Response patterns along an isofrequency contour in Cat Primary Auditory Cortex (AI) to stimuli varying in Average and Interaural Level

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Kyle T. Nakamoto¹, Jiping Zhang², L.M. Kitzes²
Department of Cognitive Science¹, Department of Anatomy and Neurobiology²,
University of California at Irvine

Contact Information
L. M. Kitzes
Department of Anatomy and Neurobiology
University of California, Irvine
Irvine, CA. 92697-1275, USA
Tel: 949-824-6469
Email: lmkitzes@uci.edu
Abstract

The topographical response of a portion of an isofrequency contour in primary cat auditory cortex (AI) to a series of monaural and binaural stimuli was studied. Responses of single neurons to monaural and a matrix of binaural CF tones, varying in average binaural level (ABL) and interaural level differences (ILD), were recorded. The topography of responses to monaural and binaural stimuli was appreciably different. Patches of cells that responded monotonically to increments in ABL alternated with patches that responded nonmonotonically to ABL. The patches were between 0.4 and 1 mm in length along an isofrequency contour. Differences were found among monotonic patches and among nonmonotonic patches. Topographically activated and silent populations of neurons varied with both changes in ILD and changes in ABL, suggesting that the area of responsive units may underlie the coding of sound level and sound location.
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Introduction

A central issue in auditory physiology is the way an auditory stimulus is "represented" by populations of neurons. At the lowest level of the central auditory system, the auditory nerve, responses can be directly related to physical properties of the stimulus (Rose et al., 1967; Kim and Molnar, 1979; Sachs and Young, 1979; Young and Sachs, 1979; Kim et al., 1990). At higher levels of the auditory system, the superior olivary complex (SOC) and above, units start to reflect derived cues, such as interaural disparities in time and level (Tsuchitani and Boudreau, 1969; Irvine, 1986; Sullivan and Konishi, 1986; Wagner et al., 1987; Manley et al., 1988; Irvine et al., 1996; Samson et al., 2000). Binaural neurons sensitive to high frequency stimuli compare the sound pressure level (SPL) at each ear and respond to relative interaural level in addition to absolute level.

Understanding the way in which auditory cues are represented at higher auditory levels is essential for understanding the processing of sound in the auditory system. An auditory dimension that has been shown to be topographically organized in the primary auditory cortex (AI) is tonal frequency. An orderly representation of tonal frequency has been found in several species (Merzenich et al., 1975; Reale and Imig, 1980; Kelly et al., 1986; Phillips et al., 1988; Thomas et al., 1993). With the exception of the ferret, low frequencies are represented caudally; high frequencies are represented rostrally. Furthermore, a narrow band of frequencies is represented along the entire extent of a dorso-ventral strip in AI (isofrequency contour). Since a narrow band of frequencies is represented as an isofrequency contour, and not as a point, it has been hypothesized that other auditory dimensions are represented along an isofrequency contour (Tunturi, 1952).
The nature of these dimensions is not fully understood.

The distribution of AI cell’s sensitivity to azimuth has been studied using freefield stimuli. These studies show that units with the same azimuth preference tend to be clustered together along an isofrequency contour (Middlebrooks and Pettigrew, 1981; Rajan et al., 1990; Clarey et al., 1994). The entire frontal field is represented along an isofrequency contour. However, there is no consistent evidence for a systematic topographical representation of azimuthal location along an isofrequency contour (Middlebrooks and Pettigrew, 1981; Rajan et al., 1990; Clarey et al., 1994). In addition to clusters of units with the same preferred azimuth, cells that respond monotonically or nonmonotonically to stimulus level occur in clusters, which repeat along and across the isofrequency dimension (Clarey et al., 1994).

Monaural frequency and intensity tuning properties have been shown, mainly in studies in cats, to vary systematically along the isofrequency axis (for review see Schreiner et al. 2000). Frequency bandwidth near threshold has been shown to be topographically organized. Frequency bandwidth is narrowest in the central region of AI with a tendency to increase both dorsally and ventrally (Heil et al., 1992; Schreiner and Sutter, 1992; Schreiner, 1995). Low-threshold neurons tend to be found in the central strip of AI, surrounded by regions with higher thresholds. A consistent correlation between best response level and threshold has been demonstrated (Schreiner et al., 1992). Monotonicity has also been shown to vary along an isofrequency contour. In most cases monotonicity has been shown to be lowest in the central region of AI, increasing both dorsally and ventrally (Heil et al. 1994; Schreiner et al. 1992; Sutter and Schreiner 1995).
Binaural interactions have also been shown to vary along an isofrequency contour. Characterization of the binaural interaction typically depends on whether the response to contralateral stimuli is inhibited, facilitated or both (mixed) by ipsilateral stimulation. Alternating bands of facilitatory and inhibitory responses have been reported to occur orthogonal to isofrequency contours in the cat (Imig and Adrian, 1977; Middlebrooks et al., 1980) as well as in radial columns of facilitatory and inhibitory responses (Imig and Adrian, 1977). Recent research using more detailed binaural classification schemes have found circumscribed areas of facilitatory, inhibitory and mixed responses in the owl monkey (Recanzone et al., 1999), rat (Kelly and Sally, 1988), guinea pig (Rutkowski et al., 2000) and ferret (Kelly and Judge, 1994). In most cases, rather than bands of binaural interaction orthogonal to isofrequency contours, these papers reported that binaural interaction characteristics change as an electrode is moved orthogonal to an isofrequency band. Units exhibiting the same binaural interaction aggregate in clusters, which vary in size and shape and may extend across isofrequency bands.

Binaural responses of individual cells in AI may not be fully captured by a classification system limited to facilitatory, inhibitory, or mixed (Semple and Kitzes, 1993a, b). For example, a binaural classification of EI, EE, EO/F is independent of binaural level. Collapsing binaural responses into these categories precludes demonstrations of systematic influence of binaural level on the binaural interaction within and across cells. A systematic topographical change in the response of AI cells may be found if the full binaural response of each cell is analyzed.
This study concentrated on the topographical response of single units in small portions of an isofrequency contour to a large set of stimuli varying in interaural level differences (ILD) and average binaural level (ABL). Due to time constraints imposed by the isolation of single units and recording responses to a large set of stimuli, only a portion of an isofrequency contour in each animal could be studied in detail.

Materials and Methods

Animal Preparation

Five healthy adult cats were screened for evidence of pathology or infection in the external ears. An injection of pentobarbital sodium was used to induce anesthesia (40 mg/Kg weight). A solution of 5% dextrose in lactated Ringer's solution with 250 mg of pentobarbital sodium per 1000 mL was administered continuously by IV drip to maintain areflexia and body fluid. Atropine sulfate (0.048 mg) and Dexamethasone (0.044 mg) were administered to minimize bronchial secretions and cerebral edema, respectively. The cat was placed in a double-walled sound attenuating chamber (IAC). The skull was secured to a frame with screws and dental acrylic. The pinnae were removed and earpieces were inserted and acoustically sealed within the transected external auditory canals. A small opening was made in the bone overlying AI. Warmed mineral oil or saline was applied frequently to the cortex throughout the experiment. Body temperature was monitored via a rectal probe and maintained at 38°C by a feedback-controlled heating blanket. The experiments varied between 60 and 80 h in duration. At the end of the experiment the animal was euthanized with an overdose of pentobarbital sodium.

Stimulus generation and control.
For each ear, tympanic SPL (expressed in dB re 20 µPa) was calibrated from 100 Hz to 30 kHz in 100Hz steps under computer control using a calibrated probe tube, housed within the earpiece, and a 0.5 inch condenser microphone (Bruel and Kjaer). Acoustic calibrations for both ears were stored in a computer file for use in controlling attenuators to obtain desired SPLs. 50-ms duration tonal stimuli (6 ms rise/fall time) were presented at 800 ms intervals and repeated 40 times. Tone pips were generated digitally by a MALab system controlled by a Macintosh computer.

**Recording system**

After making a small hole in the dura, a 5 or 10-µm tip parylene-insulated tungsten microelectrode was positioned at the surface of the brain and advanced by a stepping-motor microdrive controlled from outside the acoustic chamber. The electrodes were directed orthogonal to the pial surface of AI. The location of each electrode penetration was marked on a picture of the exposed area of AI. The dimensions of the exposed area were measured using a mm ruler included in the photograph. At the conclusion of the recording period, the bone overlaying all of auditory cortex was removed and another picture was taken in order to locate the area recorded within AI, as determined by the surface features of the cortex.

**Data collection procedure**

Neuronal activity was amplified and sent to a digital oscilloscope and a Macintosh computer for display and analysis. The latency of each single unit discharge was time linked to a protocol of the stimulus configuration (1µs resolution) and stored in a computer file. Single units were isolated within a 2 by 2 mm area between the dorsal limit of the ectosylvian gyrus and AII. Data were usually collected from units in the middle
layers (III and IV) of AI. In general, the response of the cell was recorded over a 50-ms window, starting at stimulus onset. In the few cases in which the response lasted longer than the 50-ms window, the window was extended to capture the entire response. To study the response of groups of AI neurons within an isofrequency contour to a single stimulus, all stimuli presented to a single animal used the same frequency. Using a single frequency allows for a direct comparison of the response of individual units against each other and provides a topographical map of the responses of AI units to a single stimulus frequency. The characteristic frequency (CF), i.e. the tone frequency that evoked a response at the lowest monaural or binaural level, of each cell was determined audio-visually. The CF of the first recorded cell in each experiment determined the frequency of the stimuli for that animal. The five frequencies used in the experiments were 8.0 (01k001), 8.7 (01k003), 12.5 (01k004), 12.5(01k008), and 11.8(01k009). Only cells that had a CF within ± .15 octaves of the fixed frequency were included in the study.

A series of stimuli, varying in SPL, was used to determine the monaural and binaural characteristics of each cell. A contralateral monaural rate/level function 0-80 dB SPL in steps of 10 dB SPL was obtained to assess the monaural response of the neuron. If the neuron was excited by ipsilateral stimulation, its ipsilateral monaural rate/level function was obtained. A stimulus matrix was used to study the binaural response of cells within an isofrequency contour. The matrix was composed of 5 ILDs (± 20, ± 10, 0) by 6 ABLs (20,30,40,50,60,70). ILD is defined as the contralateral level minus the ipsilateral level. ABL is defined as the contralateral level plus the ipsilateral level divided by two. The stimulus matrix is shown in Fig. 1 A, E, B and F. The stimulus points in Fig. 1 A & B are plotted in terms of the derived cues ABL and ILD. The same
stimulus points are plotted in terms of SPL at the contralateral and ipsilateral ears in Fig 1 E and F. Thus, the two formats are equivalent in that the stimulus matrix can be interpreted in terms of either derived cues or SPL at the two ears.

**Data Analysis**

*Monaural Classification*

Units were classified into four categories based on their monaural response properties. Neurons were classified as EE if they responded to stimulation of both ears; EO if they responded to stimulation of the contralateral ear alone; and OE if they responded to stimulation of the ipsilateral ear alone. Neurons that responded weakly to stimulation of either ear, but responded strongly to binaural stimulation were designated PB (predominantly binaural).

*Binaural Interaction Classification*

Units were divided into four classes based on their binaural interactions. If the binaural response was 20% greater than the sum of the monaural response it was classified as facilitatory (F). If the binaural response was 20% less than the monaural response of the dominant ear it was classified as inhibitory (I). If the cell displayed both facilitation and inhibition it was classified as mixed (M). If the binaural response was within 20% of the sum of the monaural response it was classified as non-interacting (N).

*ABL and ILD Preference*

In order to study the topographical distribution of binaural level responses, a measure of AI cell responses to ILD and ABL was created. The Preferred Binaural Combination (PBC) i.e., the area within the binaural stimulus matrix in which the
response of the cell was ≥ 80% of the maximum response, was measured for each cell. The PBC was used as a measure of the cell’s area of strongest response. An index of preferred ILD (PILD) was defined as the average ILD of the stimulus points in the PBC. An index of preferred ABL (PABL) was defined as the average ABL of the stimulus points in the PBC. If the cell had two distinct PBCs along its respective dimension (ILD or ABL), it was classified as multi-peaked (MP). Cells that had a PBC that included all ILDs or ABLs were classified as unselective to level (UL) for that respective dimension.

**Binaural Monotonicity**

A measure of the response of AI cells to binaural level was created to study the topographical distribution of binaural monotonicity. The stimulus matrix was divided into five separate functions (Fig. 1C, D), one for each ILD. The monotonicity of the response function at each ILD was evaluated separately. The function was classified as nonmonotonic if its response decreased at higher ABLs by >30% from a maximum response. If the majority of the ABL response functions were monotonic, the cell was classified as binaurally monotonic (BM); if the majority of functions were nonmonotonic, the cell was classified as binaurally nonmonotonic (BNM). If the maximum response at a particular ILD was < 10 spikes, it was excluded from the analysis. If the cell had a maximum response at an ILD that was monotonic and a maximum response at an ILD that was nonmonotonic then the cell was classified as mixed. 15 of the neurons (11%) had mixed response functions. These cells, classified as mixed response (MR), were excluded from analysis, however their spatial positions and responses are included in the topographies.
Saturating and non-saturating binaurally monotonic cells

A measure of saturation was created to determine if there were any systematic differences among the BM cells. Saturation was determined using the ABL response function in which the maximal response occurred. This ABL response function was used because saturation diminishes as the stimulus is moved away from the optimal binaural configuration. Saturation was defined according to the percentage of response change at the highest levels of ABL (((response at 70 ABL/Response at 60 ABL) - 1)*100). If the change was less than 10%, the cell was classified as saturating. If the change was more than 10%, the cell was classified as non-saturating.

High and low binaurally nonmonotonic cells

A measure of the degree of nonmonotonicity was created to determine if there were any systematic differences among the BNM cells. The degree of nonmonotonicity was determined using the ABL response function which included the cell’s maximum response, because averaging across ILD reduces the degree of nonmonotonicity. The degree of nonmonotonicity was defined according to the percentage of change from the maximum response to the response at the highest ABL level (((response at 70ABL/maximum response of cell)-1)*100). If the change was between 30% and 50%, the cell was classified as a low BNM cell. If the change was greater than 50% the cell was classified as a high BNM cell.

RESULTS

Complete responses to the monaural stimuli and the binaural matrix were collected from 130 neurons in the AI of five animals. Due to the long duration of the
experiment, a measure of the animal’s condition over time was necessary to ensure that there was no progressive deterioration of the responsiveness of the auditory system. We adopted a measure that was used previously for this purpose (Phillips et al., 1994) viz., unit threshold. There was no evidence of a progressive deterioration of unit thresholds during any experiment.

*Single cell response to the stimulus matrix*

The response of two cells to the stimulus matrix is displayed in the two columns of Fig. 1. Responses of a BNM cell are displayed in Fig. 1A, C & E. The same data are plotted in Fig. 1A and Fig. 1E, demonstrating the relationship between representation of the response in terms of SPL at the contralateral and ipsilateral ear and the derived cues ILD and ABL. It’s monaural classification was EO and it’s binaural classification was classified as Mixed. It's PBC, shown as the black area in Fig. 1A & E, included three points in the matrix of the derived parameters ABL and ILD: ABL 30, ILD 0; ABL 30 ILD 10; ABL 40 ILD 10 and in Fig. 1E, included contralateral (contra) 30, ipsilateral (ipsi) 30; contra 35, ipsi 25; contra 45, ipsi 35. All of the ABL functions of this unit were nonmonotonic (Fig. 1C). The response functions of this unit, determined at 0 ILD, was classified as highly nonmonotonic. The unit's PILD was +7 ILD and its PABL was 33 ABL. As this unit was nonmonotonic with regard to both contralateral and ipsilateral stimulus level, it is an example of a TWIN cell (Semple and Kitzes, 1993a, b). Responses from a BM cell are displayed in Fig. 1B. It’s monaural classification was PB and it’s binaural classification was facilitatory. It's PBC included three points: ABL 50, ILD 10; ABL 60, ILD 10; ABL 70, ILD 10. The response is displayed in terms of SPL at the
contralateral and ipsilateral ears in Fig. 1F. All of the ABL functions for this unit were monotonic (Fig. 1D). Saturation was determined at 10 ILD, with less than a 10% increase in response, this cell was classified as a saturating monotonic cell. This unit's PILD was +10 ILD and its PABL was 60 ABL. For these two cells, and the great majority of cells in our sample, the PBC was limited to an area of 3-6 adjacent stimulus points, and the response systematically declined as the stimulus was moved away from the optimal stimulus configuration.

Population Data

The distribution of cells over the various response classifications is displayed in Table 1. The majority of cells were EO. The binaural interaction classification of the majority of cells was classified as Mixed. Nearly half of the cells were binaurally nonmonotonic (BNM) and a slightly smaller proportion were binaurally monotonic (BM). While the majority of cells in our total sample base preferred contralateral ILD’s, the percentage of midline and contralateral preferential cells varied across animals. The percentage of midline preferential cells ranged from 15-50% and the percentage of contralaterally preferential cells varied from 20-60%. The percentage of ipsilateral, UL and MP cells was comparable across animals. The distribution of the PABLs of the cells had two peaks, one centered at 30.6 ABL and the other at 60.9 ABL. The percentage of high(> 45 ABL), and low PABL (≤ 45 ABL) preferential cells varied from 40-55% and 31-50%, respectively, between animals.

The relationship, between binaural monotonicity and other response classifications are displayed in Table 2. With the exception of OE cells BM and BNM cells were evenly distributed over the monaural classifications. The binaural interaction
classifications of facilitatory and inhibitory were not predictive of binaural monotonicity. There was a higher percentage of BNM Mixed cells than there were BM Mixed cells, however the difference was not statistically significantly. (Chi-Squared 1.723, df =1, P>=.05). Preferred average binaural level (PABL) and Binaural monotonicity were correlated. The majority of BM cells had a high PABL and the majority of BNM cells had a low PABL.

*Topographical response of an isofrequency contour within AI*

Figures 2 and 3 illustrate the responses of all units studied during a single experiment to the stimulus matrix. The maximum responses of AI cells to 40 repetition of an effective stimulus can vary from ten spikes to over a hundred spikes (Table 3). These contour graphs are based on the spike count at the indicated ABL and ILD. The absolute spike counts were used because such maps are a more accurate index of what is available to the auditory system to code stimuli. The blank circles in the lower left panel of each figure indicate the spatial position of the units that were studied in that experiment. Each panel represents interpolated responses of the set of cells isolated within an isofrequency contour to the indicated stimulus. The collection of panels demonstrates that the topography of the responses of the set of units within an isofrequency contour is a function of both ILD and ABL.

Complete data were collected from 24 units in experiment 01k001 (Fig. 2). These units were isolated over a small portion of the isofrequency contour, spanning 2.2 mm dorso-ventrally (DV) and .9 mm anterior-posteriorly (AP). Multiple changes in response pattern occurred within this small portion of the isofrequency contour as a function of
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ILD and ABL. From +0.4 to -0.8 mmDV, a focus of activity developed in the posterior area with increasing ABL at ILDs favoring the contralateral ear, i.e., ILD 10 and 20. This focus was absent at ILDs favoring the ipsilateral ear, i.e., ILD -10 and -20. In the dorsal portion of the field, centered at 0.8, a "doughnut" shaped focus is evident at 20 - 40 dB ABL at the contralateral ILDs. This focus decreased with increasing ABL. The form of this focus appears inverted at the two ipsilateral ILDs, particularly at the lower ABLs, in that there is a clear focus of activity that is surrounded by an area of reduced activity. The transition of these response patterns, as a function of ILD, from being "doughnut" shaped to a central focus is apparent at the lower ABLs at 0 ILD.

Fig. 3 illustrates another case in which cortical units within two closely juxtaposed areas of an isofrequency contour exhibit different responses to increasing ABL. Complete data were collected from 21 units that were isolated in an area spanning 0.5 mm AP and 1.2 mm DV of an isofrequency contour. Dorsal to 0.2mm, activity increased monotonically with ABL at all ILDs. Though it might appear that this behavior is overly dependent on the most posterior unit, it is true of the central portion of the response field centered at 0.0 AP. The behavior of units isolated ventral to -0.1 and centered at about 0.0 AP differed significantly from the monotonic behavior of the units in the more dorsal areas. For these units, activity increased nonmonotonically at all ILDs, reaching maximal levels from 40 to 60 dB ABL.

The contribution of ipsilateral stimulation to the magnitude, type and spatial distribution of the binaural response is evident in the comparison of the binaural data with the monaural data obtained from the same units. Figures 4 and 5, respectively, illustrate the response of all units in Figure 2 & 3 to contralateral monaural stimulation at the
indicated stimulus levels. In experiment 01k001, multiple changes in the topography of
responses to monaural and, as just discussed, binaural stimulation occurred within a small
portion of the isofrequency contour as a function of level (Fig. 2 and Fig. 4). A focus of
activity developed in the ventral-posterior area, from +0.2 to –0.8 mm DV, with
increasing monaural level (Fig. 4). The overall pattern of this focus of activity resembled
the response to binaural stimuli favoring the contralateral ear. However, the monaural
activity was quite different from the response to binaural stimuli favoring the ipsilateral
ear. In the dorsal portion of the field, spatially diverse activity was evoked by monaural
contralateral stimuli from 20 to 50 dB SPL. As level increased, the activity shifted to an
anterior focus at the anterior area centered at +0.4 DV. The focus of activity anteriorally
at 0.4 DV was not active in the binaural condition at ILDs favoring either the
contralateral or ipsilateral ear. In the dorsal area, there was a “doughnut” shaped focus in
the binaural condition at 20 to 40 ABL at contralateral ILDs and an inverted focus at the
same ABLs at ipsilateral ILDs (Fig. 2). Similarly the focus of activity in the posterior
area, centered approximately at 0.8 DV, evoked in the binaural condition is not apparent
in the monaural condition. At 20 to 50 dB SPL in the monaural condition, the response
in the dorsal area appears to be a combination of both contralateral ILD and ipsilateral
ILD responses at low ABLs.

The nonmonotonicity ventral to -0.1 in experiment 01k008 appeared most clearly
at ILDs ≥ 0 in the binaural condition (Fig. 3). This nonmonotonicity was even more
obvious in the monaural condition (Fig. 5), reaching maximal levels from 30 to 40 dB
SPL. In the binaural condition there were three conditions in which the contralateral
level was 40 dB SPL, viz., ABL 30, ILD 20; ABL 40, ILD 0; ABL 50 ILD –20. Only at
ABL 50, ILD -20 was the response of the same magnitude as the response in the monaural condition. This is paradoxical in that, of these three stimulus configurations, the response evoked by the most ipsilateral ILD, i.e. with the largest ipsilateral component, is the most similar to the monaural contralateral response. Moreover, this activity was largest at 0 ILD (60 dB) and smallest at 20 ILD, where the ipsilateral component was only 20 dB. The threshold, magnitude and spatial distribution of activity evoked binaurally dorsal to 0.2 differed greatly from activity evoked monaurally. Binaurally, activity in this area is evident at 30 ABL at all ILDs, whereas response threshold in the monaural condition was 50 dB SPL. At no level of monaural stimulation did activity in this area resemble the activity evoked by binaural stimuli at any ILD at ≥ 40 ABL. In all binaural conditions with the same contralateral SPL (50 dB): ABL 60, ILD -20; ABL 50, ILD 0; ABL 40, ILD 20, the activity evoked binaurally dorsal to 0.2 mm was at least four time as large as that evoked monaurally. It is clear therefore, that the influence extorted by ipsilateral stimulation varied topographically across the units studied in this cortex.

**Distribution of BNM and BM cells**

The topographic distribution of BM and BNM cells for each animal is shown in Fig. 6. In each case, BNM (black circles) and BM (white circles) cells are grouped. Cells with mixed responses are displayed as white triangles. BNM units in 01k001 predominated between .4 and 1.4 mm DV, whereas BM units predominated between 0.2 and -.8 mm DV (Fig. 6A). 01k008(C) and 01k004(E) were similar to 01k001 (A) in that BNM units predominated in one half of the recorded area and BNM units predominated
in the other. In 01k003 (D), BM units predominated between 0.3 and 0 mm, while BNM units predominated both dorsally and ventrally. In 01k009 (B), with the exception of 1 BM unit, a patch of 16 BNM units ascended posteriorally from -0.2 to 0.7 mm DV. From -0.2 to -0.5 DV there appeared to be a mixture of BNM and BM cells. Overall, the patches varied dorsal-ventrally from .4-1.0 mm in length. Since we recorded only from cells whose CF was within ± .15 octaves of the fixed frequency, the anterior-posterior dimension of these patches remains to be studied.

The ABL function that contained the maximum response of the component cells was used to compare the different BM and BNM patches. There were two reasons for using the ABL function that contained the maximum response rather than the average across ILD. For cells with a BNM response, the maximum nonmonotonicity, in general, was at the ABL function that contained the maximum response. Averaging across ILD could reduce the nonmonotonicity, compared to the maximum ABL function, by as much as 35%. For cells with a BM response, the most saturation tended to occur at the ABL function that contained the maximum response, as compared to other ABL functions. Averaging across ABL functions in a BM cell can appreciably reduce the amount of saturation, as compared to the maximum response function.

Each line graph in Fig. 7 illustrates the ABL function that contained the maximum response of one cell. With the exception of 01k004 (D) a particular type of response function dominated each BM patch. In the BM patches in 01k008 (B) and 01k003 (C), the majority of cells (8/9 and 7/7, respectively) saturated (thick line graphs), in contrast to 01k001 (A) in which the majority of cells (7/10) in the BM patch did not saturate (thin
line graphs). Thus, monotonic patches can be characterized as having a particular degree of saturation and that degree of saturation differs across BM patches.

Four out of the six BNM patches, viz. Dorsal in A, dorsal and ventral in C and possibly ventral in D, consisted of cells with similar BNM response functions. The mean nonmonotonicity and standard deviation of each of the patches shows that there is a difference between patches across animals (Table 4). In 01k001(A) cells with a high degree of nonmonotonicity (thin lines) dominated the BNM patch. 01k003(C) is of particular interest because the dorsal BNM patch was composed of cells with a low degree of nonmonotonicity (6/7) whereas the ventral patch was composed of cells with a high degree of nonmonotonicity (6/7). The nonmonotonicity in these two patches significantly different ($t = -2.6$, df = 5, $P < 0.01$). 01k009 was not included in Fig. 7 because its BNM patch had no clear organization. Overall, these results suggest that there is a difference in the degree of nonmonotonicity between different nonmonotonic patches and some evidence is provided that these differences can be grouped in to low and high degrees of nonmonotonicity.

When presented in terms of spatial contours, the response of the BM and the BNM patches is as a function of ILD and ABL are quite apparent (Figure 8). There were three patches in 01k003, a BNM patch in the dorsal (0.4 to 0.6 mm DV) and the ventral area (-0.4 to 0 mm DV), with a BM patch located between them (0 to 0.4 mm DV). When each patch was plotted separately, the monotonicity of the central patch and nonmonotonicity of the patches dorsal and ventral became clearly visible. At low stimulus levels, the stronger responses are from the BNM patches, whereas at high levels the stronger responses are from the BM patch.
**Monaural Response Topographical Distribution**

Similar to previous findings, clusters of EO, OE and EE/PB cells were found in this study. Clusters of EO and EE/PB cells were found in all five animals (Fig. 9). In 01k001(A) there were three clusters: an EO cluster in the dorsal area (1 to 0.4 mm DV), surrounded by an EE/PB cluster (1.4 to -0.2 mm DV), and a second EO cluster in the ventral area (0 to -0.8 mm DV). In 01k009 (B) there was a large cluster of EO cells in the ventral area (0 to –1 mm DV), a cluster of EE/PB cells in the central area (0 to –0.6 mm DV), a second cluster of EO cells located dorsally (0.2 to -0.2 mm DV), and a second EE/PB group in the most dorsal area (0.6 to 0 mm DV). In 01k008 (C) there was a cluster of EE/PB cells in the dorsal (0.6 to 0.2 mm DV) and ventral areas (-0.2 to –0.6 mm DV), and a group of EO cells located anteriorally (0.2 to –0.6 mm DV). In 01k003 (D) there were two clusters: a cluster of EO cells in the ventral area and a cluster of EE/PB cells in the central area. In 01k004 (E) there were three clusters: a cluster of EE/PB cells located dorsally (0.8 to 0.4 mm DV), a cluster of EO cells posterior-ventrally (0.4 to -0.8 mm DV) and a patch of OE cells in the central area (0.4 to 0 mm DV).

Overall, clear clusters of monaural response types, varying dorsal ventrally from .4 to 1.2 mm in length, were found in all experiments.

**Topographical Distribution of Binaural Interaction Types**

The topographic distribution of binaural interactions for all animals is displayed in Fig. 10. In all five animals clusters of facilitatory, inhibitory, and mixed cells were found. There were four clusters in 01k001(A), a ventral cluster of mixed cells (0 to -0.8
mm DV), a dorsal cluster of mixed cells (1.4 to 0.4 mm DV), a central cluster of inhibitory cells (0.8 to 0.4 mm DV) and a central cluster of facilitatory cells (0.2 to -0.2 mm DV). In 01k009 (B) there was a large cluster of facilitatory cells (0.4 to -0.8 mm DV) wrapped around a smaller cluster of inhibitory cells (0 to –1 mm DV) and a cluster of mixed cells (0.6 to 0 mm DV). A small cluster of facilitatory cells was found in the most dorsal area (0.8 to 0.6 mm DV). In 01k008 (C) there were four clusters: two clusters of facilitatory cells (0.4 to 0 mm DV and –0.4 to –0.8 mm DV), a cluster of mixed cells located in the posterior-central area (0 to –0.4 mm DV), and a cluster of inhibitory cells located in the anterior-central area (0 to -0.6 mm DV). The data from 01k003 (D) segregated into three clusters: a cluster of facilitatory cells (0.6 to 0.2 mm DV), a cluster of mixed cells (0.3 to 0 mm DV) and a cluster of inhibitory cells (0 to –0.2 mm DV). In 01k004 (E) there was a large cluster of inhibitory cells in the ventral area, a second cluster of inhibitory cells in the central area (0.6 to 0.2 mm DV), a cluster of mixed cells in the central area (0 to -0.2 mm DV) and a cluster of facilitatory cells in the dorsal area (0.6 to 0.2 mm DV). In general, clusters of mixed, facilitatory and inhibitory binaural interactions, varying in dorso-ventral length from 0.4 to 1.4 mm, were found. In several cases (Figure 10 A, B, C) the clusters did not extend across the anterior-posterior dimensions of the isofrequency contour. Thus, the data obtained from each of the five animals in the study demonstrate that cell exhibiting various types of binaural interaction occur in relatively segregated patches within a 1.5-2.0 extent of an isofrequency contour in primary auditory cortex.
**ILD Topographical Distribution**

The topographic distribution of PILD for all animals is displayed in Fig. 11. The PILD of the cells were parsed into three groups, viz., contralaterally preferential, midline preferential and ipsilaterally preferential cells. Four groups are evident in 01k001(A); two clusters of contralaterally preferential cells (0.4 to 0.6 mm DV), followed by a group of midline preferential cells (0.2 to 0.4 mm DV and 0.0 and -0.4 mm DV), followed by a second, smaller, group of midline preferential cells (-0.8 to –0.4 mm DV). In 01k009 (B) there was a distinct group of ipsilaterally preferential cells in the dorsal most area, and a group of contralaterally preferential cells in the ventral area. Between these two groups was a cluster of midline preferential cells. In 01k008 (C) a thin strip of ipsilaterally preferential cells separated two clusters of contralaterally preferential cells. In 01k003 (D) the ILD preference of the cells was mixed throughout the recorded area. In 01k004 (E) there was a clear contralaterally preferential group in the ventral area, with a small group of ipsilaterally preferential cells located dorsally. Thus, in 4 of the 5 cases, analyses of the preferred ILD of the units strongly suggest that units with similar PILD values tended to occur in distinguishable closely juxtaposed patches. Although these data provide no evidence of an orderly representation of azimuth they do indicate a more coarse segregation in terms of the representation of contralateral, ipsilateral and midline acoustic fields.

**ABL Topographical Distribution**

As discussed earlier, the distribution of PABL in each animal appeared to fall most easily into two groups, viz., high PABL (> 45 ABL) and low PABL (≤ 45 ABL). In four of the five animals, high PABL and low PABL cells were separated into dorso-
ventrally alternating patches (Fig. 12). In 01k001(A) the topographic distribution of PABL was divided into two clear groups, a dorsal group of low PABL cells (0.5 to 1.4 mm DV) and a ventral group of high PABL cells (–0.8 to 0.5 to mm DV). In 01k008 (C) there was a group of high PABL cells in the dorsal area (0.1 to 0.6 mm DV) and a group of low PABL cells in the ventral area (–0.6 to 0.1 mm DV). In 01k003 (D) there were three patches: two patches of low PABL cells located dorsally and ventrally (0.4 to 0.8 mm DV and –0.4 to 0.1 mm DV), and a patch of high PABL cells located in the center (0.1 to 0.4 mm DV). In 01k004 (E) there was a patch of low PABL cells that started in the dorsal-anterior area and extended ventral-posteriorly and a patch of high PABL cells that continued in the same orientation to the ventral-posterior area. Anterior to both groups were cells in the opposite PABL category. The distribution of the PABL of cells in 01k009 (B) was not organized into dorsal-ventrally alternating patches. There was a group of low PABL cells that extended from the center of the field (–0.3 mm DV) to the dorsal posterior limit. High PABL cells boarded this group on three sides. The dorsal-ventral length of the patches of high and low PABL cells varied from –0.4 mm to 1.0 mm.

As the level of a binaural stimulus increased, the cells responding within their PBC (preferred binaural combination) shifted differentially among the binaural monotonicity classifications. For example, in 01k003 there was a dorsal patch of low BNM cells, a ventral patch of high BNM cells, and a central patch of saturating BM cells (Fig 7C). In Fig. 13 the distribution of cells of 01k003 responding within their PBC (≥ 80% of maximum response; gray area) is displayed as a function of ABL. At 30 ABL, cells within the dorsal and ventral BNM patches responded within their PBC. From 40
–50 ABL the response shifted from the high BNM to the saturating BM cells. At high ABLs (60- 70 ABL) only the saturating BM cells responded within their PBC. In general, at low ABLs the PBC response started with high and low BNM cells and then with increasing ABL shifted to low BNM cells and saturating BM cells, and finally to saturating and non-saturating BM cells.

Discussion

Within an isofrequency contour there is a large amount of variance in the responsiveness of closely juxtaposed cells to changes in level. However, there is a topographical organization of responsiveness to binaural level. This study demonstrated that the topography of activity evoked in a small portion of an isofrequency contour depends on the ABL and ILD of a binaural stimulus. Relatively small changes in either parameter can produce broad changes in the activity evoked within a mm expanse of an isofrequency contour. Underlying the broad changes are patches of binaurally monotonic units alternating with patches of binaurally nonmonotonic units. Moreover, some evidence has been provided that nonmonotonic patches differ from each other, as do monotonic patches.

Patches of units responding most strongly to ILDs favoring contralateral space, ipsilateral space or the midline occur within less than one or two mm of each other. In one case, patches most responsive to each of the three categories of ILD were found within a 0.6-mm expanse of an isofrequency contour. In each experiment, patches of units that responded most strongly to the upper half of the ABL range were separated
from patches of units that responded most strongly to the lower half of the ABL range. This study also demonstrated that the topography of activity evoked by binaural stimuli differed significantly from the topography of activity evoked by monaural stimuli.

Topography of Monaural Responses

The distribution of units classified monaurally as EO, OE, EE/PB are consistent with previous studies. The different monaural classification types aggregate in clusters within isofrequency contours. However, in several cases these clusters do not extend across the anterior-posterior dimensions of the isofrequency contour. This suggests that the EO, OE and EE/PB units aggregate in clusters and not in strips perpendicular to the isofrequency contours.

The present data confirm previous reports (Phillips et al. 1994; Heil et al. 1994) that the topography of activity evoked by a monaural stimulus within an isofrequency contour is level dependent. In the present study no level of monaural stimulation evoked activity throughout a 2-mm portion of an isofrequency contour. Within this small region of an isofrequency contour, activity increased in one area and declined in another as stimulus level increased. This movement of activity was due to excitatory processes initiated by the stimuli and inhibitory processes evoked either in the ascending auditory system or within the cortex. The present data extend the aforementioned research by demonstrating that their prescient conclusions apply equally well to activity evoked by binaural stimuli.

The spatial distributions of monaural response parameters found in this study are not consistent with those of other studies of the monaural topography of cortical activity.
The monaural stimulus level that elicits the strongest response (SRL) has been reported to vary continuously over relatively large areas of AI (Schreiner et al. 1992; Sutter and Schreiner 1995). These authors found that higher SRLs dominate the dorsal half of AI, with a few clusters of lower SRL sites, whereas lower SRLs dominate the dorsoventral center of AI. Similarly, a metric of monotonicity was reported to vary smoothly over much of the dorsoventral extent of AI, with a centrally located nonmonotonic region and often a second area of nonmonotonicity located dorsal to this region. As will be discussed below regarding our binaural data, the juxtaposition of a zone of lower SRLs with a zone of high nonmonotonicity is quite reasonable because nonmonotonic activity should be expected to peak at a lower SPL than would monotonic activity.

The disparity between earlier descriptions of monaural response parameters varying continuously over large areas of an isofrequency contour and the present findings of rather sharp transitions from one to another form of response within a single mm or two of an isofrequency contour could be explained by three differences between our study and the earlier studies. The present data consist entirely of the activity of single units whereas the earlier data, of necessity because large areas of cortex were being mapped, consisted mostly of multi-unit recordings. It is possible that the components of the multi-unit responses were single units whose individual behavior is consistent with the very localized patches described in the present study. Since large areas of cortex were being mapped in the earlier studies, the density of recording sites was, of necessity, less than that in the present study. Identification of the spatial domain of the small patches observed here requires closely opposed recordings and, consequently, could have
been obscured by recordings made at larger intervals. Finally, smoothing algorithms were not used in the present study.

*A comparison with previous binaural studies*

The segregation into clusters of units exhibiting facilitation, inhibition, and mixed binaural interactions is similar to previous reports (Imig and Adrian, 1977; Middlebrooks et al., 1980; Reale and Kettner, 1986; Kelly and Sally, 1988; Kelly and Judge, 1994; Liu and Suga, 1997; Rutkowski et al., 2000). These clusters were approximately 0.5 - 1mm long dorsoventrally and vary along and across isofrequency contours. Clusters varying dorsoventrally from 0.4 to 1.4 mm long were also found in this study. Our data are consistent with previous reports that these clusters do not form contours perpendicular to the isofrequency contours.

The BNM and BM categorization is a functionally different classification than the binaural interaction classification. The topographical distribution of binaural interactions is a representation of the distribution of aural interaction across AI. The topographical distribution of binaural monotonicity is a representation of the distribution of responses to increases in binaural level. A direct relationship between binaural monotonicity and binaural interaction was not found in this study.

The patches of BNM and BM responses are consistent with a previous study (Clarey et al., 1994) which showed that monotonic and nonmonotonic responses were segregated into repeating groups along and across an isofrequency contour. The sizes of the patches in the current study and in the free field study are approximately the same. Functionally, both topographies represent the distribution of responses to in binaural
level. As will be discussed below, the present data extend their results by providing some evidence that nonmonotonic patches differ from each other, as do monotonic patches.

*Representation of Level in AI*

AI does not respond independently to either ILD or to ABL; rather, determination of the responsive area is a joint function of ABL and ILD (Semple and Kitzes, 1993b; Irvine et al., 1996). Increasing ABL will change the response function of an AI neuron to changes in ILD; changes in ILD will change the response function of an AI neuron to changes in ABL. Consequently, the population of responsive units, the magnitude of their responses and the activated area of AI change with ABL and ILD. At any given stimulus level, only a subpopulation of cells will respond and the subpopulation will change as ABL or ILD changes. Considering the magnitude of change in the topographical response of AI to changes in both level and ILD, it is unlikely that a single neuron, or even a small cluster of neurons has the range of sensitivity to changes in ABL and ILD necessary to encode sound level and location. Sound level and location appear to, at least partially, be encoded by the change in the population that is responding. Activated and silent populations of neurons varied with both changes in ILD and changes in ABL, suggesting that the area of responsive units may underlie the coding of sound level and sound location.

The present study provides evidence of the spatial segregation of binaural-level response functions into nonmonotonic and monotonic patches, with further subdivisions into saturating and non-saturating BM, and high and low BNM patches. Cells with similar binaural monotonicity appear to be clustered together in alternating patches along
an isofrequency contour. As the level of a binaural stimulus increased, the maximal
response started with high and low BNM cells, shifted to low BNM and saturating BM
cells, and then shifted to saturating and non-saturating BM cells. This concurs with
previous hypotheses that the response of AI shifts from nonmonotonic to monotonic cells
as level is increased (Aitkin, 1991). The functional consequence of this clustering of
similarly responding cells is that maximal activity moves across alternating areas of an
isofrequency contour as the level of a stimulus is increased. Therefore, segregated
populations of activated and silent neurons vary with ABL and may serve as a basis for
sound level coding.

Comparison of Figures 6 and 12 reveals a close correspondence between patches
of monotonic units and high PABL units and between patches of nonmonotonic units and
low PABL units. This correspondence is consistent with the data obtained from multi-
units responses recorded along a linear sequence of penetrations within an isofrequency
contour of AI (Heil et al, 1994). Similar to the monaural condition, the congruency of a
low PABL patch with a BNM patch is quite reasonable because nonmonotonic activity
should be expected to peak at lower ABLs than would monotonic activity. This
congruency could raise the question whether the functional importance of these patches
for the coding of stimulus level is the differences among patches in PABL or to the
differences in binaural monotonicity. The population data presented in Figure 10 of the
accompanying paper (Zhang et. al) could be pertinent to this question. The arithmetic
centers of the PBCS (CBPC) of EE and EO cells are distributed over the entire range of
ABLS examined in these studies. The CPBCs of PB units varied over the upper half of
the tested range of ABLS. For each of these three large categories of cortical units, the
great majority of neurons whose CPBCs were located at low ABLs were nonmonotonic, whereas those whose CPBS were located at high ABLS were monotonic. This leads to the possibility that the functional significance of the variability of binaural monotonicity across cells is to provide the primary auditory cortex the ability to deal with the entire range of binaural stimulus level. Monotonic units appear to be focused on binaural stimuli at higher levels whereas nonmonotonic units appear to be focused on binaural stimuli at lower levels. Thus, the postulated movement of activity from patches of high PABL cells to patches of low PABL cells could be in part the consequence of the nonmonotonicity determining the ABL of low PABL neurons.

Topographical maps that do not account for ABL and ILD preferences will miss the response of a portion of AI cells. Part of AI will not respond or will respond weakly to stimuli presented monaurally or at ILDs and ABLs outside of the cells preferences. This suggests that topographical maps that do not account for this variability are likely to miss the response of a portion of AI cells and consequently result in an inadequate representation of activated neuron.

To the extent that ILD is functionally equivalent to azimuth, this study is consistent with previous work (Middlebrooks and Pettigrew, 1981; Rajan et al., 1990; Clarey et al., 1994), in that no systematic topographical representation of azimuth was found. Rather, azimuth representation appears to be distributed in clusters, with the majority of cells favoring contralateral space. In the auditory system, frequency is organized spatially in the cochlea and as a consequence of precise anatomical connectivity, the topography of the cortex reflects this organization. Similarly primary visual (VI) and somatosensory (SI) cortex reflect the spatial representation inherent in
their respective sensory epithelia. However, there is no representation of space in either of the auditory sensory epithelia. ILD, and auditory spatial cues in general, are derived cues and it appears that it is not necessary for them to be topographically represented in AI. Spatial representation in AI may be derived from connectivity between patches rather than by topographical order. The intra-cortical axons that are preferentially distributed within an isofrequency contour are ideally situated to serve this purpose. (Matsubara and Phillips, 1988; Wallace et al., 1991).

**Influence of Ipsilateral stimulation**

It has been shown that lesions in AI do not affect auditory localization in the field ipsilateral to the lesion (Jenkins and Merzenich, 1984). This raises the question about the function of the large topographically organized responses of AI (Fig. 2, 3, 8 and 11) to stimuli at ipsilateral ILDs as compared to contralateral ILDs. Physiological research has given support to the idea that each AI is independently capable of coding sound localization in the contralateral sound field (Phillips and Irvine, 1981). It has been suggested that the ipsilateral representation in AI is necessary for fine spatial localization (Rajan et al., 1990), however this has not been tested behaviorally. Another possibility, of course, is that the topographical response at ipsilateral ILDs serves another function besides spatial localization.

**Representation of Isofrequency contour**

This study demonstrates that in the binaural condition, similar to the monaural condition (Phillips et al., 1994), an isofrequency contour is not representative of the functional response of primary auditory cortex to a given stimulus. While an
Response of AI to stimuli varying in ABL and ILD

isofrequency contour is representative of the threshold responses of AI cells, it is not indicative of the response of AI to binaural stimuli at moderate to high levels. The thresholds of AI cells vary greatly such that at any given stimulus level only a portion of the cells in an isofrequency contour respond. Overall, changes in the frequency, ABL, or ILD of a stimulus will evoke a response from a subpopulation of cells in AI, and the subpopulation will change with changes in a stimulus’s frequency, ABL, or ILD. This suggests that isofrequency contours may not be functionally important. A more useful functional representation could be a measure of the spatial distribution of activity as a function of stimulus level.
References


Tunturi AR. A difference in the representation of auditory signals from the left and the right ears in the isofrequency of the right middle ectosylvian auditory cortex of the dog. *Am J Physiol* 712-727, 1952.


Figure Legend

Figure 1

The stimulus matrix was composed of 30 points, each point was repeated 40 times. ABL and ILD have a direct relationship to dB SPL. ILD: contralateral dB – ipsilateral dB. ABL (contralateral dB + ipsilateral dB)/2. A stimulus with an ILD of +20 and an ABL of 30 is equivalent to a stimulus with a contralateral level of 40 dB SPL and an ipsilateral level of 20 dB SPL. A and E: responses of a Binaurally Nonmonotonic cell are represented on the two pairs of axes. B, D and F: responses of a Binaurally Monotonic (BM) cell. A, B, E, F: response magnitude indicated by gray scale. C & D: ILD of response functions indicated to right of each graph.

Figure 2

The topographical response of all cells in experiment 01k001 to each condition is presented. Each contour graph represents the response of all neurons to the indicated stimulus. The z-axis is response magnitude as indicated by the gray scale. The x-axis is the anterior-posterior distance in mm along the cortex. The y-axis is the dorsal-ventral distance in mm along the cortex. The open circles in the lower left graph indicate the spatial position of the electrode penetrations.

Figure 3

The topographical response of all cells to each condition is presented for animal 01k008. (See legend of Fig. 2 for explanation of axes and data panels)
Figure 4

The topographical response of all cells in 01k001 to the monaural contralateral rate/level function is presented. (See legend of Fig. 2 for explanation of axes and data panels)

Figure 5

The topographical response of all cells in 01k008 to the monaural contralateral rate/level function is presented. (See legend of Fig. 2 for explanation of axes and data panels)

Figure 6

Topographical distribution of BM and BNM cells along an isofrequency contour in each of the five animals. (○):BM cells; (●):BNM cells; (△) mixed cells. The various lines represent blood vessels, which prohibited recording within those areas. Clear patches of BM and BNM cells are present in all graphs except for 6B.

Figure 7

Topographical distribution of maximum ABL response functions of individual cells for 01k001, 01k003, 01k004, and 01k008. AP: x axis; DV: y axis. The x-axis of the line graphs is ABL. The y-axis is the response of the cell in %, compared to the maximum response of the cell. Shaded lines separate BNM and BM areas. Shaded response functions in the BNM patches are cells with low binaural monotonicity; normal line graphs indicate cells with high binaural monotonicity. Thick line graphs in the BM
patches indicate saturating response functions; normal line graphs indicate non-saturating response functions. Line graphs with plus signs indicate mixed cells.

**Figure 8**
The topographical response of all cells to each condition is presented for animal 01k003. The axis are the same as Fig 2, however in this figure each of the patches in plotted separately.

**Figure 9**
Topographical distribution of monaural response types. The lines separate the different response types.

**Figure 10**
Topographical distribution of binaural interaction classifications. F: facilitatory; I: inhibitory; M: mixed. The lines separate the different response types.

**Figure 11**
Topographical distribution of PILD for all animals. PILD: average ILD of the stimulus points in the PBC. Positive numbers represent PILDs that favor the contralateral ear and negative numbers represent PILDs that favor the ipsilateral ear. The other ILD preferences were unselective to level (UL) and multi-peaked (MP). The dotted lines indicate groups of contralaterally (C), midline (M) and ipsilaterally (I) preferential cells.
Figure 12

Topographical distribution of PABL for all animals. PABL: average ABL of the stimulus points in the PBC. UL: unselective to level; MP: multi-peaked. The lines separate high PABL (>45 ABL) from low PABL (≤ 45 ABL) areas.

Figure 13

The change in PABL response for 01k003 as a function of ABL. The x and the y axis respectively represent the AP and DV. Grey areas represent cells that are responding within their PABL, which is ≥ 80% of their maximum response. White areas represent a response which is < 80% of their maximum response. ●: BNM cells with low nonmonotonicity; ■: BNM cell with high nonmonotonicity; ▲: saturating BM cells. In this animal there were no non-saturating BM cells. The graphs from left to right represent increasing ABL.
Response of AI to stimuli varying in ABL and ILD

Table 1. Distribution of the various classifications. N: number of cells; % percentage of cells.

<table>
<thead>
<tr>
<th>Monaural Response</th>
<th>N</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>EO</td>
<td>62</td>
<td>48%</td>
</tr>
<tr>
<td>OE</td>
<td>10</td>
<td>7%</td>
</tr>
<tr>
<td>EE</td>
<td>27</td>
<td>21%</td>
</tr>
<tr>
<td>PB</td>
<td>31</td>
<td>24%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Binaural Interaction</th>
<th>N</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facilitatory (F)</td>
<td>49</td>
<td>37%</td>
</tr>
<tr>
<td>Inhibitory (I)</td>
<td>39</td>
<td>30%</td>
</tr>
<tr>
<td>Mixed (M)</td>
<td>40</td>
<td>31%</td>
</tr>
<tr>
<td>Non-interacting(N)</td>
<td>2</td>
<td>2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Binaural Monotonicity</th>
<th>N</th>
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</thead>
<tbody>
<tr>
<td>Binaurally Monotonic (BM)</td>
<td>51</td>
<td>39%</td>
</tr>
<tr>
<td>Binaurally Nonmonotonic (BNM)</td>
<td>62</td>
<td>48%</td>
</tr>
<tr>
<td>Mixed Response (MR)</td>
<td>17</td>
<td>13%</td>
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<table>
<thead>
<tr>
<th>PILD</th>
<th>N</th>
<th>%</th>
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</thead>
<tbody>
<tr>
<td>Con (≥ +10 ILD)</td>
<td>53</td>
<td>41%</td>
</tr>
<tr>
<td>Ipsi (≤ -10 ILD)</td>
<td>20</td>
<td>15%</td>
</tr>
<tr>
<td>Mid (&gt; -10, &lt;+10 ILD)</td>
<td>39</td>
<td>30%</td>
</tr>
<tr>
<td>UL or MP</td>
<td>18</td>
<td>14%</td>
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<table>
<thead>
<tr>
<th>PABL</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>High PABL (&gt;45 ABL)</td>
<td>58</td>
<td>45%</td>
</tr>
<tr>
<td>Low PABL (&gt;45 ABL)</td>
<td>58</td>
<td>45%</td>
</tr>
<tr>
<td>UL or MP</td>
<td>14</td>
<td>10%</td>
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Table 2. Distribution of binaural monotonicity over the monaural classification, binaural interactions classification, and PABL.

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<tr>
<th>Monaural Response</th>
<th>BM</th>
<th>BNM</th>
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<tr>
<td>EO</td>
<td>42%</td>
<td>45%</td>
</tr>
<tr>
<td>OE</td>
<td>10%</td>
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<td>EE</td>
<td>37%</td>
<td>44%</td>
</tr>
<tr>
<td>PB</td>
<td>45%</td>
<td>48%</td>
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<table>
<thead>
<tr>
<th>Binaural Interaction</th>
<th>BM</th>
<th>BNM</th>
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</thead>
<tbody>
<tr>
<td>Facilitatory (F)</td>
<td>43%</td>
<td>41%</td>
</tr>
<tr>
<td>Inhibitory (I)</td>
<td>39%</td>
<td>48%</td>
</tr>
<tr>
<td>Mixed (M)</td>
<td>37%</td>
<td>52%</td>
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<table>
<thead>
<tr>
<th>PABL</th>
<th>BM</th>
<th>BNM</th>
</tr>
</thead>
<tbody>
<tr>
<td>High PABL (&gt;45 ABL)</td>
<td>95%</td>
<td>13%</td>
</tr>
<tr>
<td>Low PABL (&lt;45 ABL)</td>
<td>2%</td>
<td>87%</td>
</tr>
<tr>
<td>UL or MP</td>
<td>3%</td>
<td>0%</td>
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Table 3. Distribution of the maximum spike count of the cells.

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<th>Maximum Spike Response</th>
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<tr>
<td>1-10</td>
<td>0</td>
</tr>
<tr>
<td>11-20</td>
<td>4</td>
</tr>
<tr>
<td>21-30</td>
<td>10</td>
</tr>
<tr>
<td>31-40</td>
<td>24</td>
</tr>
<tr>
<td>41-50</td>
<td>30</td>
</tr>
<tr>
<td>51-60</td>
<td>28</td>
</tr>
<tr>
<td>61-70</td>
<td>20</td>
</tr>
<tr>
<td>71-80</td>
<td>13</td>
</tr>
<tr>
<td>81-90</td>
<td>5</td>
</tr>
<tr>
<td>91-100</td>
<td>4</td>
</tr>
<tr>
<td>&gt;100</td>
<td>3</td>
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Table 4. The mean and standard deviation for each of the Binaurally nonmonotonic patches.

<table>
<thead>
<tr>
<th>Animal</th>
<th>Mean Binaural Nonmonotonicity</th>
<th>Stdev</th>
</tr>
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<tbody>
<tr>
<td>01k001</td>
<td>79%</td>
<td>25%</td>
</tr>
<tr>
<td>Dorsal 01k003</td>
<td>53%</td>
<td>24%</td>
</tr>
<tr>
<td>Ventral 01k003</td>
<td>87%</td>
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<tr>
<td>01k004</td>
<td>54%</td>
<td>28%</td>
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<tr>
<td>01k008</td>
<td>55%</td>
<td>30%</td>
</tr>
<tr>
<td>01k009</td>
<td>67%</td>
<td>21%</td>
</tr>
</tbody>
</table>
Response of AI to stimuli varying in ABL and ILD -47-

Figure 2
Response of AI to stimuli varying in ABL and ILD -48-
Response of AI to stimuli varying in ABL and ILD -49-

Figure 4
Response of AI to stimuli varying in ABL and ILD -50-
Response of AI to stimuli varying in ABL and ILD -51-
Response of AI to stimuli varying in ABL and ILD -52-

Figure 7
Figure 9
Response of AI to stimuli varying in ABL and ILD -55-

Figure 10
Figure 11
Response of AI to stimuli varying in ABL and ILD -58-

Figure 13