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Auditory cortical responses to amplitude modulations with spectra above frequency receptive fields: evidence for wide spectral integration

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Abstract Auditory neurons typically respond to a restricted range of frequencies and amplitudes of pure tone stimuli. These findings have led to the concept of the classical frequency receptive field. Over the last few years evidence has accumulated that stimuli outside the frequency and amplitude boundaries of a neuron's receptive field can influence responses to stimuli inside the classical receptive field. We could recently show that sinusoidally amplitude-modulated pure tones could excite cortical neurons although all of their spectral components were above the spectral range of pure tones effective to excite the neuron. This result demonstrated that neurons in the auditory cortex integrate over spectral ranges that are much wider than is evident from responses to pure tones. Here, using sinusoidally amplitude-modulated pure tone stimuli we determine electrophysiologically the high-frequency boundaries of the spectral integration capabilities of auditory cortical neurons in anaesthetized Mongolian gerbils under normal conditions and under the influence of the microiontophoretically applied $GABA_A$-receptor antagonist bicuculline. Our results demonstrate that some auditory cortical neurons integrate over the gerbil's entire audible spectrum. Therefore, the classical excitatory frequency receptive field of an auditory cortical neuron, as determined with pure tone stimuli, cannot provide a satisfactory description of its spectral integrative properties.

Key words Periodicity coding · Microiontophoresis · Bicuculline · GABA · Mongolian gerbil

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Abbrevations *AI* primary auditory cortex · *AM* 100% sinusoidally amplitude-modulated pure tone · *BF* best frequency (=iso-intensity pure tone frequency that elicits the strongest response) · *BIC* (−)-bicuculline-methiodide · *BMF* best modulation frequency · *BP* band-pass filter characteristic · *BS* band-suppression filter characteristic · *CF* characteristic frequency of a unit (=pure tone frequency with the lowest threshold) · *CX* complex filter characteristic · *df* degrees of freedom · *fc* carrier frequency of an AM · *fm* modulation frequency of an AM · *FRF* frequency response function (=a plot of discharge rate, corrected for spontaneous activity against pure tone frequency) · *FRR* frequency response range (=range of frequencies of pure tones presented at a given intensity that elicit an excitatory response) · *GABA* γ-aminobutyric acid · *HP* high-pass filter characteristic · *ICC* central nucleus of the colliculus inferior · *LP* low-pass filter characteristic · *MRR* modulation frequency response range (=range of modulation frequencies that elicit an excitatory response for a given carrier frequency) · *MTF* rate modulation transfer function (=a plot of discharge rate, corrected for spontaneous activity, over modulation frequency) · *NS* non-selective filter characteristic · *SD* standard deviation

Introduction

In auditory research it is common practice that neurons are first characterised on the basis of their responses to single pure tones of different frequency and amplitude. This practice was motivated by the idea that auditory neurons act as spectral band-pass filters responding only to a discrete spectral portion of the acoustic surround: the concept of the classical frequency receptive field, comprised of an excitatory frequency receptive field and inhibitory sidebands. Consequently, many studies have tried to explain neuronal responses to complex auditory stimuli on the basis of this classical frequency receptive field (e.g. Suga 1965; Erulkar et al.

1968; Sinex and Geisler 1981; Shore et al. 1987; Schulze et al. 1997).

In contrast to this view, it is a well-known phenomenon in the visual system that stimuli presented outside the classical visual receptive field may influence neural responses to stimuli presented within the excitatory portion of the classical receptive field in a facilitatory or inhibitory fashion (e.g. Li et al. 1991; for a review see Allman et al. 1985). For the auditory system several studies reported similar results (Oonishi and Katsuki 1965; Ehret and Merzenich 1988; Nelken et al. 1994a, b).

We could recently demonstrate that a number of neurons in the primary auditory cortex (AI) of the Mongolian gerbil (*Meriones unguiculatus*) can be excited by complex sounds with a spectrum completely outside a unit's frequency response range (FRR = range of frequencies of pure tones of a given intensity that elicit an excitatory response). That is, these units responded to stimuli that had no spectral component within the units' FRRs (Schulze and Langner 1997a). In particular, we determined a unit's FRR with pure tones and then presented AMs with all three spectral components far above the FRR. We found that about 75% of the units in the low-frequency area [with best frequencies (BFs) up to about 3 kHz] responded to such stimuli and that these responses were sharply tuned to a certain range of envelope periodicities.

These results showed that the excitatory receptive fields of these neurons were broader than expected on the basis of their responses to single pure tones. In particular, it has to be distinguished between first, the spectral receptive field a given unit exhibits when only single-frequency channels (pure tone stimulation) are activated at a time – in this paper referred to as 'classical frequency receptive field' – and second, a spectral receptive field comprising all frequency channels that constitute the spectral input of that unit (as revealed by stimulation with complex stimuli, i.e. simultaneously activating multiple frequency channels) – here simply referred to as 'spectral receptive field'. Note that according to this definition the 'classical frequency receptive field' is part of the 'spectral receptive field'.

The present study aimed at a quantification of the excitatory portion of this spectral receptive field, i.e. the excitatory spectral range over which such neurons integrate. For this purpose we (1) determined the boundaries of spectral integration by systematically shifting the spectrum of the AM stimuli to higher frequencies, and (2) suppressed inhibitory influences by microiontophoretic application of the $GABA_A$-receptor antagonist (−)-bicuculline-methiodide (BIC).

Parts of this study have been published in abstract form (Schulze and Langner 1997b).

Materials and methods

Animals

Six adult, male Mongolian gerbils from our own breeding colony were used in this study.

Surgery

Animals were prepared for electrophysiology under deep general (Halothane; Hoechst) and local (Gingicain, Hoechst) anaesthesia. During surgery animals were placed on a feedback-controlled heating blanket which kept body temperature around 37 °C. The skin covering the skull was partly removed and the skull was carefully cleaned. Additionally, the dorsal part of the musculature over the temporal bone on the (left) recording side was removed. The auditory cortex was exposed by a craniotomy, leaving the dura intact. A platinum wire reference electrode was implanted between the dura and the skull over the right parietal cortex. A 2.5-cm-long aluminium bar was fixed to the frontal bones with dental acrylic and served as a head anchor for stereotaxic fixation during the experiment. The exposed dura was covered by an isotonic sodium chloride solution or by paraffin oil, to prevent it from drying out.

For electrophysiology the animals were transferred to an anechoic, sound-attenuating chamber where they remained on the heating blanket with only their heads fixed. Anaesthesia was maintained during the course of the experiment by intraperitoneal application of a mixture of ketamine (Ketavet, 50 mg ml^{-1}), xylazine (Rompun, 2%) and isotonic sodium chloride solution (mixture 9:1:10, application rate 0.06 ml h^{-1}). At the end of the experiment (after 23–27 h) animals were sacrificed by an intrapulmonary injection of T61 (Hoechst).

Electrophysiological recordings and microiontophoresis

Neuronal responses of single and multi-units were recorded extracellularly from the left AI using glass-insulated tungsten microelectrodes with impedances ranging from 0.7 MΩ to 1.0 MΩ. Under microscopic control the electrode was positioned over the cortex and then advanced through the dura in a dorsoventral direction using a remote-controlled piezo-micromanipulator. Alignment of recording tracks was tangential to the cortical surface (cf. Thomas et al. 1993) and positions of tracks were measured relative to lambda. Spacing of recording sites was between 100 μm and 200 μm in dorsoventral and in rostrocaudal direction.

Unit activity was amplified (5000–10000×), band-pass filtered (1–3 kHz, 3 dB/octave), fed into a level discriminator and displayed on an oscilloscope. Additionally, a high-resolution storage oscilloscope was triggered by discriminated events (''spikes'') to allow the distinction between single and multi-units. Both the amplified signal from the electrode and the output of the level discriminator were monitored on an audio analyser. Spikes were displayed on-line as point-plots (dot raster diagrams), and spike intervals were stored with 10-μs resolution for off-line analysis.

For microiontophoresis, micropipettes were pulled from theta septum capillaries. A tungsten microelectrode was inserted into one compartment and the other compartment was filled with a solution of the $GABA_A$-receptor antagonist BIC (Sigma, 10 $mmol \cdot l^{-1}$, pH 3.0). The tip diameter of the latter compartment was 8–10 μm. BIC was applied by an iontophoretic current of +40 nA controlled by a one-channel Iontophor-3 unit. The application current was maintained throughout the experiments in which the influence of BIC was investigated. In between periods of application (normal condition) a continuous retaining current of −40 nA was applied. Electrophysiological recordings with the tungsten wire compartment were carried out as described above.

Acoustic stimulation; experimental protocol

All auditory stimuli were delivered free-field through an attenuator (HP 350D), an amplifier (STAX SRM-1/MK-2), and an electrostatic speaker (STAX SR lambda pro). The speaker was mounted about 2 cm in front of the animal's head. Prior to each experiment the output of the speaker was measured using a 1/2-inch condenser microphone (Brüel & Kjaer 4134) placed at the position of the animal's head and facing the speaker. During the recordings the microphone was positioned next to the head of the animal (i.e. at

the same distance from the flat speaker as the head). The signal from the microphone was amplified (Brüel & Kjaer 2610) and monitored on a signal analyser (Brüel & Kjaer 2033). The speaker's output was flat within ± 5 dB and no distortions could be measured for signal levels up to 100 dB SPL. Stimulus levels of ≥90 dB SPL were not used.

At each recording site where auditory responses could be encountered the (single or multi-) unit's characteristic frequency (CF = pure tone frequency with the lowest threshold) and corresponding minimal threshold were determined manually with tone bursts generated by a multifunction signal generator (Wavetek 146) using audio–visual criteria, that is, sound pressure level was increased until spikes time locked to the pure tone stimulation could be detected both with the audio analyser and on an oscilloscope. Stimulus level was set to 30 dB above the unit's minimal threshold for all further measurements (except for three units where the minimal threshold was above 60 dB SPL. For these units stimulus intensity was set to 20 dB above threshold).

The units' response properties to tones and 100% AM signals were studied. Neuronal activity was recorded during a 50-ms pre-stimulus period, a 200-ms stimulus period, and a 150-ms post-stimulus period. All stimuli were produced by a computer-controlled multifunction generator (HP 8904 A) with 5-ms linear rise and fall times. 10–20 repetitions were presented with stimuli randomised separately for each repetition. AM stimuli were generated by adding three spectral components, viz., *fc* (carrier frequency), *fc*–*fm* (carrier frequency–modulation frequency; =lower sideband), and *fc* + *fm* (upper sideband), with all components starting with phase zero and with the sidebands set to half the amplitude of the *fc*.

Pure tone bursts with frequencies ranging from 50 Hz to 40 kHz were used to record a unit's frequency response function (FRF; = plot of discharge rate against pure tone frequency). For each unit, two sets of tone bursts with equidistant frequency steps on a linear scale were presented, one set covering a large frequency range (up to 40 kHz) with low resolution and a second set covering a small frequency range around the unit's CF with high resolution. Next, several sets of AM stimuli were presented. In the first stimulus set, the *fc* of the AM was set to a frequency well above the unit's FRR (between 5 kHz and 10 kHz above the upper limit of the FRR). As a rule, frequency modulations ranged from 0 Hz (=unmodulated carrier) to 5 kHz for each *fc* tested, with equidistant *fm* steps on a linear scale. Except for the lowest *fc* tested, the resulting spectra of the AM signals were always completely outside the unit's FRR. For the lowest *fc* tested, the lower sideband of the AM (*fc*–*fm*) could be located within the unit's FRR (these cases will be discussed separately). If the unit responded to the AMs, additional AM sets were presented with the *fc* shifted to higher frequencies until no further neuronal responses were evoked (Fig. 1).

In addition to the experiments described above, the influence of BIC on the neuronal responses was studied in two animals. For this purpose, the same experiments as described above were repeated under the influence of BIC, i.e. sets of AM stimuli were tested with increasing *fc* as long as unit responses could no longer be evoked. Due to the influence of BIC the number of effective stimulus sets (*fc*s) often exceeded the number of effective stimulus sets presented before the application of BIC, i.e. under the influence of BIC excitatory responses often could be evoked by AM stimuli with even higher spectral contents compared to the condition before the application of BIC.

Data analysis

Spontaneous activity was determined by calculating the average discharge rate during all pre-stimulus periods of a given stimulus set. Tonic and phasic-tonic responses were quantified on the basis of the average discharge rates during the entire stimulus period. For purely phasic responses average discharge rate was evaluated during a time window comprising the duration of the response only. Spontaneous activity was subtracted from all response measures. Neuronal response latencies were determined from point-plots by determining the first simultaneous appearance of spikes in at least three repetitions.

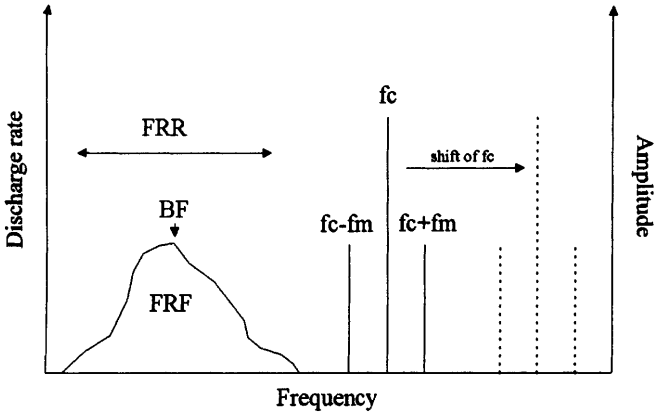


Fig. 1 AM stimulation paradigm. A schematic frequency response function (FRF), obtained from responses to pure tones of different frequencies, is shown on the *left*. The *right* part shows the spectral position of the 100% sinusoidally amplitude-modulated pure tone (AM) stimuli relative to the FRF. The spectrum of an AM consists of three components, the carrier frequency *fc* and two sidebands *fc*–*fm* and *fc* + *fm*. During the experiments the AMs were shifted from lower (*solid lines*) to higher spectral ranges (*dotted lines*). In most cases AM spectra were located completely above the unit's frequency response range (FRR). *BF* best frequency; *fm* modulation frequency

From the FRF the BF (tone burst frequency that elicited the highest discharge rate; cf. Fig. 1) and the FRR were determined. Responses to AM stimuli were quantified separately for each *fc* tested using plots of discharge rate corrected for spontaneous activity over modulation frequency. Such plots will be referred to as rate modulation transfer functions (MTFs). Best modulation frequencies (BMFs) and modulation frequency response ranges (MRRs; = range of modulation frequencies that elicit an excitatory response for a given *fc*) were determined from these MTFs.

Six categories of neuronal filter characteristics were differentiated on the basis of the shapes of FRFs and MTFs for responses to pure tones and AMs, respectively, viz., band-pass (BP), low-pass (LP), high-pass (HP), complex (CX), band-suppression (BS), and nonselective (NS), as defined elsewhere (Heil et al. 1995; Schulze and Langner 1997a).

For both pure tone and AM experiments stimulus selectivity was assessed by Q_{3dB} factors, determined from FRFs and MTFs, respectively. Q_{3dB} factors were defined as BF or BMF divided by the bandwidth of the FRF or MTF, respectively, 3 dB below the maximum.

Results

Database

Neuronal responses from a total of 80 recordings sites (5 single units and 75 multi-units, 2–4 waveforms) with low BFs and CFs (up to 3 kHz) from the left primary auditory cortices of six adult, male Mongolian gerbils were included in this study. Two sets of pure tone stimuli and up to seven sets of AM stimuli with different carrier frequencies were tested for each unit. A proportion of 29 units from two gerbils was also tested under the influence of iontophoretically applied BIC.

General response characteristics of units in the low-frequency area of the AI

Response characteristics to pure tones and AM stimuli were generally similar to those described in earlier studies on the auditory cortex of the gerbil (Thomas et al. 1993; Schulze and Langner 1997a), and will therefore only briefly be described here.

Responses to pure tones

All units in our sample displayed either a phasic (79%) or a combined phasic-tonic (21%) response to pure tones. FRFs were assigned to BP (49%), CX (42%), or LP (9%) categories. Band-suppression or non-selective filter characteristics were never observed. The absence of units classified as HP is due to the fact that all units in our sample were taken from the low-frequency area of the AI. Response latencies ranged from 9.4 ms to 43.3 ms with a mean of 17.8 ± 5.3 ms (±SD). Sharpness of tuning, expressed as Q_{3dB} values, ranged from 0.2 to 8.1 (mean 1.7 ± 1.7). Response thresholds ranged from −2 to 68 dB SPL (mean 34.6 ± 15.4). All distributions were positively skewed.

Responses to AM stimuli with a spectrum outside a unit's FRR

Out of our sample 76 units were tested for responses to AM stimuli located outside their FRR. Tonic response components were more often elicited by such AM stimuli (cf. Schulze and Langner 1997a) than by pure tones: 28% of the units responded in a purely tonic fashion to AMs. Combined phasic-tonic responses to AMs were observed in 28% of the units and purely phasic responses in 44%. The proportion of units that exhibited tonic response components was therefore almost three times higher for AM than for pure tone stimuli. MTFs were classified as BP (55%) or CX (38%). Five units (7%) did not respond to AM stimuli spectrally located outside their FRR, but interestingly two of these units were responsive to these stimuli under the influence of BIC (see below). Response latencies to AM stimuli ranged from 9.0 ms to 90.4 ms with a mean of 27.7 ± 10.7 ms (±SD). Sharpness of AM tuning, expressed via Q_{3dB} values, ranged from 0.1 to 27.5 (mean 3.9 ± 3.6). Thus, on average, responses to AM stimuli exhibited onset latencies longer than responses to pure tones and MTFs were more sharply tuned than FRFs. Both differences were highly significant (ANOVA: $P = 1.08^{-14}$, $F = 65.0$, degrees of freedom (df) = 369 for latencies; $P = 2.36^{-7}$, $F = 27.9$, $df = 320$ for Q_{3dB} values).

Effects of shift of carrier frequency on responses to AMs

The results presented above demonstrate that units in the low-frequency area of AI responded to AM stimuli spectrally well above their frequency response range. That is, these units received inputs from a much wider spectral range than what could be expected on the basis of their responses to pure tones. In this section we describe the spectral boundaries of this integration. For this purpose we recorded the responses of units to different sets of AM stimuli, starting with AMs spectrally inside the FRR and then shifting the spectrum of the AMs to higher frequencies (cf. Fig. 1). The upper boundary of integration over the population tested ($n = 71$) ranged between 4 kHz and 25 kHz with a mean (±SD) of 17.8 ± 5.0 kHz.

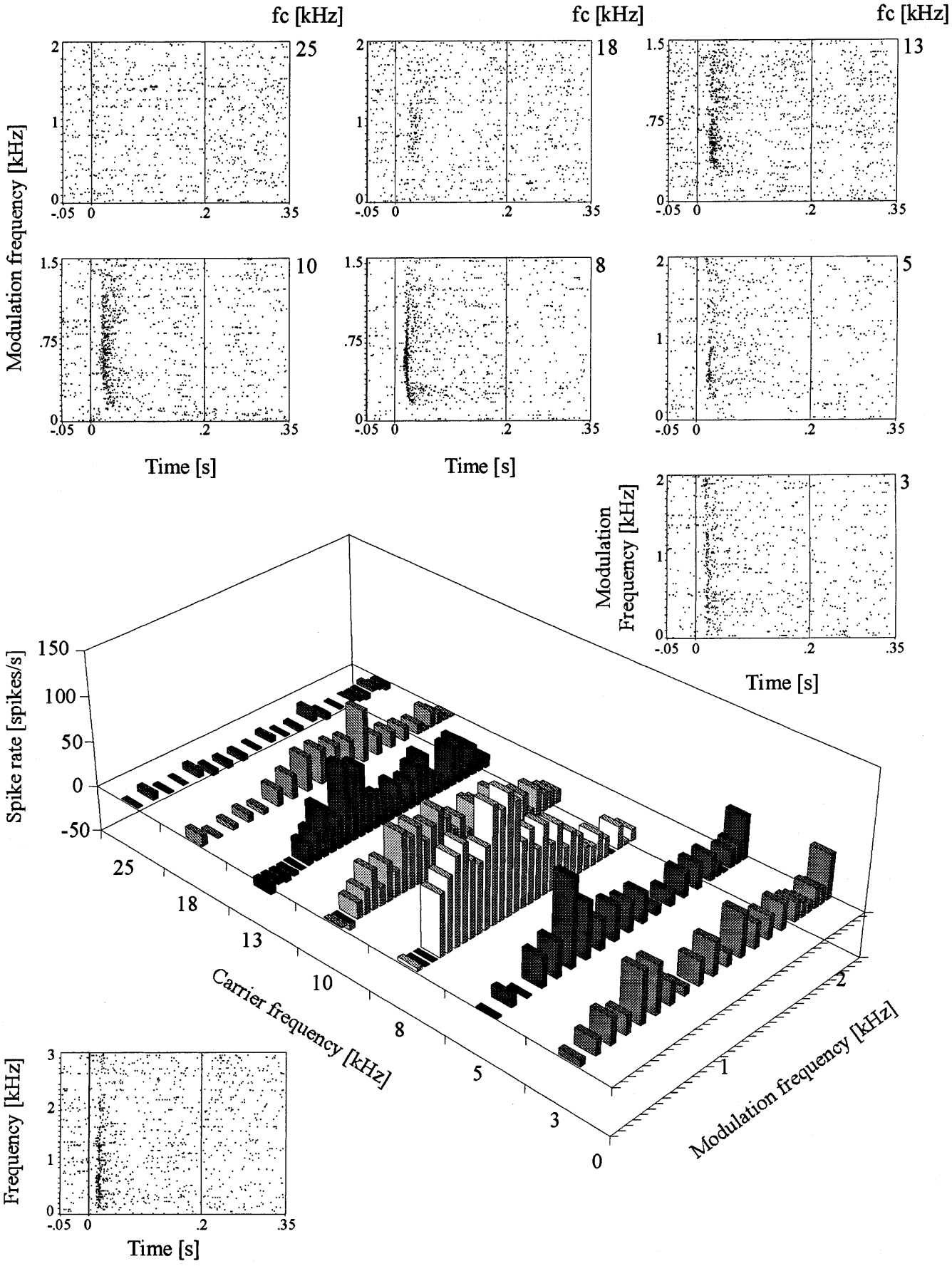
Figure 2 shows the results of such an experiment for one unit. The response to pure tones of this unit is illustrated in the lower left panel: The unit responded to low-frequency pure tones between 100 Hz and 3000 Hz (tested up to 40 kHz, not shown) with a BF of 300 Hz. Seven sets of AM stimuli with different carrier frequencies (3, 5, 8, 10, 13, 18, and 25 kHz) were presented. The responses to AMs are shown as point-plots in Fig. 2. The carrier frequencies are displayed at the upper right corner of each plot. Modulation frequencies ranged from 0 kHz to 2 kHz. The bar chart shows the MTFs for each carrier frequency.

At 3 kHz carrier frequency (lowest MTF in the bar chart) the spectrum of each of the AMs presented partially overlaps with the FRR of the unit. As can be seen from the point-plot and the MTF, the unit responded to all AMs of this set with phasic ON-responses that were not clearly tuned to a particular range of modulation frequencies. The latency of this response was 12.9 ms, measured at 2 kHz *f*m.

At 5 kHz carrier frequency a clear tuning to modulation frequency emerged: the unit responded to AMs with modulation frequencies between about 300 Hz and 1500 Hz with a BMF of 500 Hz. The spectra of these AMs ranged between 3500 Hz and 6500 Hz, and were therefore above the FRR of this unit. Interestingly, the MTF for this carrier frequency showed another peak at 2 kHz *f*m. There the lower sideband of the AM reached the FRR of the unit and therefore activated it. The latencies of these responses differed: for *f*m around 500 Hz, the latency was 17.6 ms and at 2 kHz was 13.7 ms. The latter value is close to that observed for AMs with a *f*c of 3 kHz (12.9 ms). As mentioned above,

▶

Fig. 2 Effect of shift of AM spectra. Responses of a multi-unit to AMs with different spectral contents but similar sets of modulation frequencies are shown as point-plots (*upper part*). Seven sets of AMs were presented with carrier frequencies (*f*cs) ranging from 3 kHz to 25 kHz (as identified in the *upper right corner* of each point-plot). Rate modulation transfer functions (MTFs) corresponding to each point-plot are shown in the bar chart below. The response to pure tones of this unit is illustrated in the *lower left corner*. Pure tone frequencies above 3 kHz were not responded. For the AM set with the lowest *f*c (3 kHz) each AM is partially within the FRR of the unit. With progressively higher *f*cs the AMs were shifted to spectral ranges completely outside the unit's FRR. For explanations of the responses refer to text


fc [kHz]
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25
18
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Spike rate [spikes/s]
150
100
50
0
-50
25
18
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Carrier frequency [kHz]
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Modulation frequency [kHz]
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responses to pure tones had generally shorter latencies than responses to AMs. This suggests that the two peaks of the MTF were the result of qualitatively different modes of activation of the unit: a short latency activation that can be seen if at least one spectral component of the stimulus is within the excitatory portion of the classical frequency receptive field (as defined above), and a long latency activation that can be seen if a complex stimulus like an AM is within the spectral receptive field of the unit. The latter phenomenon may play a role in temporal information processing (cf. Schulze and Langner 1997a).

For all other sets of AMs with carrier frequencies above 5 kHz the spectra were well above the FRR of the unit. A direct activation of the excitatory portion of the classical frequency receptive field can therefore be excluded. With carrier frequencies between 8 kHz and 13 kHz the unit showed strong phasic responses over a range of modulation frequencies from 150 Hz to 1400 Hz. With a *fc* of 18 kHz the response to AMs was much weaker than with lower *fc*s and was seen over a range of *fm*s only from 500 Hz to 1300 Hz. Finally, with a *fc* of 25 kHz no further responses could be evoked by the AM stimuli. Obviously, this unit from the low frequency area of AI somehow received information about complex stimuli with spectral contents up to at least 18 kHz.

A comparison of the MTFs for the AM sets of different *fc*s shows that the unit's response properties changed as a function of *fc*. This is further illustrated in Fig. 3. Figure 3A shows the entire MRR between the broken lines and the BMF (solid line) as a function of carrier frequency. As pointed out above the AM set with a *fc* of 3 kHz activated the excitatory portion of the classical frequency receptive field of the unit and was therefore not included in this plot. For this unit, BMF and MRR were relatively constant over a wide range of carrier frequencies (up to 13 kHz). For higher *fc*s the BMF shifted to higher values and the MRR narrowed before the response finally disappeared. Figure 3B illustrates the change in latency with *fc*. At a *fc* of 5 kHz the latency of the response to AM was 17.7 ms. With increasing *fc*, latency first declined to 16.3 ms at 8 kHz *fc*, and then increased steadily. Note, that the shortest response latency was not observed for the AMs spectrally closest to the FRR of the unit but at some spectral distance.

The data presented so far show that neurons in the low-frequency area of AI integrate modulation information over a wide spectral range. This wide spectral integration is not reflected by the pure tone frequency response range of these units which is usually much narrower. This is illustrated in Fig. 4 which shows a scatter plot of the highest tone frequency that elicited a response against the carrier frequency of the highest effective AM set for each unit (we did not choose the highest effective lower sideband of the AMs here, because this frequency component alone was ineffective and can therefore not be the upper limit of spectral integration). Plotted are only data from those units in our sample that responded to AMs spectrally above the FRR ($n = 71$). The upper limit of spectral integration

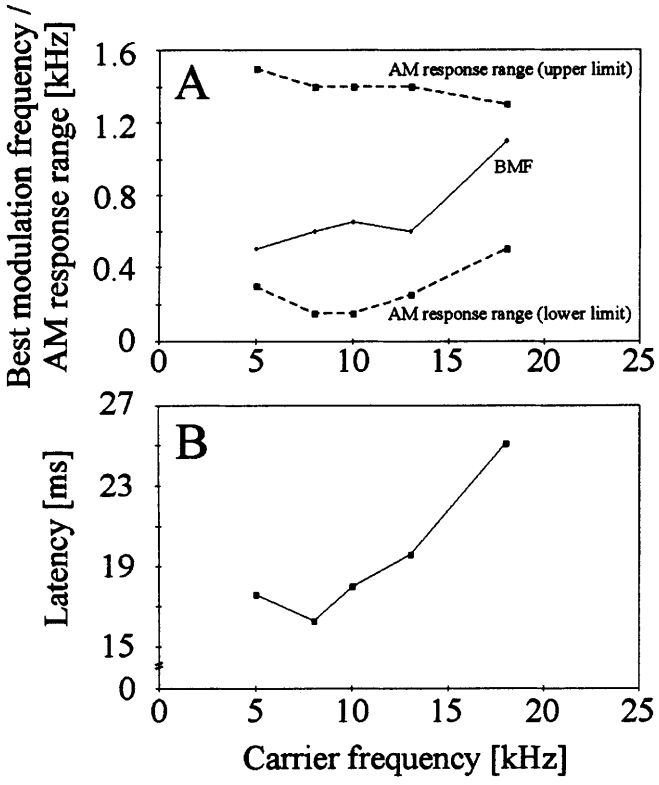


Fig. 3A, B Change of neuronal response properties as a function of *fc* for the responses shown in Fig. 2. **A** AM response range (MRR, *broken lines*) and best modulation frequency (BMF, *solid line*) as a function of *fc*. **B** Latency of the responses to AMs as a function of *fc*

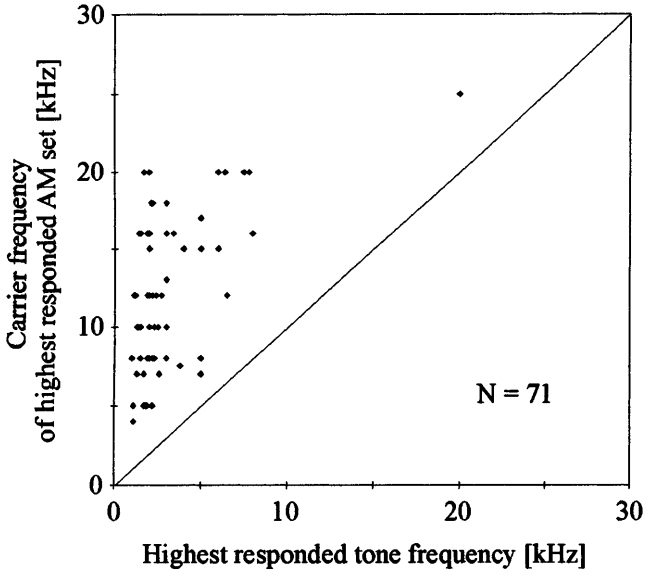


Fig. 4A Plot of the highest *fc* of AMs which evoked a response over highest pure tone frequency which evoked a response. Spectral integration of primary auditory cortex (AI) units as revealed by the AM experiments is much wider than what would be expected on the basis of the responses to tones

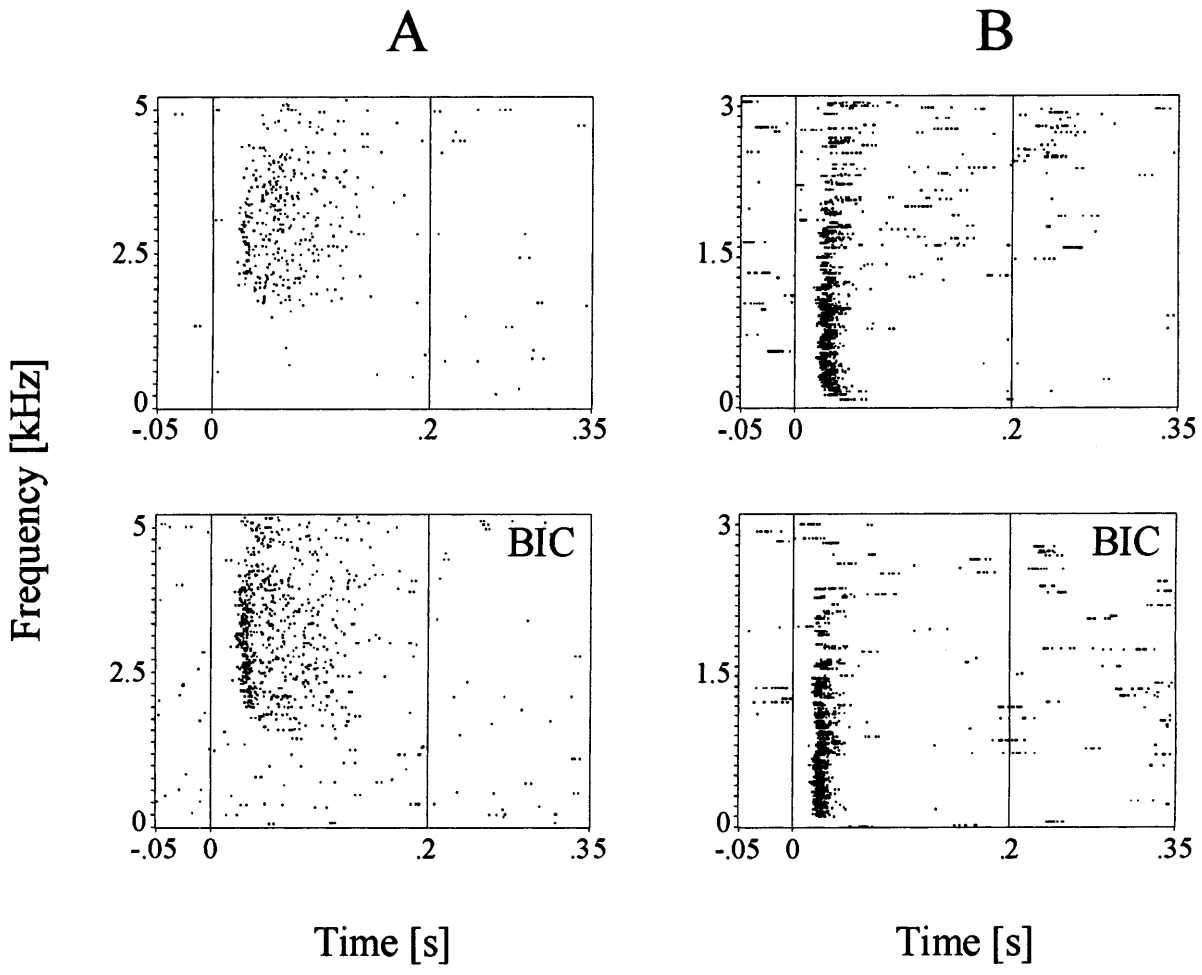


Fig. 5A, B Influence of (−)-bicuculline-methiodide (BIC) on responses to pure tones. Shown are point-plots of responses of two units (**A** multi-unit, **B** single unit) before (*upper plots*) and during (*lower plots*) the application of BIC. BIC did not significantly affect pure tone response measures like FRR or latency

(as approximated by the AM carrier) could be up to 3.5 octaves higher than the highest effective pure tone frequency.

Effects of blocking $GABA_A$-mediated inhibition

In the first part of this paper we described the wide spectral integration of units in the low frequency area of AI under normal conditions. As neuronal responses are usually sharpened by inhibitory influences, we applied the $GABA_A$-antagonist BIC microiontophoretically to block $GABA_A$-mediated inhibition. If the AM responses described above were indeed influenced by $GABA_A$-mediated inhibition, then spectral integration of cortical units should be even wider under the influence of BIC. Furthermore, comparison of the influences of BIC on the AM responses with those on pure tone responses might indicate whether the responses to both types of stimuli result from activations reaching the unit from the same or different (afferent or intracortical) projection systems.

Effects on spontaneous activity

Since many measurements (up to 12) were carried out for most of the units before and during the application of BIC, the influence of BIC on the units' spontaneous activity could be tested for significance separately for each unit (ANOVA). Out of 28 units, 11 units (39%) showed significant increases of spontaneous discharge rate, 3 (11%) showed decreases and 14 (50%) showed no significant changes at the $P < 0.05$ level. For the population of units, mean spontaneous discharge rate was lower under control condition (7.1 ± 5.9 spikes s^{-1}; mean ± SD) compared to the BIC condition (8.7 ± 4.4 spikes s^{-1}; paired *t*-test, $P = 0.05$).

Responses to pure tones

The influence of BIC on the spike rates evoked by pure tones was different for those units that discharged at low rates (<100 spikes s^{-1}) compared to those units that discharged at high rates (between 100 and 500 spikes s^{-1}) before the application of BIC. For the first group of units ($n = 7$) spike rates in response to pure tones strongly increased (mean spike rate before BIC = 63 spikes s^{-1}; mean spike rate during

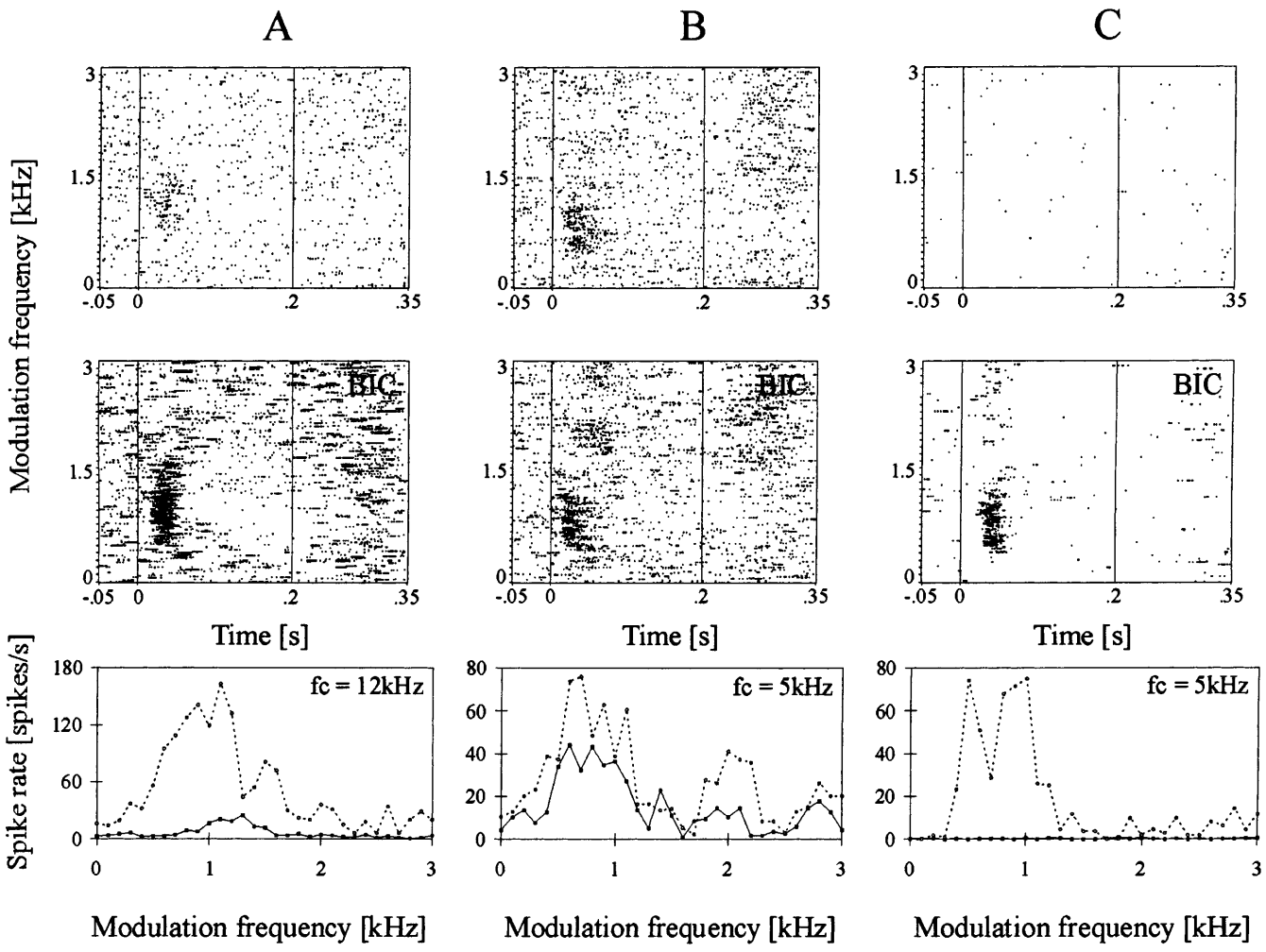


Fig. 6A–C Influence of BIC on responses to AMs. Shown are point-plots of responses of three multi-units (**A**, **B**, and **C**) before (*upper plots*) and during (*middle plots*) the application of BIC. *Bottom panels* show MTFs derived from these responses (*solid lines*: before BIC application; *dotted lines*: during BIC application). BIC increased the AM response strength and – in contrast to responses to pure tones – also enlarged MRR. Other AM tuning characteristics were not significantly changed. Some units were responsive to AMs spectrally located outside their FRRs only under the influence of BIC (**C**)

BIC = 163 spikes s^{-1}; $P = 0.01$, paired t-test). An example is illustrated in Fig. 5A: the unit discharged with a spike rate of 18 spikes s^{-1} before the application of BIC (upper plot) and with 38 spikes s^{-1} during the application (lower plot). For the group that already exhibited high tone-evoked discharge rates under control conditions ($n = 18$), changes in tone-evoked discharge rates during the application of BIC were generally weaker and showed a slight decrease over the population of units (mean spike rate before BIC = 310 spikes s^{-1}; mean spike rate during BIC = 277 spikes s^{-1}; $P = 0.04$, paired t-test). An example is illustrated in Fig. 5B. This unit discharged at rates of 466 and 460 spikes s^{-1} before and during the application of BIC, respectively. Although this decrease was also significant we suppose that it may be due to other effects than the BIC influence, possibly habituation (see Discussion).

Response latency during the application of BIC could differ by up to ±5 ms from the value under control conditions, but for the population the difference was not significant ($n = 25$; mean latency before BIC = 19.2 ms; mean latency during BIC = 19.8 ms; $P = 0.11$, paired t-test).

Interestingly, the application of BIC did not significantly alter the FRR. Fourteen out of 23 units tested (61%) showed a similar FRR before and during the application of BIC. Only 9% exhibited a slightly wider FRR (difference ≤0.25 octaves), and 30% even exhibited a smaller FRR under BIC (difference ≤1 octave; cf. Fig. 5B).

Responses to AM stimuli with a spectrum outside a unit's FRR

Responses to AMs of three units under control conditions (upper panels) and during the application of BIC (middle panels) are shown in Fig. 6. Generally, blocking $GABA_A$-mediated inhibition increased the units spike rate to AM stimuli. The mean spike rate before the application of BIC ($n = 43$) was 58.9 ± 33.1 spikes s^{-1} and 97.9 ± 40.4 spikes s^{-1} during the application of

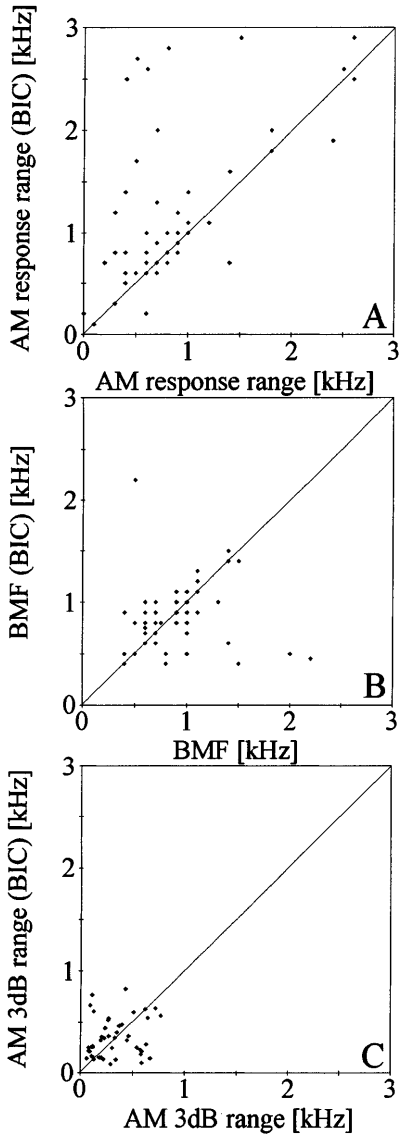


Fig. 7 Evaluation of the influence of BIC on three AM response parameters: AM response range (=MRR; **A**), BMF (**B**), and AM 3-dB range (**C**). Only the MRR was significantly affected by the application of BIC

BIC. The difference was significant (paired *t*-test, $P = 0.0004$). Figure 6A shows the response of a unit to AMs with a carrier frequency of 12 kHz and modulation frequencies varying from 0 kHz (=unmodulated carrier) to 3 kHz. Under control conditions the unit discharged at a maximal rate of 32 spikes s^{-1} (i.e. at BMF). During application of BIC that rate increased to 196 spikes s^{-1}. The MTFs in the bottom panel revealed that tuning to modulation frequencies was only slightly affected by the application of BIC: the BMF shifted slightly, from 1300 Hz in the control condition (solid line) to 1100 Hz under BIC (dotted line), and the shape of the MTF was also largely unaffected by the application of BIC: Both MTFs were classified as BP.

However, the MRR increased from 800–1500 Hz under control conditions to 300–1600 Hz under BIC. Similarly, the AM 3-dB range changed from 990–1360 Hz *f*m under control conditions to 740–1205 Hz under BIC.

Another example of the influence of BIC on responses to AMs is illustrated in Fig. 6B. For this unit, MTF was altered, being BP before and CX under BIC. The BMF shifted marginally (from 600 Hz to 700 Hz). The MRR again increased, whereas the AM 3-dB range decreased slightly under BIC.

Figure 6C shows an example of a unit that did not respond to any of the AMs presented under control conditions but exhibited a strong response to a range of these stimuli during BIC application.

Figure 7 shows, for the total sample, scatter plots of MRR (A), BMF (B), and AM 3-dB range (C) during BIC application against the control condition. Only the MRR increased significantly under BIC (paired *t*-test, $n = 52$, $P = 6.02^{-5}$); BMF and AM 3-dB range were not significantly altered (paired *t*-test: for BMFs: $n = 52$, $P = 0.23$; for AM 3-dB range: $n = 44$, $P = 0.35$).

Furthermore, no significant difference in response latency to AMs before and during BIC application could be observed (paired *t*-test: $n = 52$, $P = 0.13$).

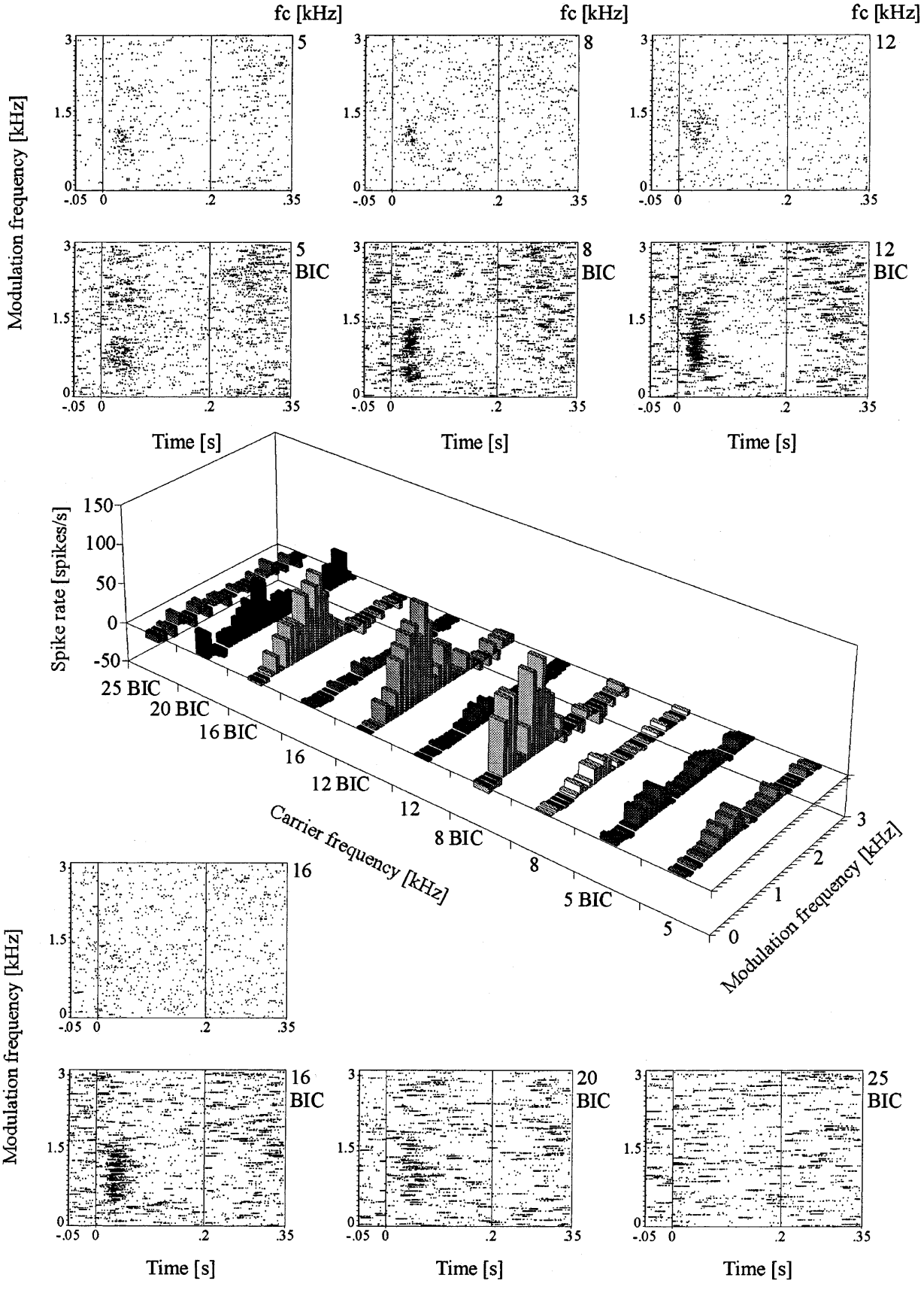
Effects of shift of carrier frequency on responses to AMs

The effects of shifting the carrier frequency of AMs on the responses under the influence of BIC were tested analogous to the experiments described above (cf. Fig. 2). Figure 8 shows the responses (point-plots and MTFs) of a unit to AMs with carrier frequencies ranging from 5 kHz to 25 kHz and modulation frequencies from 0 kHz to 3 kHz, both before and during the application of BIC. The unit responded to pure tones between 250 Hz and 1900 Hz under control conditions. During the application of BIC the upper border of the FRR increased slightly, viz. to 2000 Hz (not shown). Therefore, all AMs presented were spectrally above the FRR of the unit.

Point-plots are arranged in double rows with the control responses in the upper row and the corresponding responses under BIC below. Carrier frequency and condition [BIC/Control (=no label)] are displayed at the upper right corner of each point-plot. Under control conditions, the unit exhibited a weak response to AMs with carrier frequencies between 5 kHz and 12 kHz, but not above 12 kHz. BMF and MRR varied marginally as a function of carrier frequency (cf. Fig. 9A).

Application of BIC had three major effects on these responses to AMs: first, and in contrast to the FRRs, the MRR increased substantially (for a *f*c of 8 kHz, for example, from 900–1200 Hz to 300–1500 Hz; Figs. 8, 9A).

Second, spike rate increased (for example, for an AM with a *f*c of 5 kHz and at BMF from 44 spikes s^{-1} to 68 spikes s^{-1}, with a *f*c of 8 kHz from 48 spikes s^{-1} to


fc [kHz]
fc [kHz]
fc [kHz]
5
8
12
5 BIC
8 BIC
12 BIC
Modulation frequency [kHz]
Time [s]
Time [s]
Time [s]
Spike rate [spikes/s]
150
100
50
0
-50
25 BIC
20 BIC
16 BIC
16
12 BIC
12
8 BIC
8
5 BIC
5
Carrier frequency [kHz]
Modulation frequency [kHz]
16
16 BIC
20 BIC
25 BIC
Modulation frequency [kHz]
Time [s]
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Time [s]

◄

Fig. 8 Effects of BIC on the spectral integration. Shown are the responses to AMs of a multi-unit to sets of AMs with different *fc*s (analogous to Fig. 2) before and during the application of BIC. At the *upper right corner* of each point-plot the *fc* of the AM set is displayed. If recordings were made under the influence of BIC it is noted below the *fc*. The column chart in the middle gives the MTFs corresponding to all point-plots. Under the influence of BIC responses were elicited by AMs with even higher spectral contents than under normal conditions. For further descriptions refer to the text

151 spikes s^{-1}, and with a *fc* of 12 kHz from 32 spikes s^{-1} to 196 spikes s^{-1}). The difference was significant over the population of neurons tested (cf. above). Note that, although the $GABA_A$-mediated inhibition is suppressed by BIC, inhibitory influences are still obvious after the responses to AMs with carriers of 8 kHz, 12 kHz, and to a lesser degree 16 kHz.

Third, responses could be evoked by AMs with higher carrier frequencies. For a modulation frequency of 1 kHz, for example, the highest effective *fc* was 12 kHz under control conditions and 20 kHz under BIC (see also Fig. 9A). Across the population, 11 of the 25 units responded during the application of BIC to AMs with higher carrier frequencies (up to 40 kHz which was the highest carrier that could be tested with the equipment used) than under control conditions. (cf. Table 1).

Although the latency of the response of the unit shown in Fig. 8 to the AM signal slightly decreased under BIC (Fig. 9B, the solid line shows the latency of the response to AM under normal conditions as a function of carrier frequency, the dotted line the latency of the response to AM during application of BIC), latency differences were not significant over the population of neurons tested (cf. above). BMFs were almost unaffected by BIC (cf. Fig. 9A).

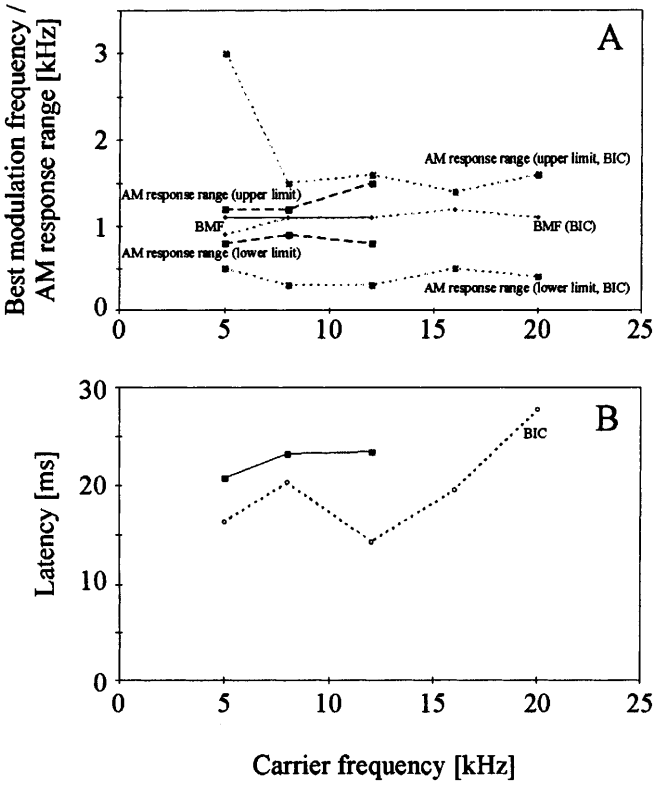

Fig. 9A, B Change of neuronal response properties as a function of *fc* for the responses given in Fig. 8. **A** AM response range (=MRR; *dashed lines*) and BMF (*solid line*) before the application of BIC and MRR (*dotted line*) and BMF (*dashed-dotted line*) during the application of BIC as a function of *fc*. **B** AM response latency before (*solid line*) and during (*broken line*) the application of BIC as a function of *fc*

Discussion

The use of multi-unit recordings

Stable recordings from a single unit are more difficult to maintain over a long period of time than from a multi-unit. Hence, as many different stimulus sets had to be tested (for the BIC experiments up to 22) which could take more than 2 h recording time per unit, this study is mainly based on multi-unit recordings.

One main finding of our study was that AM stimuli with a spectrum completely outside a units FRR could evoke responses in AI units. One might suspect that for the multi-unit recordings the pure tone responses were recorded from single units in the cluster other than the AM responses. First of all, this is unlikely because it was reported by a variety of studies that simple as well as complex response properties of single units within a multi-unit are very similar to the response characteristics of the whole cluster (Imig et al. 1990; Schreiner and Sutter 1992; Shamma et al. 1993; Schreiner and Calhoun 1994; for a discussion see Schreiner and Mendelson 1990). More importantly, if the AM responses were indeed recorded from single units that did not respond to the pure tones presented before, this would have no implications for our conclusions: these units would still have responded to a combination of spectral components but to none of these components when presented alone. The same type of argumentation is valid for the BIC experiments: It has no implication for our results

Table 1 Highest carrier frequency of 100% sinusoidally amplitude-modulated pure tones that elicited a response (*BIC* (–)-bicuculline-methiodide)

Unit	Normal (kHz)	BIC (kHz)
o-16	12	20
o-18	No response	12
o-21	20	40
p-1	16	30
p-2	16	30
p-3	16	20
p-7	8	12
p-9	8	12
p-10	No response	8
p-13	8	12
p-14	12	16

whether the single units in the cluster responded to a wider range of AM during the BIC condition compared to the control condition, or only under the influence of BIC. Indeed, the latter phenomenon was observed even for two multi-units in our sample (cf. Fig. 6C). Therefore, we conclude that the inclusion of multi-unit data in our study was not critical.

The role of distortion products

In this study we report that units in the low-frequency area of AI respond to complex (AM) stimuli which possess a spectrum completely outside the units' FRR. That is, the units responded to a combination of spectral components, each of which was ineffective in eliciting a response when presented alone. The spectral interval in which this phenomenon occurred increased under the influence of BIC. Before it can be concluded that these responses reflect a mechanism of wide spectral integration, the possibility has to be ruled out that the observed responses might be elicited by distortion products located inside the FRR of the units. A detailed discussion of this problem is given in Schulze and Langner (1997a) and will therefore only be summarised here. The most prominent distortion product, the cubic difference tone $2f1–f2$, is only of little concern here as it lies outside the FRR whenever the distance between the FRR and the *f*c is more than three times the *f*m which was the case in most experiments. The most important distortion product in the present context is the difference tone $f2–f1$ which is identical to the modulation frequency *f*m. Several lines of evidence indicate that the described responses to AMs were not elicited by this or other distortion products:

First, for about half of the units the temporal characteristics of the responses to pure tones and AMs differed. For example, many units showed a phasic response to pure tones and a tonic response to AMs. If the response to AMs was simply the result of spectral activation by a distortion product, then one should expect a similar temporal response pattern to pure tones and to AMs (although an intensity effect cannot be completely ruled out (see below for a discussion of tuning curves). Second, some units responded to AMs of high modulation frequencies but were sharply tuned to a narrow range of very low tone frequencies. Thus, the difference tones that originate from AMs with high modulation frequencies would already be located above the FRR (not shown, for an example refer to Schulze et al. 1999). Finally, the distribution of BMFs shows a systematic topography (periodotopy), with a periodotopic gradient running roughly orthogonal to the tonotopic gradient (Schulze and Langner 1997a). If the neuronal responses to the AMs with spectra above the frequency receptive fields of the units were due to distortion products (i.e. to the difference tone), a basic similarity in the topographies of BMFs and of BFs should be expected.

Effects of blocking the $GABA_A$-mediated inhibition

General effects

As detailed above, blocking of $GABA_A$-mediated inhibition led to changes in spontaneous as well as evoked spike rates: Both spontaneous and evoked spike rates could be either increased or decreased. For the majority of units (19 out of 28) increases in spontaneous spike rate, tone-evoked spike rate and/or AM-evoked spike rate were observed. For the remaining 9 units it is unlikely that ineffective BIC application could account for the absence of an effect on spike rate, because in at least some of these units (3) other BIC-induced effects were clearly observable; namely, a shift of effective *f*c to higher frequencies. Besides, the finding of unchanged response properties after BIC application in certain units has also been reported in other studies (e.g. Pollak and Park 1993).

Furthermore, we do not believe that the slight decreases in spontaneous and/or evoked spike rates we observed in some units were a result of the BIC application: as many separate experiments (up to 12) had to be carried out for a given unit before and during the application of BIC in order to characterise tone-evoked responses and responses to a variety of AM sets with different *f*cs – a procedure that could take more than 2 h we believe it is more likely that some habituation effects lead to a decrease in spike rate rather than the BIC influence. This is most obvious for the tone-evoked responses of units that discharged at high rates already under control condition: These units probably could not maintain such high discharge rates over a long period of time. The non-stationarity of spike rate over longer periods of time was also reported by Ohl and Scheich (1996). Those units, on the other hand, that discharged at low rates under control condition showed very robust BIC effects over a long period of time.

For these latter units, we reported a strong BIC-induced increase of discharge rate in response to pure tone stimulation without changing FRR. In the auditory system such an effect has been reported only for the ventral cochlear nucleus where it was considered to be involved in enhancing signal-to-noise ratio of pure tone responses (Caspary et al. 1994; Ebert and Ostwald 1995). One might speculate that $GABA_A$-mediated inhibition, in addition to its described influence on MRR, plays a similar role in auditory cortex.

Finally, as can be seen in the point-plots in Fig. 6 and Fig. 8, application of BIC often gave rise to a bursting behaviour. It is conceivable that BIC-induced bursting might be in conflict with temporal coding mechanisms. However, since the high periodicities of the AM stimuli used in this study are rate-place coded and not represented by a temporal (synchrony) code (cf. Schulze and Langner 1997a), the AM coding should not be significantly affected by BIC. The finding that BMF and Q_{3dB} values were largely uneffected by BIC (cf. Fig. 7) provides further support for this conclusion.

Effects on FRR and MRR

In our study, blocking the $GABA_A$-mediated inhibition generally led to an increase of MRR but not FRR for most of the units. Only a few units showed increases or decreases in FRR. Although an unequivocal picture of BIC effects on receptive fields has not yet emerged in the literature, this result is in contrast to several studies that reported a broadening of FRRs in the auditory system under the influence of BIC (e.g. dorsal cochlear nucleus in the rat: Yajima and Hayashi 1990; inferior colliculus and medial geniculate body in bats: Vater et al. 1992; Yang et al. 1992; Suga et al. 1997; auditory cortex analogue of the chick, field L: Müller and Scheich 1988; primary auditory cortex of the chinchilla: Wang et al. 1996). Wang et al. (1996) have reported that 28 out of 36 units showed expansions of their FRR. While it is conceivable that the effect of BIC is different between auditory cortical units and units of lower nuclei of the auditory pathway, the discrepancy with the results described by Wang et al. (1996) remains puzzling. Unfortunately, Wang et al. (1996) did not report how strongly BIC expanded the FRRs or whether there was any effect on the remaining cells (such as narrowing of FRR), but nevertheless the discrepancy with our results is obvious. This discrepancy may possibly be a result of an undersampling effect: in both the study of Wang et al. (1996) and our study the effect of BIC on the tone response properties was tested only for a small number of units. Furthermore, the units recorded in our study were all taken from the low-frequency region of AI the results of which might not necessarily generalise to all cortical units.

On the other hand, our results that the FRR of auditory cortical neurons can remain largely unaffected, become slightly enlarged, or even become narrowed by BIC corresponds to observations from the somatosensory thalamus in the cat by Hicks et al. (1986). These authors also reported decreases or slight increases of somatosensory receptive fields under the influence of BIC. Hence, the function of $GABA_A$-mediated inhibition does not always lead to a sharpening of simple receptive field properties like tuning to pure tones but may affect more complex receptive field properties as observed in this study for the AM tuning.

BIC-induced influences on complex response properties like tuning to various parameters of amplitude or frequency modulations, rate-level functions, temporal discharge patterns, binaural interaction, or selectivity for natural vocalisations have been described in a variety of mammalian auditory nuclei like the inferior colliculus, the dorsal nucleus of the lateral lemniscus, the ventral cochlear nucleus or the avian field L (Müller and Scheich 1987; Faingold et al. 1989; Pollak and Park 1993; Park and Pollak 1994; Ebert and Ostwald 1995; Le Beau et al. 1996; Yang and Pollak 1997; Caspary and Palombi 1997; Lu et al. 1998; Koch and Grothe 1998). Here we report that BIC affects the tuning of cortical neurons to AM stimuli: for a given *f*c, AM with a larger range of *f*m elicited excitatory responses compared to control condition. A similar effect on MRR was reported for inferior collicular neurons (Lu et al. 1998; cf. also Fig. 8 in Burger and Pollak 1998). Hence, one effect of $GABA_A$-mediated inhibition in AI is a sharpening of neuronal AM tuning, similar to the known sharpening of frequency tuning by lateral inhibition (cf. Suga 1995).

If a sharpening of FRR in the auditory cortex exists, it might be based on another transmitter-system, e.g. via $GABA_B$-mediated inhibition. In this case, two functionally independent GABAergic systems would be realised in the mammalian auditory cortex in a manner similarly proposed for field L of the chick (Müller and Scheich 1988). Despite some controversy in the literature, also the existence of glycine receptors in the auditory cortex can not be totally excluded (cf. Winer et al. 1995; Gopal and Gross 1996). Our observation of inhibitory influences even during the BIC condition (cf. Fig. 8) supports this assumption about the existence of two independent inhibitory transmitter-systems in the auditory cortex. Future studies will have to resolve these issues.

Integration beyond the classical excitatory frequency receptive field

The receptive field of neurons in central sensory systems is classically described to consist of an excitatory centre and an inhibitory surround (for the auditory system e.g. Abeles and Goldstein 1972; Abbas and Sachs 1976; for the visual system, e.g. Hubel and Wiesel 1962; Bishop et al. 1973; Rose 1977). In addition, the facilitatory or inhibitory influence of stimuli outside this classical excitatory receptive field on neuronal responses to stimuli within the receptive field was frequently observed in the visual (Hubel and Wiesel 1962; McIlwain 1966; Levick et al. 1972; Maffei and Fiorentini 1976; Rizzolatti and Camarda 1977; Hammond and MacKay 1981; Nelson and Frost 1985; Gilbert and Wiesel 1990; Hirsch and Gilbert 1991; Li et al. 1991, 1992; Molotchnikoff et al. 1992; Li and Li 1994; Bauer et al. 1995; for a review see Allman et al. 1985) as well as the auditory system. (Oonishi and Katsuki 1965; Ehret and Merzenich 1988; Nelken et al. 1994a, b). In the present study we describe a qualitatively different phenomenon, viz. that a complex auditory stimulus with all its components located completely outside the excitatory portion of the classical frequency receptive field can activate a unit above threshold in the absence of any stimulus or stimulus component within the excitatory portion of the its classical frequency receptive field. To our knowledge, only a few studies have described a similar result. Whitfield and Evans (1965) have reported neurons in the AI of cats which respond to sinusoidally frequency-modulated tones with a spectrum completely outside their FRR. Riquimaroux et al. (1993) reported units in the low-frequency area of the AI of the Japanese mon-

key (*Macaca fuscata*) which responded to harmonic complexes with spectra completely above the units' FRRs. Unfortunately, neither of these two studies commented on the possibility of distortions produced in their setup, preparation or stimulus design. Rajan (1997) has described responses of auditory nerve fibres and neurons in the dorsal cochlear nucleus of cats to two-tone complexes, where neither component alone elicited a response. In contrast to our conclusions Rajan concludes that the responses he measured were indeed responses to distortion products generated in the cochlea and therefore would not necessarily reflect periodicity coding.

Here we could show that units in AI obviously integrate over spectral ranges that are much wider than what would be expected on the basis of just their responses to pure tones. This is evident from the fact that these units respond to AMs with a spectrum completely outside the units' FRR. We conclude that these units received information from regions *of the cochlea* that are larger than the cochlea region where the tone frequencies are represented to which the units were tuned. Hence, the spectral receptive field of these units can be decomposed into two qualitatively different parts: one, where activation of a single frequency channel (by a pure tone) leads to an excitatory response of the units (= the classical excitatory frequency receptive field), and another one, where several frequency channels that project to this unit have to be activated simultaneously to activate the unit above threshold. Further, our microiontophoretic experiments have demonstrated that this extension could even be enlarged beyond what could be concluded on the basis of the AM experiments under normal condition: after blocking the $GABA_A$-mediated inhibition responses could be elicited by AMs with *f*cs up to 40 kHz, suggesting that some primary auditory units integrate over the whole audible spectrum of the gerbil.

One problem remains before this conclusion can be drawn: because of the large number of measurements that had to be carried out on a given unit we did not determine pure tone tuning curves but instead measured responses at 30 dB SPL above the minimum threshold of a given unit (cf. Materials and methods). One might argue that, as the lower sideband of the AM stimuli was less intense than 30 dB above minimum threshold, and as we did not measure the FRR for lower intensities, the lower sideband of the AM may have activated the classical excitatory frequency receptive field of the unit. This interpretation would only be of importance for units where the FRR for intensities lower than 30 dB above minimal threshold was wider than at 30 dB above minimal threshold, i.e. for those units whose tuning curves were not V-shaped. To exclude this possibility we measured in five units the tuning curves between minimal threshold and 30 dB above in 10-dB steps. The tuning curves of these units were V-shaped, which is also known to be the typical appearance of primary auditory cortical tuning curves (Phillips and Irvine 1981; Schreiner and Mendelson 1990; Schreiner and Sutter 1992; Heil et al. 1992). We therefore infer that even if some of the units in our sample had tuning curves that were not V-shaped for levels below those intensities used in our measurements (and because of the spectrally very high AMs we used), this would have no qualitative influence on our conclusions drawn above.

We therefore conclude that the spectral receptive field of an auditory cortical unit is wider and much more complex than the excitatory classical frequency receptive field determined with pure tone stimulation. Auditory cortical units may integrate over wide spectral ranges to extract complex information (like stimulus periodicity) from the signal. According to our data this integration process has two main characteristics: first, inputs from different spectral ranges are weighed differently, so that for low-frequency input the activation of single-frequency channels is sufficient to activate the unit above threshold, but for high-frequency inputs simultaneous activation of multiple-frequency channels is required. Second, the output of this integration process – here the tuning to AM stimuli – is secondarily sharpened by inhibition, probably via a lateral inhibition mechanism (cf. above). This relates to both MRR and effective *f*c. We can not infer from our data whether these two processes are realised in the same or different auditory nuclei, but as our BIC manipulations were carried out in the auditory cortex at least the lateral inhibition mechanism has to be realised there. Unfortunately, it is not possible to decide whether the spectral integration process itself is also realised in the auditory cortex or some other auditory nucleus, but we believe that because of its unique functional anatomy and morphology (for the cat cf. Rockel and Jones 1973; Oliver 1984; Oliver and Morest 1984; Herrera et al. 1988; Oliver et al. 1991; Schreiner and Langner 1997; for an overview see Oliver and Huerta 1991; for the marmoset cf. Garey and Webster 1989; for the gerbil: Ryan et al. 1982), the central nucleus of the inferior colliculus (ICC) may be a possible candidate. The ICC is organised into discrete isofrequency laminae where neurons of each lamina share similar BFs covering about 1/4 of an octave (Schreiner and Langner 1997). Two main cell types, disc-shaped cells and stellate cells are distinguished within the ICC (Oliver 1984; Oliver and Morest 1984; Herrera et al. 1988; Oliver et al. 1991; Oliver and Huerta 1991). Whereas the disc-shaped cells have highly oriented dendritic trees aligned in parallel with the orientation of the isofrequency laminae, the stellate cells are characterised by their oval or spherical dendritic fields crossing the isofrequency laminae. These stellate cells receive local projections from disc-shaped cells of several isofrequency laminae and may therefore integrate over more or less wide spectral ranges (cf. Meddis 1996; for a detailed description of an ICC-based model that could explain the data presented here see Schulze and Langner 1999). Biebel and Langner (1996) report units in the ICC of the chinchilla that respond to a certain range of *f*m of AM independent of *f*c. This result may be a first hint

that the spectral integration observed in cortex indeed takes place in the ICC already. In contrast to cortical units reported here, the ICC units reported by Biebel and Langner had BFs always corresponding to their BMFs. The role of the auditory cortex in AM encoding therefore seems to be a sharpening of AM tuning and a recombination of spectral (FRR) and temporal (MRR) response properties to code for more complex parameters or parameter combinations of the acoustic surround.

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