Lee et al., 2004a; Lee and Winer, 2005, 2008; Morel and Imig, 1987). The spatial spread of cells projecting to dorsal AI (Fig. 8D, gray areas) or AAF is broad within the medial-to-lateral dimension of rostral MGBv suggesting both cortical fields receive a high degree of frequency convergence. Cells projecting to a single injection site in dorsal AI formed discontinuous bands in ovoidalis (Ov) and lateralis (Lat) divisions of MGBv in the rostral third of MGB (Fig. 8D, high, low). According to prior physiologic studies in the cat (Calford, 1983; Imig and Morel, 1985), this medial-to-lateral region spans a CF range of 2 octaves or more (8 to ≥ 32 kHz). This coarse (large) frequency convergence of the rostral third of MGBv could contribute to the lower frequency resolution and higher CF scatter characteristic of dorsal AI. Collectively, this and prior studies find frequency lamina organization varies systematically along the three dimensions of the MGBv: superiorenferior, medialelateral, and rostral-caudal.

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Abbreviations

AI	primary auditory cortex
BB	broad band response area
bic	brachium of the inferior colliculus
CF	characteristic frequency at threshold
CTB	cholera toxin, subunit B
CTBG cholera toxin	subunit B conjugated to gold
cNB	central narrow bandwidth
D	dorsal nucleus of the MGB
DAB	diaminobenzidine
DD	deep dorsal nucleus of MGB
dNB1	first dorsal narrow bandwidth region
DS	dorsal superficial nucleus of the MGB
iMGBv	inferior part of the ventral division of the MGB
kHz	kilohertz
M	medial division of the MGB
MGB	medial geniculate body
MGBd	medial geniculate body, dorsal division
MGBv	ventral division and pars lateralis of the MGB
PAF	posterior auditory field
Ov	pars ovoidalis of the ventral division of the MGB
SG	medial geniculate body, supragenulate nucleus
sMGBv	superior part of the ventral division of the MGB
V	ventral division and pars lateralis of the MGB
VL	medial geniculate body, ventral lateral nucleus
IeVI	auditory cortical layers

VAF

ventral auditory field

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Fig. 1.

Characteristic frequency (CF) and frequency resolution (Q_{40}) maps of central and dorsal AI in the cat. Tessellated and smooth maps are shown for a 3×2.25 mm area of AI for case 510. The ventral part and reversal boundaries of this AI map have been removed. Interpolated iso-CF contours (black contours) are illustrated at 1/3 octave intervals and overlaid in both maps. (A) Alignment of tracer deposit with CF maps confirmed that retrograde tracers were injected into matched iso-CF contours (8 kHz) in the cNB (black dot, WAHG) and dNB (red dot, CTB) regions of AI. (B) Aligned deposit and Q_{40} maps confirm that deposit centers were cNB and dNB regions with the highest frequency resolution ($Q_{40} > 1$, green, yellow, red regions) in AI. Low frequency resolution responses were observed in surrounding broad bandwidth areas indicated in blue ($Q_{40} \leq 1$, blue regions). The autocorrelation function of this Q_{40} map (case 510) is given elsewhere (Read et al., 2001). (C) Photomontage of WAHG (W) and CTB deposit sites within the cNB and dorsal AI regions, respectively. Tissue was dual reacted and dual illuminated and the section was rotated relative to the maps in A and B. White dotted and solid lines indicate deposit and halo perimeters, respectively.

Fig. 2.

Frequency lamina organization of neurons in MGBv that project to cNB region of AI. Retrograde tracers were injected into 4 kHz (4 k, CTB) and 12 kHz (12 k, CTBG) iso-frequency contours within the cNB region in case 591. (A–C) Caudal-to-rostral series of coronal sections of MGB, separated by 240 μm . Note the gap (double-headed arrow) between labeled 4 and 12 kHz frequency laminae for cells located in sMGBv; whereas there is no gap for cells located in iMGBv.

Fig. 3.

Frequency lamina organization and divergence in iMGBv. Magnification of image area taken from within the white box labeled “a” of Fig. 2. (A) Cells projecting to low (brown, 4 kHz) and high (silver, 12 kHz) frequency contours in the cNB region fall on thalamic cell lamina that abut one another in iMGBv region. The cell that appears amber in this image (arrow) is double-labeled with both anatomic tracers. High magnification image (4x + 1.5x) taken with dual dark and bright field illumination. (B) Higher magnification image (60x) focusing on the same double-labeled cell shown in (A). Note this double label neuron is precisely located at the border of labeled iMGBv “frequency laminae” and presumably has projection fields that diverge to both 4 and 12 kHz injected areas. Cell distributions from this labeled tissue (case 510) are given in detail elsewhere (Read et al., 2008).

Fig. 4. Morphology of cNB-projecting cells located in iMGBv. Retrograde labeled (WHAG) cells within iMGBv following deposits into the cNB region. Two clusters (a, b) of the characteristically large bodied cells contain “tufted spindle” and stellate type morphologies (Morest, 1964; Winer et al., 1999). Image taken with a high magnification (60×) planapochromatic lens and dark field illumination and polarized lighting to optimize luminance contrast.

Fig. 5.

Overlapped frequency lamina organization of cNB and dorsal AI-projecting neurons in MGBv. Retrograde tracers were injected into the cNB (CTBG) and dNB (CTB) regions of the same iso-CF contour (~10 kHz) in case 750 and labeled thalamic neurons appeared white and dark brown, respectively. Double-labeled cells with a branched projection to cNB and dorsal AI appear light amber (arrows) in this image. Note the lack of a gap between cNB and dorsal AI-projecting cell lamina. Lighting and magnification specifications were the same as in Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Fig. 6.

Position plots of thalamic cells that project to cNB versus dorsal AI. Data from same brain (case 510), as shown in Fig. 1. Cells that project to cNB and dorsal AI indicated with black and red filled circles, respectively. cNB and dorsal AI cells cover a similar area in the medial-to-lateral dimension and have a complementary distribution in the inferior-to-superior dimension of sections 1–3. Dorsal AI-projecting cells were located over a larger medial-lateral area (arrows) in rostral MGBv that spanned pars ovoidalis (Ov) and lateralis (V) of the MGBv (e.g. section 4). Dorsal AI-projecting cells (red) were also located in the rostral pole (RP). Few cNB-projecting cells were observed in the three far rostral sections 4, 6 and 7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Fig. 7.

Distribution of cNB-projecting and dorsal AI-projecting neurons in thalamus. Most neurons projecting to dNB were located caudal to those projecting to dorsal AI. Most neurons projecting to either part of AI were located in the MGBv nucleus. (AeC) Percentage of cells per total labeled cells projecting to the same iso-CF contour of cNB (dark bars) and dorsal AI (light bars) are given for injection cases 510, 750 and 490. Cell position plots for coronal sections are sequentially ordered with a separation interval of 120, 480 or 600 μ m covering a total distance of with 3 mm as indicated by the gray colored horizontal axis labels in (A). Minimal label was observed in coronal sections caudal or dorsal to those quantified here. (D) Cell distributions within MGB nuclei were determined as indicated in Fig. 6 from seven sections and summed for each case. The total cell number for cells projecting to cNB/dorsal AI for cases 510, 750 and 490 were 752/1233; 534/1053; and 424/2111, respectively. Names of nuclei are abbreviated: suprageniculate (SG), medial (M), ventral (V), dorsal (D) and rostral pole (Rostral pole). Asterisks indicate significant difference between mean cell count for a given tracer in a given division as compared to the same tracer in all other divisions (t -test; $p < 0.001$). Cell counts in SG, M and RP were significantly less than in V or D but not significantly different than each other for both tracers.

Fig. 8.

Summary of thalamocortical pathway frequency organization for neurons that project to central and dorsal AI. (A) Cochleotopic and spectral resolution response properties are organized along opposing axes throughout AI. Central AI can be divided into central narrowband (cNB) and broad band (cBB) domains and dorsal AI into dorsal narrowband (dNB) and broad band (dBB) domains. Spectral resolution and CF variance are lower in cNB than dNB regions (Introduction). The precise cortical laminar pattern of these pathways to AI remains to be determined; however, principal neurons in MGBv project to layers 3 and 4. (B) The caudal third of the medial geniculate body (MGB) does not project to either cNB or dorsal AI. (C) Most neurons projecting to cNB are located in the middle third of the caudal-to-rostral extent of MGB. Projections to cNB region arise from superior (sMGBv) and inferior (iMGBv) halves of the ventral (MGBv) division of medial geniculate body (MGB). The resolution between frequency laminae increases continuously from inferior to superior MGBv (Fig. 2). Dorsal AI receives a smaller proportion of its input from the sMGBv and iMGBv (c, connections indicated by dotted lines). (D) Most projections to dorsal AI arise from the rostral third of MGB. Neurons projecting to dorsal AI are distributed within pars ovoidalis (Ov) and pars lateralis (Lat) of the MGBv and cover a large range of frequency laminae. Note the direction of caudal-to-rostral axis is reversed for A versus BeD.