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Mapping responses to frequency sweeps and tones in the inferior colliculus of house mice

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Abstract

In auditory maps of the primary auditory cortex, neural response properties are arranged in a systematic way over the cortical surface. As in the visual system, such maps may play a critical role in the representation of sounds for perception and cognition. By recording from single neurons in the central nucleus of the inferior colliculus (ICC) of the mouse, we present the first evidence for spatial organizations of parameters of frequency sweeps (sweep speed, upward/downward sweep direction) and of whole-field tone response patterns together with a map of frequency tuning curve shape. The maps of sweep speed, tone response patterns and tuning curve shape are concentrically arranged on frequency band laminae of the ICC with the representation of slow speeds, build up response types and sharp tuning mainly in the centre of a lamina, and all (including high) speeds, phasic response types and broad tuning mainly in the periphery. Representation of sweep direction shows preferences for upward sweeps medially and laterally and downward sweeps mainly centrally in the ICC (either striped or concentric map). These maps are compatible with the idea of a gradient of decreasing inhibition from the centre to the periphery of the ICC and by gradients of intrinsic neuronal properties (onset or sustained responding). The maps in the inferior colliculus compare favourably with corresponding maps in the primary auditory cortex, and we show how the maps of sweep speed and direction selectivity of the primary auditory cortex could be derived from the here-found maps of the inferior colliculus.

Introduction

In the midbrain inferior colliculus (IC), at least 19 major and minor pathways from auditory brainstem nuclei (Ehret, 1997a; Pollak *et al.*, 2003) converge. Input projections (Kudo & Nakamura, 1988; Young *et al.*, 1988; Helfert *et al.*, 1991; Oliver & Shneiderman, 1991), excitatory and inhibitory innervation (Oliver *et al.*, 1994; Le Beau *et al.*, 1996; Helfert & Aschoff, 1997; Ma *et al.*, 2002a,b), and intrinsic properties of IC neurons (Wagner, 1994, 1996; Kuwada *et al.*, 1997; Reetz & Ehret, 1999; Peruzzi *et al.*, 2000; Sivaramakrishnan & Oliver, 2001; Bal *et al.*, 2002) are complex. Hence, we do not understand how the diversity of neural response patterns (Ehret, 1997a) may arise and how they contribute to acoustical signal representation. One approach to understand IC function is to map the three-dimensional IC space for neural response properties to define gradients and local clusters of neurons with property combinations favourable for encoding certain sound features. Besides the well-documented tonotopy, only a few studies showed rather orderly spatial gradients (maps) of tone response thresholds (Stiebler, 1986), latencies (Schreiner & Langner, 1988a), sharpness of frequency tuning (Stiebler, 1987; Schreiner & Langner, 1988a,b), shapes of tuning curves (Ehret *et al.*, 2003), frequency resolution (Ehret, 1997a; Schreiner & Langner, 1997), best-modulation frequency to amplitude-modulated tones (Schreiner & Langner, 1988a,b; Langner *et al.*, 2002) and best-azimuth angle (Aitkin *et al.*,

1985; Binns *et al.*, 1992). Some of these maps appear concentric on frequency band laminae (according to Schreiner & Langner, 1997; this term will be used here instead of isofrequency planes), others as gradients along one of the spatial dimensions of the IC (Ehret, 1997a).

Here, we examine the spatial pattern of responses to frequency sweeps, tone response patterns, tuning curve shapes and sharpness of tuning in the main (central) nucleus of the inferior colliculus (ICC). Our first goal is to investigate the selectivity of neurons to directions (upward, downward) and speeds of linear frequency sweeps as a function of neuron location. Although responses to frequency sweeps have been studied (Suga, 1969; Clopton & Winfield, 1974; Vartanian, 1974; Pollak *et al.*, 1978; Vater, 1981; Poon *et al.*, 1991, 1992; Fuzessery, 1994; Felsheim & Ostwald, 1996; Fuzessery & Hall, 1996; Ferragamo *et al.*, 1998; Lee *et al.*, 2002), spatial distributions of sensitivities to sweep parameters are unknown. The mapping aspect is important, however, because maps of sweep direction and speed have been found in the primary auditory cortex (AI) (Mendelson *et al.*, 1993; Shamma *et al.*, 1993; Nelken & Versnel, 2000). Hence, we propose how collicular maps (three-dimensional space) may turn into cortical maps (two-dimensional space).

Our second goal relates to mechanisms shaping neural preferences for speeds and directions of frequency sweeps. It is unclear how far inhibitory mechanisms influence directional selectivities of neurons (e.g. Suga, 1969; Mendelson *et al.*, 1993; Fuzessery, 1994; Felsheim & Ostwald, 1996; Fuzessery & Hall, 1996). By correlating responses to frequency sweeps with responses to tones and shapes of frequency tuning curves, we will show whether sweep responses can be predicted from responses to stationary tones.

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Materials and methods

Animals and surgery

Recordings were taken from female house mice (*Mus domesticus*, four subjects outbred strain NMRI, 17 subjects hybrids of outbred strain NMRI and feral mice), aged 12–15 weeks. Surgical anaesthesia was induced with ketamine (Ketavet, 120 mg/kg body weight) and xyla-zine (Rompun, 5 mg/kg) intraperitoneally. The skin over the dorsal surface of the skull was removed and a 1.5-cm-long brass bar fixed to the frontal-parietal bones with cyanoacrylate glue and cement (Technovit 3040). The bar was locked into a metal holder to immobilize the mouse head. The skull and the dura over the IC contralateral to the direction of the sound source were removed. The animal was then placed on a feedback-controlled heating pad which maintained its rectal temperature at $37 \pm 1 °C$. Warm Ringer's solution was applied on the brain after every electrode placement. During the recording session (lasting up to about 8 h), a light anaesthetic state was maintained by administering doses of ketamine (35 mg/kg) and xylazine (1 mg/kg) when necessary (about every 20–45 min). During the whole recording session, animals were monitored by a video-camera, which showed that the animals remained quietly, without indication of pain or distress (no body or pinna movements were observed), but responded with a light withdrawal reflex in response to toe pinch. At the end of the recordings, the still anaesthetized animals were killed by cervical dislocation. The experiments were carried out in accordance with the European Communities Council Directive (86/609/EEC) and were approved by the appropriate authority (Regierungsprä-sidium Tübingen, Germany).

Neurophysiological recording

Steel electrodes (impedance 2–5 MΩ, modified after Green, 1958) were placed stereotaxically (with reference to the λ-point of the skull) on the visible surface of the IC. The alignment of the electrode tip with the λ-point was done under microscopic control (OPMI 11, Zeiss, Oberkochen, Germany) with remote-controlled motorized microdrives for both rostrocaudal and mediolateral coordinates (PM 10, Science Products, Hofheim, Germany). The precision of the alignment of the electrode tip with the λ-point was in the order of $\pm 40 \mu m$. After this calibration of the electrode position in the horizontal plane, the electrode tip was moved by the microdrives to a position above the IC that was defined in the horizontal plane (rostrocaudal and medio-lateral coordinates) by the readings (10 μm accuracy) from microdrive scales. Then, the electrode tip was advanced in a dorso-ventral orientation into the ICC by another remote-controlled microd-rive (SPI Nanostepper, Scientific Precision Instruments, Oppenheim, Germany). Sampling did not include the most anterior, posterior, medial and lateral parts of the IC, and was restricted to 0.85–1.8 mm caudal and 0.5–2.0 mm lateral of the λ-point. This area of recording has been shown to correspond to the ICC of the mouse (Sidman *et al.*, 1981; Stiebler & Ehret, 1985; Romand & Ehret, 1990).

Neural responses (action potentials) were amplified 2000–10,000 times and band-pass filtered (0.4–4 kHz; JHM NeuroAmp 401, Helbig Messtechnik, Mainaschaff, Germany). The responses were fed in parallel: (i) to a computer (Macintosh Power PC 7300 with American Instruments Powerlab System, software: chart 3.6.1, digiti-zation rate 20 kHz and 16-bit amplitude resolution, WissTech, Spech-bach, Germany) for online control; (ii) to a window discriminator (Heinecke, Pöcking, Germany) to be transformed into standard TTL pulses that were passed to the same computer for storage and offline analysis and to another computer (PC Pentium) for taking automatic tuning curves; and (iii) to an oscilloscope and audio-monitor for audio-visual control.

Stimulus generation

Bursts of pure tones and frequency sweeps were used as acoustic stimuli. Tones used as search stimuli were produced by a generator (Kenwood AG-253, Hames, München, Germany) and shaped by an electronic switch (Uni-Konstanz-Elektronik, Konstanz, Germany) into 60-ms tone bursts (including 5 ms rise and fall times) with 120-ms intertone intervals. Tones (50 ms duration including 5 ms rise and fall times, 60-ms intertone intervals) used for the measurement of exci-tatory tuning curves were generated by a computer-controlled program (PC Pentium with a TMS320C30 D/A converter at 120 kHz conversion rate, software by Dr Ekkehard Schulze-Krüger). Linear frequency sweeps of defined (digitally set) sweep speed, frequency range and sweep direction were generated by a digital sweep generator (Hewlett-Packard 33120 A, Hewlett-Packard, Böblingen, Germany) triggered by the electronic switch that also controlled the timing of the sweeps (see below). The output signals of all above-mentioned equipment were adjusted in level (Kenwood RA 920 A attenuator, Hames, München, Germany), monitored by an oscilloscope and fed: (i) through a power amplifier (Denon, PMA-1060, Dörner, Ulm, Ger-many) to a dynamic speaker (CF-12HC-4) for sounds below 15 kHz; and (ii) through a custom-made voltage amplifier and power supply to an electrostatic speaker (Machmerth *et al.*, 1975) for sounds of 15 kHz and higher frequencies. The speaker system covered frequencies between 1 and 100 kHz and had a flat ± 6 dB response in a range of 1–50 kHz at the site of the animal's pinna.

The mouse was placed in a soundproof and anechoic room. Sounds were presented free-field from anterior, 45° to the right of the mouse sagittal plane and thus contralateral to the recorded IC (Egorova *et al.*, 2001). The distance between the animal and the speakers was 30 cm. The sound pressure levels of tones and frequency sweeps used in the experiments were measured at the animal's right pinna (Brüel and Kjaer, 6.5 mm calibrated microphone 4135 with preamplifier 2633 and measuring amplifier 2636, Brüel & Kjaer, Quickborn, Germany). At the maximum sound pressure levels used (about 90 dB), harmonic distortions were at least 35 dB (mostly more than 50 dB) below the level of the fundamental frequency (spectrum analyser, Ono Sokki CF-5220, Compumess Electronic, Unterschleißheim, Germany).

Experimental procedure

After isolating the response of a single neuron (spikes of defined shape and amplitude) with a characteristic frequency (CF) aimed to be near 20 kHz (most sensitive hearing range in mice; Ehret, 1974), the neuron's CF and tone threshold were determined audio-visually in order to centre the following measurements at the approximate CF. Then, the conventional excitatory tuning curve was taken automati-cally (computer-controlled) over a frequency range of about one and a half octaves below and above the CF and sound pressure levels from 0 dB SPL up to 90 dB SPL. Stimulus presentation was performed in pseudo-random sequences of $15 \times 45 = 675$ different frequency–intensity combinations. The recorded data were used for determining the exact CF, which was necessary for setting the parameters of the 300 kHz/s frequency sweeps (see below), and for offline analysis of excitatory receptive field properties.

Linear frequency sweeps (upward and downward sweeps) of sweep speeds (rate of change of frequency) of 300 kHz/s, 600 kHz/s and 3 MHz/s having durations (including rise and fall times of 5 ms) of 120 ms, 120 ms and 60 ms, respectively, were used. Thus, the sweeps of 300 kHz/s speed covered a frequency range of 36 kHz, sweeps of 600 kHz/s a range of 72 kHz, and sweeps of 3 MHz/s a range of 180 kHz. At 600 kHz/s speed, frequencies swept from 1 to 73 kHz (upward sweep) or from 73 to 1 kHz (downward sweep), at 3 MHz/s

speed from 1 to 181 kHz or from 181 to 1 kHz, respectively. At 300 kHz/s speed, the sweeps started about two octaves below (upward sweep) or one octave above (downward sweep) a neuron's CF. Frequency sweeps (at levels of up to 50 dB above threshold) across these frequency ranges ensured that the sweeping tones started outside the excitatory (and the suggested inhibitory) receptive fields of neurons (Egorova *et al.*, 2001) so that tones swept through receptive fields without producing any onset or offset transients. The chosen sweep speeds and durations were within the ranges found in communication calls of mice (Ehret, 1975; Haack *et al.*, 1983; Ehret & Riecke, 2002). Similar sweep speeds have already been used in earlier studies on neural sensitivity to frequency sweeps in bats (O'Neill & Brimijoin, 2002) and non-echolocation animals like cats (Mendelson *et al.*, 1993) and ferrets (Nelken & Versnel, 2000). Every sweep of defined frequency range, direction and speed was presented 10 times at inter-sweep intervals of 250 ms, always at the three stimulus levels of 10 dB, 30 dB and 50 dB above a neuron's CF threshold. With the frequency ranges mentioned above, frequency sweeps started and ended outside the excitatory frequency tuning curves of all recorded neurons at all levels used (see Results).

Taking one whole set of data from an isolated single unit lasted about 45 min.

Data analysis

The recordings were analysed to obtain the following neural response properties.

(i) Excitatory frequency tuning curves. They were classified according to Egorova *et al.* (2001) into four classes: class I neurons had shallow slopes (< 150 dB/octave) and steep slopes (> 250 dB/octave) at their low-frequency and high-frequency sides, respectively, i.e. many of these neurons had tuning curves similar to auditory nerve fibres; class II neurons were sharply tuned, i.e. had steep slopes at both sides (low-frequency side: slope > 150 dB/octave; high-frequency side: slope > 250 dB/octave), and some neurons had closed or tilted tuning curves because of strong inhibitory input; class III neurons had shallow slopes at both sides (low-frequency side: slope < 150 dB/octave; high-frequency-side: slope < 250 dB/octave), i.e. had a rather broad tuning with little inhibitory influence; class IV neurons had a complex shape, i.e. more than one CF. Example tuning curves of class I–III neurons are shown in Fig. 1A (class IV neurons were not recorded in the present study). Figure 1B and C demonstrates the validity of classification of the tuning curves of our present sample according to the above-mentioned criteria of the steepness of slopes. The sharpness of tuning of class I–III neurons was evaluated by calculating Q_{10} and Q_{40} values (CF divided by the tuning curve bandwidth at 10 dB and 40 dB above the threshold at CF, respectively).

(ii) Tone–response patterns. Peristimulus time histograms (PSTHs) in response to tone bursts, collected from the responses within the whole excitatory receptive field of a neuron, were generated to classify the neurons in phasic (only one or few spikes with short latency after tone onset), phasic–tonic (a short-latency response peak followed by a tonic response at a lower rate throughout the tone duration), pauser (a phasic response followed by a pause with little activity before occurrence of the tonic component), build up (a gradual increase of spike rate after tone onset to a broad peak or a tonic level), and other (tonic, chopper, off) response types. We call this sort of PSTH a 'whole-field PSTH' in order to discriminate it from the conventional PSTHs that are usually generated at some level above threshold at the CF of a neuron. Example whole-field PSTHs of phasic–tonic, phasic, pauser and build up response types are shown in Fig. 2.
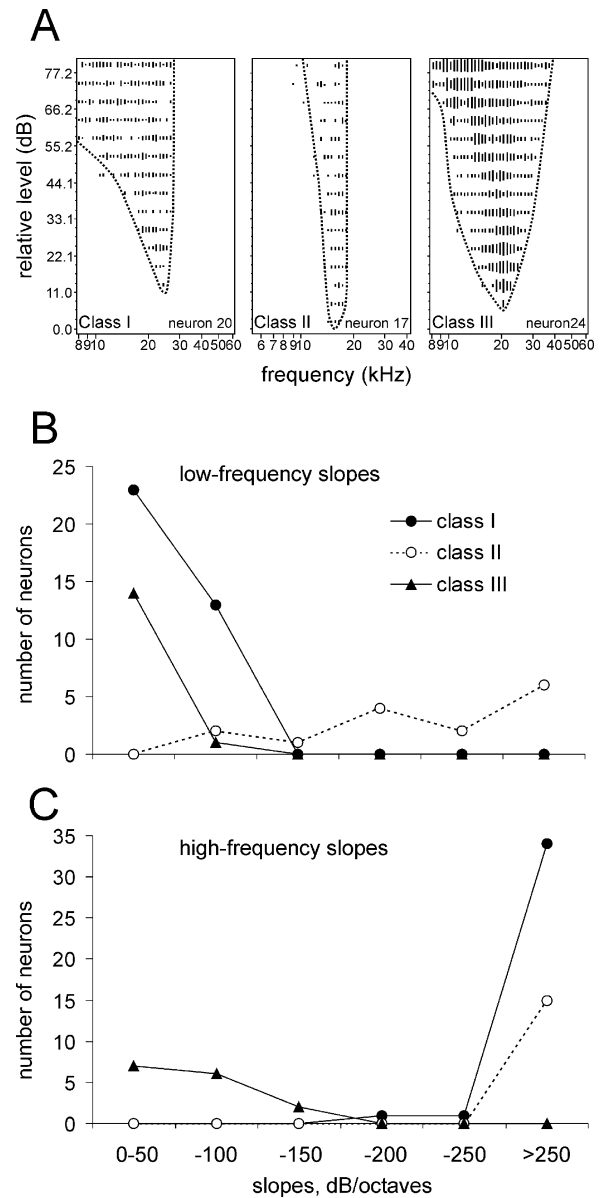

FIG. 1. (A) Examples of excitatory frequency response areas with the surrounding tuning curves are shown for a neuron each of the tuning curve class I, class II and class III. (B) and (C) Division of the tuning curves into the three classes according to the steepness of their low-frequency (B) and high-frequency (C) slopes. All class I and class III neurons have low-frequency slopes < 150 dB/octave. All except two class II neurons, which have tilted tuning curves and, thus, also belong to class II, have low-frequency slopes > 150 dB/octave. Only class III neurons have high-frequency slopes < 250 dB/octave.

(iii) Neural responses to frequency sweeps were determined with regard to preferences of sweep direction and sweep speed for sweeps presented at 30 dB and 50 dB above threshold at CF. We did not include the measurements at 10 dB above threshold for the assessment of responsiveness to frequency sweeps. All neurons responding to sweeps at 10 dB sound level responded more regularly and with higher rates at the higher sound levels, and several neurons did not respond at 10 dB but at 30 dB and 50 dB super-threshold tone level so that the responses at the higher sound levels were more reliable to characterize a neuron's preference for sweep direction and sweep speed.

The criterion for a response to a given sweep was a spike rate of at least 15% above the spontaneous activity or more than three spikes to
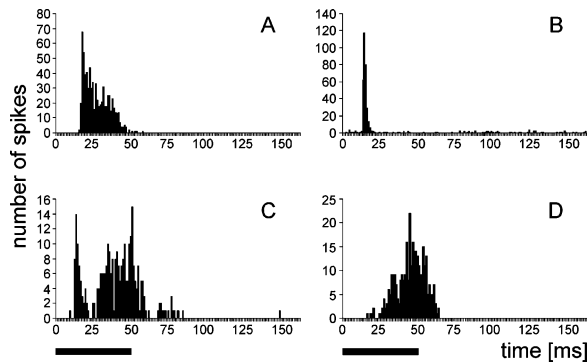
FIG. 2. PSTHs taken from the whole excitatory area (compare Fig. 1A) of a neuron (whole-field PSTH) show (A) phasic–tonic, (B) phasic, (C) pauser and (D) build up tone response pattern.

20 stimulus repetitions (10 repetitions at 30 dB and 10 at 50 dB above threshold) in case of low ($<$ one spike/s) or no spontaneous activity. Neurons were considered direction selective when they produced at least twice the spike rate for sweeps in one direction compared with the other, at least at one of the three sweep speeds used. This criterion has widely been used before (e.g. Mendelson & Cynader, 1985; Heil et al., 1992a,b; Mendelson & Grasse, 1992; Tian & Rauschecker, 1994; Gaese & Ostwald, 1995) and corresponds to a direction-selective index of:

$$(\text{rate}_{up} - \text{rate}_{down})/(\text{rate}_{up} - \text{rate}_{down}) = \pm 0.33.$$

Results

The results are based on a sample of 66 single units from the left-side ICC of 21 mice. From each of these units, the whole set of data (described in the following) has been obtained and analysed. Further seven units with incomplete data sets (six units) or a possible location outside the ICC (one unit) are not considered here to ensure a homogenous data sample from the ICC that is used for correlations between the measures taken. Except for three mice contributing seven, nine or 10 units, the average number of successfully recorded units per mouse was two–three.

The locations of the neurons in the ICC are shown in Fig. 3A in mediolateral (x-axis) and rostrocaudal (y-axis) coordinates with reference to the λ-point of the skull (origin of the coordinates). All locations are projected to one horizontal plane corresponding to a horizontal projection of a frequency band lamina between 15 and 20 kHz of the mouse ICC. Based on previous studies in which the tonotopy in the mouse ICC was mapped together with a histological evaluation (Stiebler & Ehret, 1985; Romand & Ehret, 1990), we were able to reconstruct the outer border of the ICC in the shown horizontal projection of the frequency band lamina (the heavy dashed line in Fig. 3A). The centre of this lamina can be assumed to be at the coordinates 1.2 mm/1.2 mm (Sidman et al., 1981; Stiebler & Ehret, 1985; Romand & Ehret, 1990). According to this delimitation of the ICC borders, all neurons of the present study belong to the ICC (Fig. 3A).

All neurons responded to pure tones and had CFs between 12 and 32 kHz. The mean CF was 18.2 kHz with a standard deviation of 3.4 kHz. The distribution of CFs of the recorded neurons on the horizontal projection of the frequency band lamina is shown in Fig. 3B. The mean CFs in the four concentric zones (I–IV, Fig. 3A and B) varied between 17 kHz and 18.8 kHz without significant differences between the zones (ANOVA). There is no statistically significant CF-bias for any of the distributions of response parameters (tuning curve
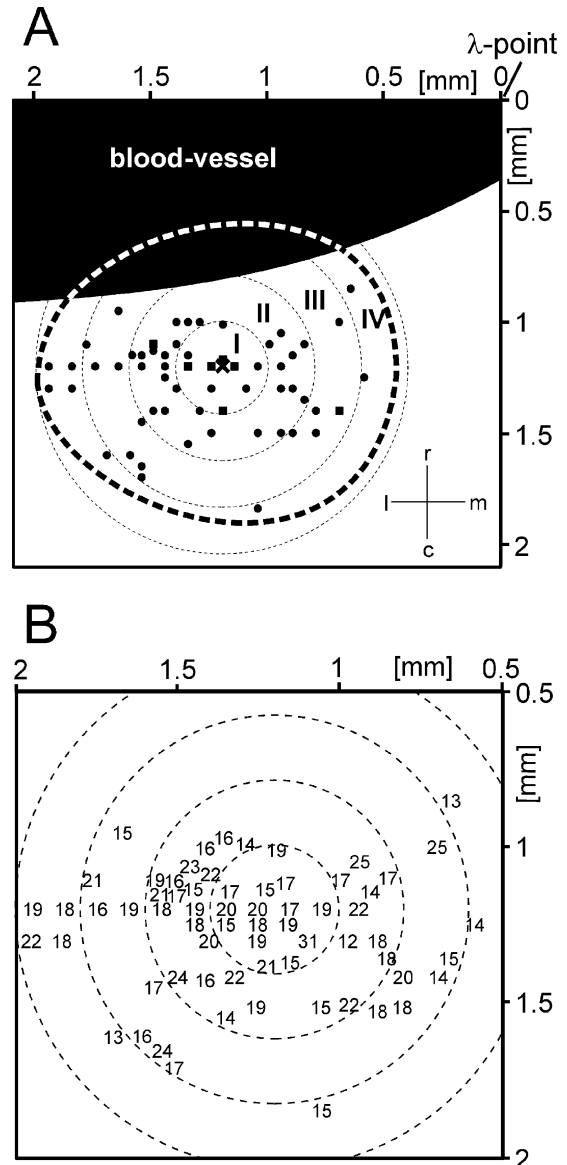

FIG. 3. (A) Locations of the recorded neurons in the ICC in mediolateral (x-axis) and rostrocaudal (y-axis) coordinates with reference to the λ-point of the skull. All recording sites are projected to the shown horizontal plane corresponding to a horizontal projection of a frequency band lamina between 15 and 20 kHz of the mouse ICC (Stiebler & Ehret, 1985; Romand & Ehret, 1990). The heavy dashed line indicates the approximate outer border of the ICC, the thin dotted lines separate the four zones (I, II, III, IV), into which the ICC was divided. Dots: sites of one recorded neuron; squares: sites of two recorded neurons; c, caudal; l, lateral; m, medial; r, rostral. (B) CFs of the recorded neurons and their locations on the shown horizontal projection of the frequency band lamina of the ICC (compare A).

classes, tone response types, behaviour to sweeping tones) studied (ANOVA). Tone–response thresholds shown in Fig. 4 varied between 0 and 35 dB SPL.

Selectivity to sweep direction: spatial distribution

All but five neurons responded at least to one of the parameter combinations used in the tests with frequency sweeps. We found 34 neurons (56% of all sweep-sensitive neurons) being direction selective at least at one of the sweep speeds used. The locations of these neurons in the ICC are shown in Fig. 5A. According to our criterion, only three neurons (9%) were direction selective at the three sweep speeds presented, the majority were selective only at one or two speeds
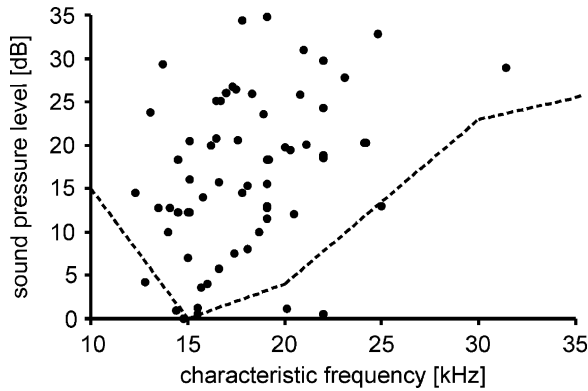
FIG. 4. Tone response thresholds plotted as a function of the characteristic frequencies for all recorded neurons. The dashed line shows the behavioural auditory threshold curve of the mouse (Ehret, 1974).

FIG. 6. Percentages of direction-selective (upward, downward) neurons in strips of 200 µm width placed along the mediolateral coordinate starting at 600 µm from the λ-point (mid-sagittal plane).

(Fig. 5B–D) and non-selective at the other(s). However, only one neuron (marked with a square in Fig. 5A) changed its selectivity with changing sweep speed from downward selective (300 kHz/s) to upward selective (600 kHz/s). This neuron is not considered in the following quantifications of sweep direction selectivity.

Non-direction-selective neurons were distributed all over the recorded ICC space (Fig. 5A). Downward sweeps were preferred by 20 (59%) and upward sweeps by 13 (38%) of the direction-selective neurons. For a statistical analysis of the spatial distribution of sweep direction selectivity in the ICC, we divided the ICC containing direction-selective neurons (Fig. 5A) along the mediolateral coordinate into strips of 200 µm width, starting at 600 µm from the mid-sagittal plane. Figure 6 shows the proportions of upward-selective and downward-selective neurons in these strips. By combining the strips to a lateral zone (1.4–2 mm mediolateral coordinate) and a central zone (0.8–1.4 mm), leaving one strip for a small medial zone (0.6–0.8 mm),

a significantly non-homogeneous spatial distribution occurred for neurons preferring sweep direction (X^2-test, $P < 0.01$). Significantly more downward-selective neurons were found in the central zone compared with the medial zone (Fishers exact test, $P < 0.02$) and with the lateral zone (X^2-test, $P < 0.005$); in both the latter zones, almost all upward-selective neurons were located.

When we analysed the distribution of upward- and downward-selective neurons in the four concentric zones of the ICC indicated in Fig. 3A and B, we found a non-homogeneous distribution (X^2-test, $P < 0.05$) with downward selectivity dominating in the centre and upward selectivity in the periphery of the ICC. Thus, the direction selectivity in the ICC is compatible with two different models of spatial distributions. Both models indicate that if neurons are selective at all, they are predominantly downward selective in a central zone and predominantly upward selective in the periphery, mainly in a small medial and a larger lateral zone.

Sensitivity to sweep speed: spatial distributions

In addition to the five neurons non-responsive to sweeps at all, four neurons were non-responsive to 300 kHz/s, six neurons to 600 kHz/s and 20 neurons to 3 MHz/s. This is a statistically significant increase of non-responding neurons with increasing sweep speed ($P < 0.01$; linear regression with correlation coefficient $r > 0.9999$). Figure 5D indicates that neurons non-responding to 3 MHz/s were not evenly distributed over the frequency band lamina because many neurons in the centre (zone I) of the ICC did not respond to this speed. In order to quantify a possible concentric increase in the responsiveness to increasingly higher sweep speeds from the ICC centre to its periphery, the ICC was divided into the four concentric zones (I–IV) shown in Fig. 3A and B, and the percentages of neurons responding to each sweep speed (without considering possible sweep direction preferences) plotted for each zone (Fig. 7A). It is evident that the proportion of neurons responding to 300 kHz/s constantly decreased from the centre (zone I) to the periphery (zone IV) of the ICC (from 45% to 30%) while, at the same time, the proportion of neurons responding to 3 MHz/s increased from 14% to 35%. These decreases or increases are both statistically significant ($P < 0.05$, linear regressions with correlation coefficients $r > 0.95$ in both cases).

In another kind of analysis, average spike rates (including rates at both sweep directions and 30 dB and 50 dB above threshold levels) were calculated in the four zones for neurons responding to 300 kHz/s, 600 kHz/s and 3 MHz/s. This measure considers not only the distribution of responding and non-responding neurons but also possible differences in the response strength at the three speeds. The results are shown in Fig. 7B. Neurons in the centre of the ICC (zone I)
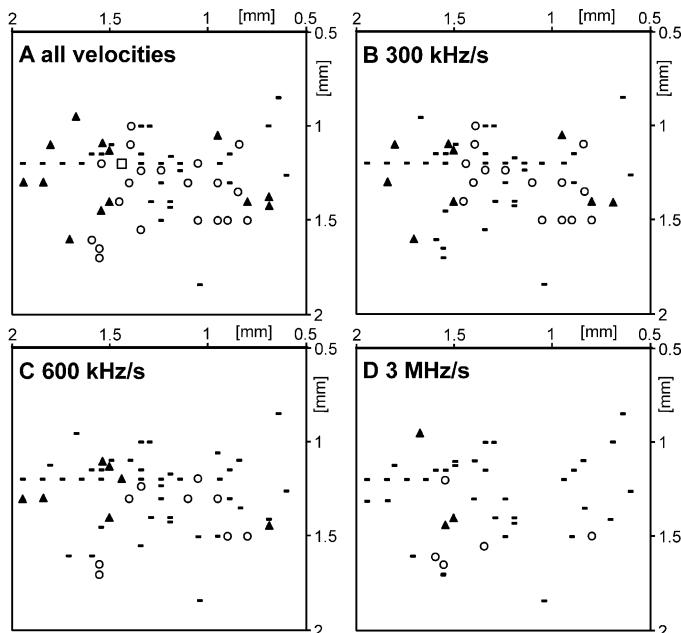

FIG. 5. Spatial distributions of neurons on the shown frequency band lamina (compare Fig. 3) according to their responsiveness to sweep speeds (A) in general, and to the speeds (B) 300 kHz/s, (C) 600 kHz/s and (D) 3 MHz/s. Neurons without selectivity to sweep direction are marked with a dash, upward-selective neurons with a triangle, and downward-selective neurons with a circle.
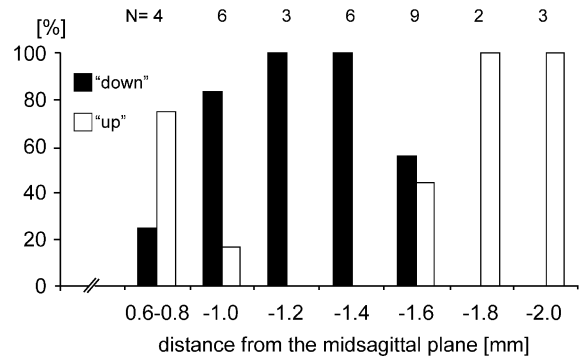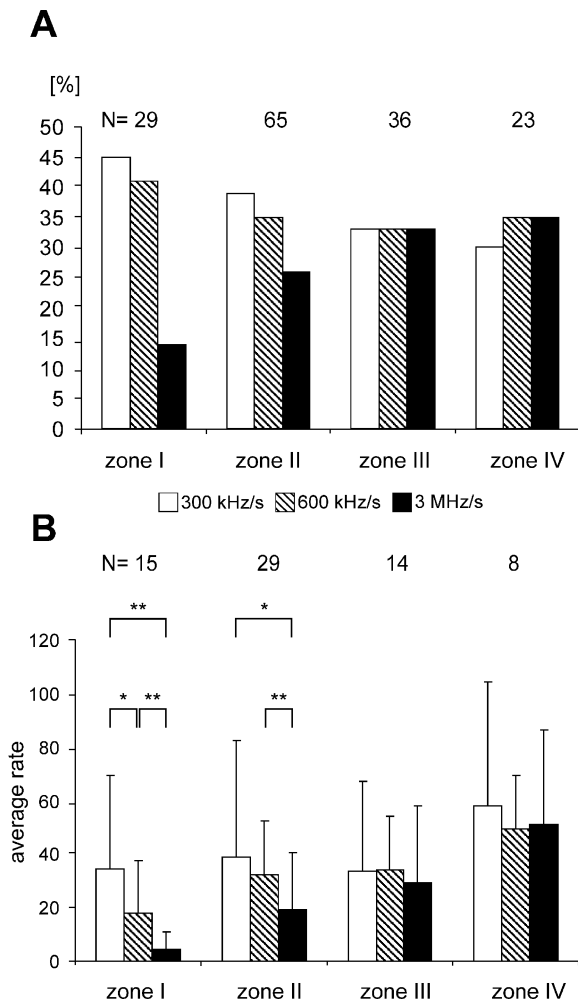
A

B

FIG. 7. (A) Percentages of neurons responding to the sweep speeds 300 kHz/s, 600 kHz/s and 3 MHz/s in the four zones of the ICC as defined in Fig. 3. (B) Average response rates of neurons in the four zones of the ICC to sweep speeds of 300 kHz/s, 600 kHz/s and 3 MHz/s. Statistically significant differences between the average rates are indicated: $^*P < 0.05$; $^{**}P < 0.01$.

responded with significantly higher rates to 300 kHz/s than to 600 kHz/s ($P < 0.05$; paired t-test) and 3 MHz/s ($P < 0.01$), and they responded with higher rates to 600 kHz/s than to 3 MHz/s ($P < 0.01$). In the pericentral zone (zone II), higher response rates to 300 kHz/s and 600 kHz/s were observed compared with the rates to 3 MHz/s ($P < 0.05$, $P < 0.01$, respectively). No such differences were found in the two more peripheral zones of the ICC (zones III and IV) (Fig. 7B).

Taking this evidence together, our results indicate that neurons in the centre of the ICC prefer low sweep speeds. At more peripheral locations, neurons still respond to low sweep speeds but increase their responsiveness to successively higher sweep speeds so that at the medial, lateral, rostral and caudal periphery of the ICC, neurons do no longer differentiate between sweep speeds but, on average, respond with similar average rates to the range of sweep speeds presented in this study. This description is summarized in Fig. 8.

Tone–response types: spatial distributions

Neurons were of various tone response types (Fig. 2) that occurred with the following rates: phasic–tonic: 29 neurons (44%); phasic: 15 neurons (23%); build up: 13 neurons (20%); pauser: five neurons (7%); other types (chopper, tonic, off): four neurons (6%). The spatial distribution of the tone response types in the ICC is shown in Fig. 9A,
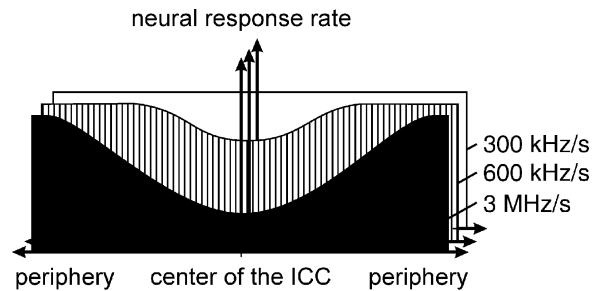

FIG. 8. Summary scheme of the average responsiveness of neurons at locations from the centre to the periphery of a frequency band lamina for the three sweep speeds indicated. In the periphery, the responsiveness to the three speeds is similar and high, in the centre, response rates only to the slowest speed are high. ICC, central nucleus of the inferior colliculus.

and a quantitative evaluation with regard to the distribution of response types in the four zones of the ICC in Fig. 9B.

Only neurons of the phasic–tonic response type were found with similar proportions in all zones of the ICC (Fig. 9B). Phasic responses to tonal stimuli were not present in the centre of the ICC (zone I), and build up, pauser and other types were not found in the periphery (zone IV) (Fig. 9A and B). By combining the two central zones (I + II) and the two peripheral zones (III + IV), the distribution of phasic–tonic, phasic and the remaining response types was significantly non-homogenous (X^2-test, $P < 0.02$), mainly because phasic responding was rare in the central zones and all other response types (except phasic–tonic) were rare in the peripheral zones. That is, the central ICC is characterized by a high diversity of neural response types, especially relatively high incidences of build up responses, while phasic and phasic–tonic responses dominate in the periphery.

Tuning curve shapes and Q-values: spatial distributions

We obtained 36 (54%) neurons of class I, 15 (23%) of class II, 15 (23%) of class III and no neuron of class IV tuning curve shapes. The spatial distribution of neurons of the tuning curve classes is shown in Fig. 10A. The quantitative evaluation of tuning curve shapes with regard to the position of the neurons in the ICC (Fig. 10B) stresses the first impression (Fig. 10A) of neurons of class I tuning curves being present in all four zones (I–IV, Fig. 3A) of the ICC, neurons of class II tuning curves being concentrated rather in the centre, and neurons of class III tuning curves being located mainly in the periphery. This view is supported by statistical tests showing a significantly non-homogenous distribution of tuning curve shapes in the four zones of the ICC (X^2-test, $P < 0.01$), mainly because class II neurons were rare in the two peripheral zones and class III neurons were lacking in the centre zone.

Sharpness of frequency tuning is often expressed by Q-values (see Materials and methods). In order to test whether sharpness of tuning changes systematically over the ICC space, Q_{10} and Q_{40} values of all tuning curves were averaged separately in each of the four zones. The result is shown in Fig. 11. Sharpness of tuning expressed both by Q_{10} (Fig. 11A) and Q_{40} (Fig. 11B) varies significantly between the centre and the periphery of the ICC (ANOVA, $P < 0.01$ in both cases). The comparison of the Q-values in the four zones shows (U-test) the indicated significant differences (Fig. 11A and B), which is strong evidence for a decrease of the average sharpness of tuning in the periphery of the ICC compared with the centre.

Relations among tuning curves, tone response types and sweep responses

First, we tested whether neurons of a given tuning curve class showed tone responses according to certain tone response types. To do this,
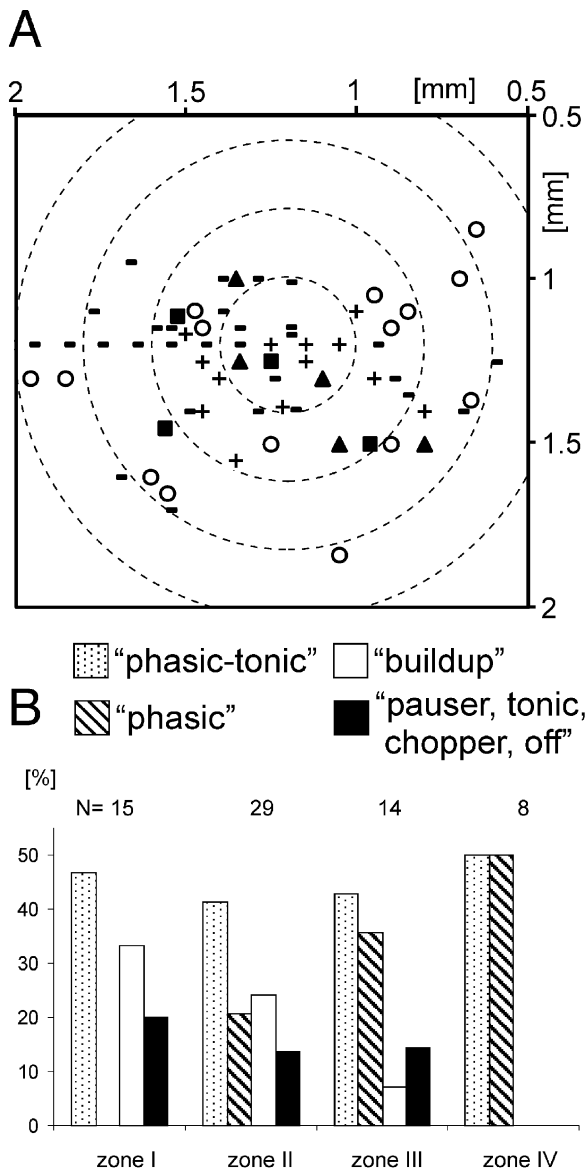
FIG. 9. (A) Spatial distribution of neurons on the shown frequency band lamina (compare Fig. 3) according to their tone response type. The symbols indicate the locations of the following response types: dashes: phasic–tonic; circles: phasic; crosses: build up; triangles: pauser; squares: other types (tonic, chopper, off). The four zones of the ICC are bordered by dashed lines. (B) Percentages of neurons of different tone response types in the four zones (I–IV) of the frequency band lamina shown in (A). In the centre (zone I) there are no phasic responders, in the periphery (zone IV), are only phasic–tonic and phasic types.
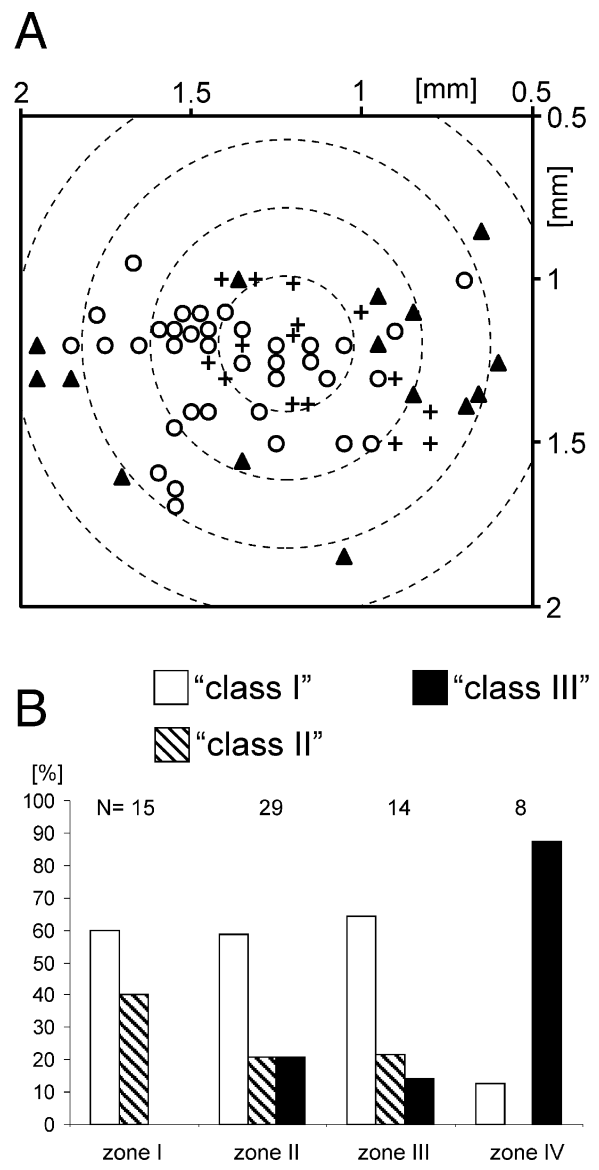

FIG. 10. (A) Spatial distribution of neurons on the shown frequency band lamina (compare Fig. 3) according to belonging to different classes of frequency tuning curves. Circles: class I; crosses: class II; triangles: class III. (B) Percentages of neurons of the tuning curve classes in the four zones of the frequency band lamina shown in (A). In the centre (zone I), there are no class III tuning curves, in the periphery (zone IV) are no class II tuning curves.

pauser, chopper and tonic response types were added to the phasic–tonic responses so that neurons of the tuning curve classes I–III were divided into phasic, build up and phasic–tonic (including other) responders (Fig. 12). A X^2-analysis revealed a strong trend for a non-homogenous distribution ($P < 0.07$), mainly because sharply tuned class II neurons and broadly tuned class III neurons did rarely show phasic and build up responses, respectively (Fig. 12).

Next, we looked for relationships between tuning curve classes and responsiveness to frequency sweeps. Figure 13 shows the numbers of neurons in the three tuning curve classes that did not respond to each of the three sweep speeds. It is evident that only a few neurons of tuning curve class III did not respond to frequency sweeps independent of the

sweep speed. We compared the found numbers of non-responsiveness to frequency sweeps (21, 20, 4 cases for tuning curve classes I, II, III, respectively) with expected numbers (25, 10, 10 cases for tuning curve classes I, II, III, respectively) based on the numbers of neurons in the tuning curve classes (X^2-test). The result was a significant difference between found and expected ($P < 0.05$), because class II (III) neurons were more (less) frequently non-responsive to frequency sweeps than expected under the hypothesis of no selectivity. There was no statistically significant relationship between tuning curve class and selectivity for sweep direction (X^2-test, $P > 0.1$).

Finally, we looked for relationships between tone response types and preferences in response to frequency sweeps. We grouped the tone response types together as mentioned above for the comparisons with tuning curve classes. Statistical tests, however, did not show any significant relations.
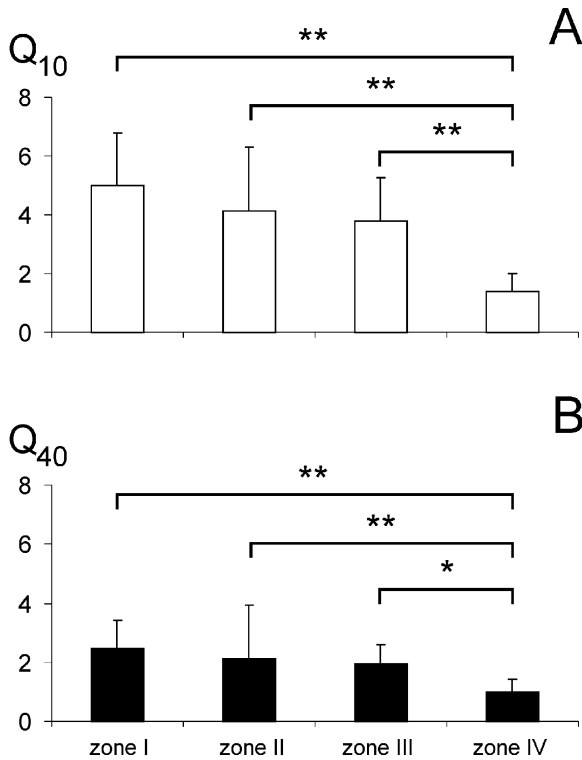
FIG. 11. Average sharpness of frequency tuning in the four zones (I–IV) of the frequency band lamina (compare Fig. 3). Sharpness of tuning is expressed by (A) the Q_{10} values and (B) Q_{40} values of the frequency tuning curves. Significant differences between average Q values of the zones are indicated. $^*P < 0.05$; $^{**}P < 0.01$.

FIG. 12. Percentages of the tone response types phasic–tonic (including pauser, chopper, tonic), build up and phasic in the three classes of frequency tuning curves.

FIG. 13. Numbers of neurons in the three classes of frequency tuning curves that did not respond to the sweep speed of 300 kHz/s, 600 kHz/s or 3 MHz/s.

Discussion

Comparison with mouse IC studies

Our study included neurons of CFs mostly from the centre (15–20 kHz) of the mouse hearing range (1–100 kHz) where behavioural auditory thresholds are lowest (Fig. 4, Ehret, 1974) and frequency band laminae (previously called isofrequency planes) in the mouse ICC have the largest spatial extension (Stiebler & Ehret, 1985). We found tone response thresholds (Fig. 4) in the same range as obtained in the mouse ICC before (Ehret & Moffat, 1985; Egorova et al., 2001). The tuning curves obtained here divided up into classes I–III with proportions similar to those described in previous studies (Egorova et al., 2001; Ehret et al., 2003). Only complex (class IV) tuning curves, which were found in small numbers (2–10%) in the previous studies (Ehret & Moffat, 1985; Egorova et al., 2001; Ehret et al., 2003), did not occur in our present recordings, which may be explained by the smaller number of units here. The range of Q_{10} values found here closely reproduces the range previously described (Ehret & Moffat, 1985; Egorova et al., 2001).

General aspects of tone response patterns

The tone response types seen in the present study (Fig. 2) have been obtained in the ICC of the mouse (Willott & Urban, 1978; Ehret & Moffat, 1985) and of other mammals (e.g. Rose et al., 1963; Bock et al., 1972; Pollak et al., 1978; Vater, 1981; Semple & Kitzes, 1985; Aitkin et al., 1994) before. The present determination of tone response types is new, however, and not identical with previous ones in the above-mentioned and other studies. Here, we evaluated tone response patterns from PSTHs representing the sum of all responses to tones obtained from the excitatory receptive field [the area inside the
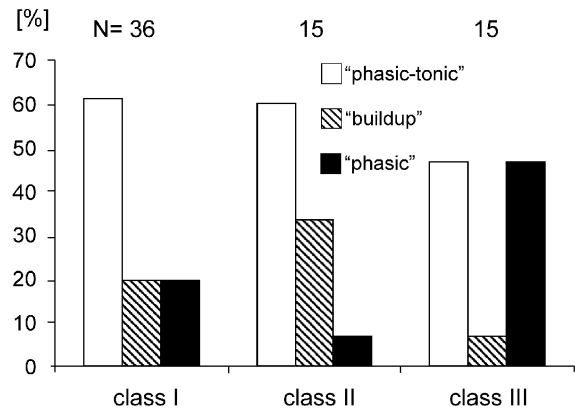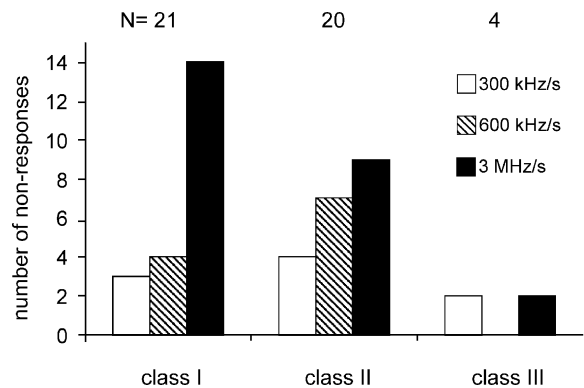
excitatory tuning curve (Fig. 1A) of a given neuron, so-called 'whole-field PSTHs']. Usually, tone response patterns have been estimated from PSTHs taken from responses to tones of a certain sound pressure level above the response threshold at the CF of a given neuron. One disadvantage of the thus defined tone response patterns is their dependence on the sound pressure level (Ehret & Moffat, 1985; Ehret & Merzenich, 1988). It is interesting to note that tonic, phasic–tonic and pauser (including chopper) responses are most affected by changing sound levels, that is, tonic and phasic–tonic responses tend to change mainly to pauser (chopper) responses with increasing sound level. Purely phasic and build up (long latency) responses are much less affected by changes of sound levels (Ehret & Moffat, 1985; Ehret & Merzenich, 1988). Another disadvantage of the conventionally defined tone response patterns is their frequency dependence. A neuron may respond tonically or phasic–tonically at its CF and phasically at the borders of its receptive field, as suggested by the changes of the response rate in the receptive field of neuron 24 (Fig. 1A). Thus, the so-far-used conventional (but variable) tone response pattern (conventional PSTH) does not characterize a neuron's responsiveness to tones unequivocally, whereas our whole-field PSTH does for a given sound stimulus. The whole-field PSTH is the key feature of a neuron's response pattern of the same rank as the excitatory tuning curve is of a neuron's receptive field. Hence, it seems to make little sense to map tone responses based on conventional PSTHs, but it makes much sense to map tone response types based on whole-field PSTHs, because maps arising from the latter would characterize stable gradients of basic neural responsiveness. Needless to say that the proportions of
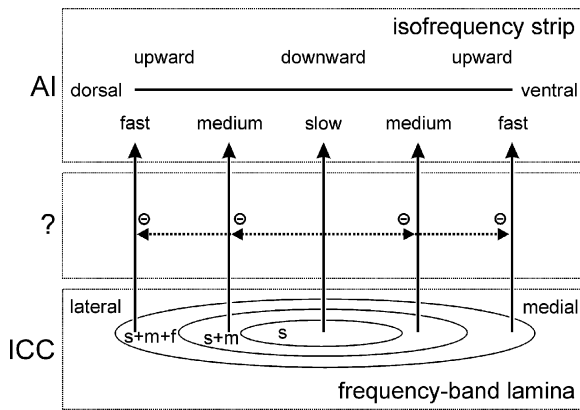
FIG. 14. A model of the transfer of information about sweep speed [slow (s), medium (m), fast (f)] and sweep direction (upward, downward) from a frequency band lamina of the central nucleus of the inferior colliculus (ICC) to an isofrequency strip of the primary auditory cortex (AI). The basis of the model is the present data on the ICC and mapping data from the cat AI (Mendelson *et al.*, 1993). Essential for turning the collicular map into the cortical map are inhibitory connections (dotted horizontal arrows between the information flow from the ICC to the AI) that prevent more peripheral (dorsal and ventral) areas of AI from being activated by slow-speed information (further descriptions in the text).

neurons of the various tone response types found in the present study deviate from the proportions found in the literature (e.g. Pollak *et al.*, 1978; Vater, 1981; Ehret & Moffat, 1985; Semple & Kitzes, 1985; Ehret & Merzenich, 1988).

An important aspect of recent research is the question in how far response patterns of ICC neurons reflect extrinsic properties mainly determined by the innervation patterns or intrinsic properties of the neurons. Intracellular recordings from ICC neurons using current injections for eliciting action potentials from the cells have characterized three basic response types: pure onset; sustained with regular firing; sustained adapting (Wagner, 1994; Pedemonte *et al.*, 1997; Reetz & Ehret, 1999; Peruzzi *et al.*, 2000; Sivaramakrishnan & Oliver, 2001; Bal *et al.*, 2002). Taking these intrinsic properties, 'pure onset' cells are expected to show a 'phasic' response type in extracellular recordings (present study) and neurons with some intrinsically 'sustained' firing would be the basis for most of the remaining response types (phasic–tonic, tonic, pauser, build up, chopper). The exact specification of the latter response types would then be mainly due to the excitatory and inhibitory innervation patterns, an aspect that will be followed up in the discussion of collicular maps.

Responses to frequency sweeps

The great majority of neurons (92%) in the mouse ICC responded to frequency sweeps, which is similar to the percentages found in studies on the ICC of bats (100%, Suga, 1969; 90%, Pollak *et al.*, 1978; 96%, Vater, 1981) and rats (100%, Vartanian, 1974; Felsheim & Ostwald, 1996; 95%, Lee *et al.*, 2002). These data suggest that virtually all ICC neurons may respond to frequency sweeps if the sweep parameters (sound level, sweep direction, sweep speed) are appropriately set. The latter might not have been the case in studies in which only 71% (bat, Fuzessery, 1994) or 74–77% (rat, Poon *et al.*, 1991, 1992) of the neurons responded to frequency sweeps.

Selectivity to sweep direction (upward, downward) as defined by the direction-selective index of 0.33 is a property of about half (56%) of the sweep-sensitive neurons in the ICC of the mouse. Despite some variation found in previous studies, this proportion is similar to those found in the ICC of the rat (66%, Vartanian, 1974; 32%, Lee *et al.*, 2002) and pallid bat (50%, Fuzessery, 1994), in the AI of the rat (44%, Ricketts *et al.*,

1998) and cat (65%, Mendelson & Cynader, 1985; 59%, Mendelson & Grasse, 1992; 45%, Mendelson *et al.*, 1993), and in the anterior auditory field of the cat auditory cortex (66%, Tian & Rauschecker, 1994). Several studies have shown (Vater & Schlegel, 1979; Vater, 1981; Mendelson & Grasse, 1992; Fuzessery, 1994; Tian & Rauschecker, 1994; Gordon & O'Neill, 2000; O'Neill & Brimijoin, 2002) that direction selectivity of many neurons may depend on sweep speed (compare Fig. 5), sound level, and monaural or binaural stimulation. That is, direction selectivity is not a constant property of neurons in the IC and AI. Nevertheless, if ICC neurons show a direction selectivity at all, the direction they prefer (upward or downward) depends, to a high degree, on their location in the ICC (Figs 5 and 6), which is discussed below.

Preferences for sweep speeds have been found for neurons in the IC and auditory cortex whenever a large range of speeds was tested (Mendelson & Cynader, 1985; Poon *et al.*, 1991; Heil *et al.*, 1992a; Mendelson & Grasse, 1992; Mendelson *et al.*, 1993; Tian & Rauschecker, 1994, 1998; Felsheim & Ostwald, 1996; Ricketts *et al.*, 1998; Nelken & Versnel, 2000; Lee *et al.*, 2002). Sweep speeds employed in these and other studies (Vater, 1981; Fuzessery, 1994; Ferragamo *et al.*, 1998; Gordon & O'Neill, 2000; O'Neill & Brimijoin, 2002) together ranged between 5 kHz/s and 25 MHz/s, which is about the range of speeds observed in animal sounds including echolocation sounds and human speech. Neurons may show all-pass, high-pass, low-pass and band-pass characteristics to sweep speeds (Mendelson & Cynader, 1985; Poon *et al.*, 1991; Heil *et al.*, 1992a; Mendelson & Grasse, 1992; Mendelson *et al.*, 1993; Tian & Rauschecker, 1994; Felsheim & Ostwald, 1996; Ricketts *et al.*, 1998). Most of our neurons responded well to the lowest speeds tested (300 kHz/s, 600 kHz/s) and significantly less to the highest (3 MHz/s) (Figs 5 and 7B). Thus, the neurons in the ICC of the mouse, in general, seem to prefer medium speeds, considering the range mentioned above, and may not be sharply tuned to sweep speeds in the range of 300–600 kHz/s, which are speeds occurring in harmonics of wriggling calls of young mice and distress calls of young and adult mice.

Maps of tuning curve shapes and tone responses

The here-found distribution of neurons of different tuning curve shapes on frequency band laminae of the ICC (Fig. 10A) confirm the previously obtained concentric map (Ehret *et al.*, 2003), with a decrease of the proportion of sharply tuned class II neurons from the ICC centre to the periphery and a simultaneous increase of the proportion of broadly tuned class III neurons over the same space. Together with these changing proportions of tuning curve classes over collicular space, the average sharpness of tuning decreases in the periphery of a frequency band lamina (Fig. 11). This is very similar to what has recently been demonstrated (Ehret *et al.*, 2003). The following can be inferred from the spatial distribution of tuning curve types in the ICC (Egorova *et al.*, 2001; Ehret *et al.*, 2003). (i) In the centre of a frequency band lamina, generally strong inhibitory influences on neurons dominate while, in the periphery, inhibitory influences are weak and excitation converges. (ii) The distribution of class I tuning curves in the ICC (Fig. 10) indicates that not much specialized excitatory tuning (similar to that of auditory nerve fibres) is abundant virtually all over a frequency band lamina. From these two points and the before-mentioned differences in intrinsic properties of neurons, a third point follows. (iii) Individual response characteristics of neurons at certain locations in the ICC can only be predicted as probabilities derived from the mapping experiments.

In our study, we present the first set of data on the spatial distribution of tone response types across a frequency band lamina of the IC (Fig. 9). On the background of a high abundance of phasic–tonic responses everywhere, the increase of phasic responses towards the periphery of the ICC and the parallel decrease of build up responses is

very clear. We suggest the following mechanisms behind these patterns. Build up responses of neurons in the dorsal cochlear nucleus have been shown to arise from excitatory–inhibitory interactions and result from a strong and fast inhibition overriding the excitation (Voigt & Young, 1980, 1990; Rhode *et al.*, 1983; Manis, 1990; reviews in Rhode & Greenberg, 1992; Young & Davis, 2002). If this is true for neurons in the ICC, the gradient of build up responses reflects a general gradient of decreasing inhibition from the centre to the periphery of the ICC, as mentioned in the discussion of maps of tuning curve shapes. As discussed for tone response types, purely phasic responses may be due to intrinsic onset-spiking properties of neurons. Hence, we suggest that such neurons are distributed across a frequency band lamina of the ICC with a gradient and proportions similar to those found here for the phasic tone response type. Data from the only available mapping study of intrinsic response properties of ICC neurons (Reetz & Ehret, 1999) support this view, because the onset-spiking neurons reported were concentrated at the lateral, medial and caudal periphery of the ICC, just where we detected the highest incidences of phasic neurons (Fig. 9).

Maps of direction and speed of frequency sweeps

Our present results are the first showing maps on a frequency band lamina of the ICC both for sweep speed and selectivity to sweep direction. Selectivity to sweep direction, found in just more than half of the recorded neurons, is clustered medially, centrally and laterally in the ICC (Figs 5 and 6) in strips of changing the preferred direction (upward, downward, upward) or is arranged in a concentric manner with downward-preferring neurons in the centre and upward-preferring neurons in the periphery. As the model of the three strips is reaching higher significance levels than the concentric one in our data evaluation, we presently prefer the strip model of direction selectivity. Preferences for sweep speed show a concentric gradient from the centre to the periphery of the ICC with neurons in the centre preferring low speeds and in the periphery all the tested (including high) speeds (Figs 7 and 8). The features of these maps are highly interesting.

(i) Assuming the strip model of direction selectivity as valid, the maps are not congruent, their geometry is different with the result that all combinations of directions and speeds can be realized by local neuron clusters on frequency band laminae in the ICC. For example, combination sensitivity for fast and slow upward sweeps is located medially and laterally, for slow downward sweeps right in the centre, and for fast downward sweeps in the caudal part of the central area.

(ii) Both maps seem not to be 'exclusive', i.e. direction-selective neurons are mixed with non-selective neurons on the frequency band lamina, and speed-sensitive neurons increase their responsiveness to higher speeds, while they continue to be sensitive to low speeds, with increasing distance from the centre of the frequency band lamina.

Provided that similar maps are present in the IC of other mammals, it does make little sense to compare and discuss proportions of upward vs. downward selective or fast vs. slow speeds preferring neurons unless the positions of the recorded neurons in the ICC are known. If, for example, electrodes were placed only right in the centre of the ICC, our present results would predict a strong bias for neurons preferring slow speed downward sweeps.

Correlations among maps of neural response properties: hints at mechanisms

Three of the maps appear to be concentric on frequency band laminae – the decrease of sharpness of tuning from the centre to the periphery on the basis of a decrease of abundance of class II and an increase of class III neurons, the decrease in number of the build up and the increase of the phasic response type from the centre to the periphery, and the increase in the neural responsiveness to high sweep speeds. We

argue that all three maps are due to the same mechanisms, namely a general gradient of decreasing inhibitory influence on neurons and an increase of abundance of intrinsically phasically responding neurons from the centre to the periphery of frequency band laminae. In the centre, sharply tuned class II neurons cannot respond to fast sweeps because of strong inhibition within and lateral of their excitatory response area (Egorova *et al.*, 2001), with the effect that fast sweeping tones do not remain long and efficiently enough in the excitatory response area to elicit a response. In the periphery, broadly tuned class III neurons with little inhibitory influence can well respond to fast sweeps, because of the broad tuning they can collect sufficient sound energy of the sweeping tone in their excitatory receptive field to elicit a fast spike that is not suppressed by fast and strong inhibition. Neurons of class I tuning curves and suggested phasic–tonic (including tonic, pauser, chopper responses) responding, which occur in high rates all over a frequency band lamina (Ehret *et al.*, 2003; present study), are not necessary for these explanations and it remains to be clarified whether and how they contribute to the collicular sensitivity in responding to frequency sweeps of different speeds.

The map of direction selectivity for frequency sweeps with three strips of rostrocaudal orientation at different mediolateral coordinates of a frequency band lamina (Figs 5 and 6) has to be confirmed in further tests and may differ from the other three maps. Three basic models to generate direction selectivity have been discussed in the literature, which are summarized in Fuzessery & Hall (1996). Two of the mechanisms involve lateral inhibition from only one side (high- or low-frequency side). By blocking the inhibition, however, Fuzessery & Hall (1996) showed that these models cannot explain most of the data on direction selectivity of collicular neurons. They propose that spectro-temporal information is collected by the dendritic trees of a direction-selective neuron that must be asymmetric with regard to its excitatory input from the collicular tonotopy. In addition, the excitation should be controlled by GABAergic inhibition before action potentials are generated. Another mechanism might involve direction selectivity of projections to the ICC. Rhode & Greenberg (1992) mention that onset-neurons in the posteroventral cochlear nucleus are direction selective to linear frequency sweeps. Hence, this selectivity might be projected in banded patterns to the ICC as is seen for several ascending input projections (e.g. Kudo & Nakamura, 1988). Further work has to clarify this issue.

The previously described (Ehret, 1997a) and presently found maps of neuronal response properties within frequency band laminae of the ICC show that functional properties of this midbrain centre of the auditory pathways are not uniformly distributed in the neural space of the ICC. Our mapping data do not lead to a clear distinction between maps showing gradients of neuronal response properties along spatial dimensions of the ICC and maps representing clusters of locally varying composition of neuronal response properties. This is because maps of different geometries have been described for different response properties and because maps are not exclusive (see above). Furthermore, the combination of data from many animals to common maps may lead to average pictures of response gradients built upon stepwise changing response properties of local neural clusters in single animals.

Frequency sweep representation in the ICC compared with the auditory cortex

Spatial representations of sweep direction and speed in the AI have only been studied in the cat (Heil *et al.*, 1992b; Mendelson *et al.*, 1993) and ferret (Shamma *et al.*, 1993; Nelken & Versnel, 2000). Clearest maps for both parameters have been obtained in the cat (Mendelson *et al.*, 1993), so we will use this study for comparison.

Figure 14 shows a hypothetical frequency band lamina of the ICC and an isofrequency strip of corresponding best frequency of the AI. On the two dimensions of the frequency band lamina, the concentric arrangement of responsiveness to increasing sweep speed (slow → slow + medium → slow + medium + fast) is indicated. On the one-dimensional (with regard to the functions of interest) isofrequency strip of the AI, the average dorsoventral gradient of preference of sweep speed (fast → medium → slow → medium → fast) and of direction selectivity (upward → downward → upward) is shown. The arrows connecting the ICC with the AI symbolize the assumed information flow from the centre of the ICC to the centre of the AI and from more peripheral areas of the ICC to more dorsal and ventral locations on the isofrequency strip. Between these arrows, centrifugally orientated inhibitory connections (broken arrows ending with a minus symbol) prevent more dorsal or ventral locations of AI to be activated, if low-speed information is passing from all over the ICC to the AI. Thus, only the low-speed information from the centre of the ICC reaches the centre of AI. If the pericentral and the peripheral ICC signal medium speeds, the centrifugally orientated inhibition prevents the information from the ICC periphery to reach the AI so that only two locations in AI, somewhat dorsal and somewhat ventral of the centre, are activated. Finally, if the peripheral ICC signals fast speeds, the AI is activated only at one dorsal and one ventral location. Thus, the concentric speed map of the ICC may be transformed into the speed map of the AI found by Mendelson *et al.* (1993). This transformation may explain why AI has only one central area with preference of slow speeds and two gradients towards the dorsal and ventral direction each with preference of increasingly faster speeds.

Our model also explains the transformation of direction selectivity. The central ICC transmits information about downward selectivity to the centre of the AI. Information about upward selectivity is transferred by the medial and the lateral ICC. As upward-preferring neurons in the ventral AI occupy a smaller and more variable area than in the dorsal AI (Mendelson *et al.*, 1993), we assume that the small upward-selective area of the medial ICC sends its information to the ventral AI. By that, the lateral ICC is assumed to transmit information about upward sweeps to the dorsal AI (Fig. 14).

This model of information transfer between the ICC and the AI derived from the preferences of neural responses to parameters of frequency sweeps (Fig. 14) is compatible with the further maps of neural response parameters in the ICC (e.g. Ehret, 1997a; Langner *et al.*, 2002; Ehret *et al.*, 2003) and maps and patchy distributions in AI (e.g. Ehret, 1997b; Schreiner, 1998). Generally, it shows how information mapped on frequency band laminae of the three-dimensional collicular space may be transformed to maps and patches on isofrequency strips of the two-dimensional auditory cortex. Now, it will be important to show at which level of the ascending auditory pathways in and between ICC and AI, and how the centrifugally orientated inhibition indicated in the model is realized, which is necessary to suppress excitatory input to more peripheral locations of an AI isofrequency strip if more central locations are activated.

Acknowledgements

Abbreviations

AI, primary auditory cortex; CF, characteristic frequency; IC, inferior colliculus; ICC, central nucleus of the inferior colliculus; PSTH, peristimulus time histogram.

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