The responses of single units in the inferior colliculus of the guinea pig to damped and ramped sinusoids

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Abstract

Temporal asymmetry can have a pronounced effect on the perception of a sinusoid. For instance, if a sinusoid is amplitude modulated by a decaying exponential that restarts every 50 ms, (a damped sinusoid) listeners report a two-component percept: a tonal component corresponding to the carrier and a drumming component corresponding to the envelope modulation period. When the amplitude modulation is reversed in time (a ramped sinusoid) the perception changes markedly; the tonal component increases while the drumming component decreases. The long-term Fourier energy spectra are identical for damped and ramped sinusoids with the same exponential half-life. Modelling studies suggest that this perceptual asymmetry must occur central to the peripheral stages of auditory processing (Patterson and Irino, 1998). To test this hypothesis, we have recorded the responses of single units in the inferior colliculus of the anaesthetised guinea pig. We divided single units into three groups: onset, on-sustained and sustained, based on their temporal adaptation properties to suprathreshold tone bursts at the unit's best frequency. The asymmetry observed in the neural responses of single units was quantified in two ways: a simple total spike count measure and a ratio of the tallest bin of the modulation period histogram to the total number of spikes. Responses were more diverse than those observed with similar stimuli in a previous study in the ventral cochlear nucleus (Pressnitzer et al., 2000). The main results were: (1) The shape of the responses of on-sustained units to ramped sinusoids resembled the shape of the responses to damped sinusoids. This is in contrast to the response shapes in the VCN, which were always similar to the stimulating sinusoid. (2) Units classified as onsets often responded only to the damped stimuli. (3) All units display significant asymmetry in discharge rate for at least one of the half-lives tested and 20% showed significant response asymmetry over all of the half-lives tested. (4) A summary population measure of temporal asymmetry based on total spike count reveals the same pattern of results as that obtained psychophysically using the same stimuli (Patterson, 1994a). © 2001 Elsevier Science B.V. All rights reserved.

Key words: Temporal asymmetry; Brainstem; Onset unit; Amplitude modulation

1. Introduction

In the natural world, communication sounds are typically asymmetric in time (e.g. glottal pulses of speech) and human listeners perceive temporal asymmetry over

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Abbreviations: AIM, auditory image model; BF, best frequency; CAP, compound action potential; DCN, dorsal cochlear nucleus; IC, inferior colliculus; MPH, modulation period histogram; NAP, neural activity pattern; PSTH, peri-stimulus time histogram; p/t, peak-to-total ratio; STI, strobed temporal integration; tsc, total spike count; VCN, ventral cochlear nucleus

a wide range of conditions. To investigate temporal asymmetry, Patterson (1994a) compared the perceptions of a sinusoid multiplied with a periodically decaying exponential function and a sinusoid multiplied with a periodically rising exponential function (Fig. 1). These stimuli were termed 'damped' and 'ramped' sinusoids, respectively. These sounds have two different perceptual components: one is a continuous tone with the pitch of the carrier; the other is a drumming sound, produced by the repetitive stream of abrupt onsets (damped) or offsets (ramped) of the stimuli. The longer the half-life of the exponential modulator, the stronger the tonal component.

Damped and ramped sinusoids with the same half-

life have the same long-term Fourier energy spectra. However, human listeners can discriminate them over a range of half-lives between about 1 and 32 ms where the ramped sinusoid has a stronger tonal quality than the damped sinusoid. The perceptual asymmetry increases with carrier frequency between 400 and 4800 Hz (Patterson, 1994a). Similar results were obtained with ramped and damped stimuli using noise carriers instead of sinusoidal carriers. In this case, the continuous component is a hiss rather than a tone, but the sounds can be discriminated on the basis of the relative loudness of the continuous hissing component and the drumming component (Akeroyd and Patterson, 1995). The continuous component of the perception becomes stronger with increasing half-life, which led Irino and Patterson (1996) to determine the half-live of a damped sound that produces a continuous tonal component with the equivalent relative strength to that produced by a given ramped sound. They found that the half-life of a damped sinusoid has to be, on average, four times the half-life of the ramped sinusoid.

The perceptual data obtained with psychophysical experiments were reported in conjunction with models of the auditory system designed to explain the perception (Patterson, 1994a,b; Akeroyd and Patterson, 1997; Irino and Patterson, 1996; Patterson and Irino, 1998). The initial stage of the auditory image model (AIM, Patterson et al., 1992) is a cochlea simulation, which consists of a gammatone auditory filterbank followed by a bank of two-dimensional adaptive thresholding units. The former performs the spectral analysis and converts the sound wave into a simulation of basilar membrane motion; the latter transduces the membrane motion and converts it into a form of multi-channel, neural activity pattern (NAP). Based on the NAP, Irino and Patterson (1996) developed a measure to quantify perceptual asymmetry. The activity in the region of a peak in the NAP is divided by the activity in the entire cycle to produce a measure of the ratio of the transient and continuous components in the NAP. This ratio was designated the peak concentration. Dividing the peak concentration in response to a damped sound by that in response to a ramped sound produces a peak concentration ratio, which was their summary measure of asymmetry.

It was argued that spectral models of perception cannot explain the perceptual differences between ramped and damped sounds (Patterson, 1994a). Auditory spectra created by integrating the rectified output of each channel of a gammatone auditory filterbank showed that for half-lives in the range 2–16 ms, the width of the spectral peak of a damped sinusoid is narrower than that of a ramped sinusoid. In this regard, the auditory spectrum of a damped sound is more similar to that of an unmodulated sinusoid than to the auditory spectrum

of a ramped sound, but listeners chose the ramped stimuli as having the stronger sinusoidal component.

The use of cochlear filterbanks, either alone or in conjunction with models of transduction, failed to produce sufficient asymmetry to account for the perceptual data (Irino and Patterson, 1996). For this reason, Patterson and Irino (1998) argued that a more central process must enhance temporal asymmetry further. Two mechanisms were discussed that represent a more central stage of processing in the auditory system: autocorrelation as described by Meddis and Hewitt (1991a,b) and strobed temporal integration (STI) as employed by AIM. It was shown that autocorrelation models are unlikely to be able to explain temporal asymmetry because autocorrelation is a time-symmetric process and thus reduces temporal asymmetry (Patterson and Irino, 1998). Time interval models based on STI, however, seem to provide a better explanation of the perception of damped and ramped sounds (Patterson, 1994b; Irino and Patterson, 1996 and Patterson and Irino, 1998). By applying STI to the NAPs, a representation of the distribution of time intervals in the NAPs is obtained. The NAPs are presented as a set of channels with rising centre frequency on the ordinate and activity in these channels is shown as a function of time. After STI, the same set of channels is presented but now activity is shown as a function of time interval. This representation reveals that, although the number of time intervals at the carrier period is the same for ramped and damped sinusoids in the carrier channel, ramped sinusoids produce proportionately more carrier periods in the part of the response away from the transient (see figure 4 in Patterson, 1994b). In addition, ramped sinusoids produce more carrier periods in channels away from the carrier channel and they produce carrier periods over a wider range of channels.

The current study was motivated by the hypothesis that a more central mechanism that enhances temporal asymmetry is required to explain the perceptual data. This study examines processing of temporal asymmetry in the inferior colliculus (IC), which is the recipient of all ascending auditory information at the level of the midbrain. To date there are three other physiological studies that have looked at the temporal asymmetry in the processing of damped and ramped sinusoids beyond the neural transduction stage. The first study (Fay et al., 1996) investigated the responses of goldfish saccular afferents to damped and ramped sinusoids. Fay et al. (1996) showed that goldfish can discriminate between ramped and damped sinusoids and that they perceive the ramped sinusoid as more like an unmodulated tone. The physiological study of saccular afferent responses revealed that damped sinusoids evoke fewer spikes and produce less overall phase-locking to the carrier frequency than ramped sinusoids, which correlates with

the behavioural results in that the neural responses to ramped sinusoids are more similar to the ones evoked by unmodulated sinusoids. Note, however, that phase-locking may not be essential for distinguishing damped and ramped sounds, since damped and ramped noises are also perceived differently (Akeroyd and Patterson, 1995). To explain their results, Fay et al. (1996) suggested a hypothesis first postulated by Furukawa et al. (1978; 1982), which assumes that saccular hair cells contain arrays of neurotransmitter release sites distributed with respect to release threshold. In a sound-adapted state, all release sites with thresholds below the on-going intracellular excitation level would be depleted of neurotransmitter and so a slight decrement in stimulus level would result in excitation falling below the threshold for any site capable of releasing neurotransmitter, while a stimulus increment would tend to move the excitation level above the threshold for fully replenished sites.

The second physiological study measured single-unit responses in the ventral cochlear nucleus (VCN) of the guinea pig (Pressnitzer et al., 2000). The three main unit types in the VCN (onset, chopper and primary-like) code temporal asymmetry in different ways and to varying degrees. Two measures were used by Pressnitzer et al. (2000) to quantify their data: the peak-to-total ratio (p/t) and the total spike count (tsc). The p/t was derived from the asymmetry measure introduced by Irino and Patterson (1996). It was obtained by dividing the peak activity of a unit's response to a ramped or damped stimulus by the overall activity within the modulation period. The higher the p/t, the stronger is the transient component of the response and the weaker is the continuous component. Damped sinusoids consistently produced a higher p/t than ramped sinusoids. This asymmetry was greatest at modulation half-lives of 4 and 16 ms; it was severely reduced at 1 ms and absent at 64 ms. Onset units had the highest p/t followed by chopper units and then primary-like units. Primary-like units, which most closely reflect the activity at the level of the auditory nerve, responded with a higher number of spikes to ramped than to damped stimuli. The asymmetry in the spike rate was enhanced by chopper cells. Pressnitzer et al. (2000) concluded that there was an enhancement of temporal asymmetry in the VCN by both onset and chopper units in comparison to primary-like; chopper units seem to code the sound of a sinusoid with higher spike rates while onset units code the temporal asymmetry by means of high p/t.

The third study measured responses of cortical neurones in awake marmosets to a similar set of stimuli (Lu et al., 2001). While the responses of cortical neurones show more distinct types of behaviour in response to damped and ramped stimuli than their VCN counterparts, Lu et al. (2001) hypothesised a physiological correlate to temporal asymmetry. The correlate was based on differences in discharge rates in response to damped and ramped sinusoids. No reliable temporal code for the asymmetry was found for cortical neurones at a modulation period of 25 ms.

In this paper, we use the asymmetry measures developed by Pressnitzer et al. (2000) and measure responses for three groups of units in the IC: onset, on-sustained and sustained units. The responses of single units to temporal asymmetry in the IC were more diverse than in the VCN. The asymmetry in p/t values observed in the VCN (Pressnitzer et al., 2000) persists in units of the on-sustained types. It is absent in sustained units and very large in onset units due to a lack of responses to ramped stimuli. The results show that all units respond with a significantly different discharge rate to at least one of the half-lives tested. However, sustained units showed less overall asymmetry than any unit type investigated in the VCN. A population measure of temporal symmetry introduced by Lu et al. (2001) in a study in the auditory cortex was applied to our total population of IC units, irrespective of unit type. The analysis showed a close match between the number of units showing asymmetry at a given half-life and the pattern of results obtained psychophysically using the same stimuli (Patterson, 1994a).

2. Materials and methods

2.1. Anaesthesia and surgical preparation

The experiments where performed on 15 post-weaned pigmented guinea pigs (*Cavia porcellus*) of either sex, weighing between 288 and 468 g. The animals were anaesthetised with urethane (1.5 g/kg, i.p.) and Hypnorm was given as supplementary analgesia, (1 mg/kg, i.m.). Anaesthesia and analgesia were maintained at a depth sufficient to abolish the pedal withdrawal reflex. Additional doses of Hypnorm or urethane (1 ml/kg Hypnorm, 1 ml urethane respectively) were given on indication. Incisions were pre-infiltrated with the local anaesthetic lignocaine (s.c.). The guinea pig's core temperature was monitored with a rectal probe and maintained at 37°C using a thermostatically controlled heating blanket (Harvard Apparatus). The surgical preparation and stimulus presentation took place in a sound attenuated chamber (IAC). The trachea was cannulated and on signs of suppressed respiration, the animal was ventilated artificially with a pump (Bioscience UK).

The animal was placed in a stereotaxic frame, which had ear bars coupled to hollow speculae designed for the guinea pig ear and the mouthpiece of the head holder was modified for guinea pigs (Winter and Palm-

er, 1990). An incision was made into each tragus to allow better fitting of the speculae. In order to expose the left bulla, a mid-sagittal scalp incision was made and the muscles attached to the temporal and occipital bones as well as the periosteum were scraped away and partly removed. A hole was made into the bulla and a silver coated wire inserted to contact the upper boundary of the round window of the cochlea. The hole was resealed with vaseline, leaving a small opening to allow for sound–pressure equalisation.

Compound action potentials (CAP) were measured in order to evaluate the hearing ability of the animal. The CAP threshold was determined at selected frequencies (1, 2, 3, 4, 5, 7, 10, 12 and 15 kHz). After initially measuring the CAP a craniotomy was performed to expose the cortex overlying the right IC. The dura was removed and the exposed cortical surface was covered with 1.5% agar to prevent desiccation. In an attempt to reduce brain pulsations and thus increase stability, the membrane overlying the foramen magnum was often fenestrated. The CAP thresholds were determined at intervals during the experiments. In the case where the CAP thresholds had deteriorated by more than 10 dB and were non-recoverable (for example, by removing fluid from the bulla) the experiment was terminated. At the end of each experiment, the animal was overdosed with sodium pentobarbitone or perfused with vascular flush (0.9% NaCl) followed by fixative (1% glutaraldehyde, 3% formaldehyde solution). For reconstructing the electrode tracks, the fixated IC was sectioned in 50-μm thick slides and stained with cresyl violet.

The experiments performed in this study have been carried out under the terms and conditions of the project licence issued by the United Kingdom Home Office to the fourth author.

2.2. Data collection

Stimuli were digitally synthesised on-line, converted into analogue signals and transmitted over a loudspeaker coupled to the left speculum. The sound system was calibrated by using a condenser microphone (B&K 4134) attached to a 1 mm diameter, calibrated probe tube that was inserted into the speculum close to the eardrum.

The activity of single units in the IC was recorded extracellularly with glass-coated tungsten electrodes (Merrill and Ainsworth, 1972). Spikes were recorded from the IC contralateral to sound stimulation. Vertical electrode penetrations were made stereotaxically into the IC through the overlying cerebral cortex. A broadband noise stimulus was presented and the electrode was advanced by a hydraulic microdrive (Kopf Instruments, 607 W). The neural activity, picked up by the

electrode, was monitored over a loudspeaker. A sudden change from the initial random activity to a response, synchronised with the repetition rate of the broadband noise, indicated entrance into the IC.

The neural activity was amplified ($\times 1000$) and a window discriminator (Digitimer D130) was used to discriminate the action potentials, which were then converted into logic pulses. The data were buffered by an event timer and forwarded via an optical interface to an array processor card (AP2, Tucker Davies Technologies) in a personal computer. The data were stored with 1-μs resolution and analysed off-line.

Single units were isolated using broadband noise and sinusoidal tones as search stimuli. The duration of the search stimuli was 50 ms and the repetition rate was 4/s. The unit's best frequency (BF) and excitatory threshold were determined using audio-visual criteria. The spontaneous activity was measured over a 10 s period. For each unit, a peri-stimulus time histogram (PSTH) was generated from spike times collected in response to 250 sweeps of a 50-ms tone at the unit's BF. The level of the tone was initially 20 dB, and then 50 dB suprathreshold. Rise–fall time of the tone was 1 ms ($\cos^2$ gate) and the starting phase was randomised. The tone bursts were repeated with a period of 250 ms. Sustained activity was calculated in a 20-ms window commencing 20 ms after response onset.

2.3. Damped and ramped stimuli

The damped and ramped sinusoids consisted of sinusoids at the unit's BF, that were periodically amplitude modulated by an exponential function, which was either a decaying exponential, resulting in a damped stimulus or a rising exponential resulting in a ramped stimulus. The amplitude envelope for one cycle of the damped stimulus is given in Eq. 1.

$$E(t) = 1/\sqrt{\text{hl}}\, e^{-t\ln 2/\text{hl}} \tag{1}$$

where t is the time within $[0:1/f_m]$, hl the half-life and f_m the modulation frequency. The modulation period $1/f_m$ was set at the largest integer number of carrier periods less than or equal to 50 ms. This ensured that the discontinuity in the envelope that occurs at the end of each modulation cycle, occurs at an upward-going zero-crossing of the carrier. Ten modulation periods were constructed; producing a duration of approximately 500 ms. The sampling rate was 50 kHz. The starting amplitude was normalised by dividing it by the square root of the half-life to provide approximately constant loudness (Patterson, 1994a). The half-life of the exponential was 1, 4, 16 or 64 ms. The level of the stimuli was set approximately 15 dB above the unit's excitatory threshold to ensure that the stimuli were on the rising
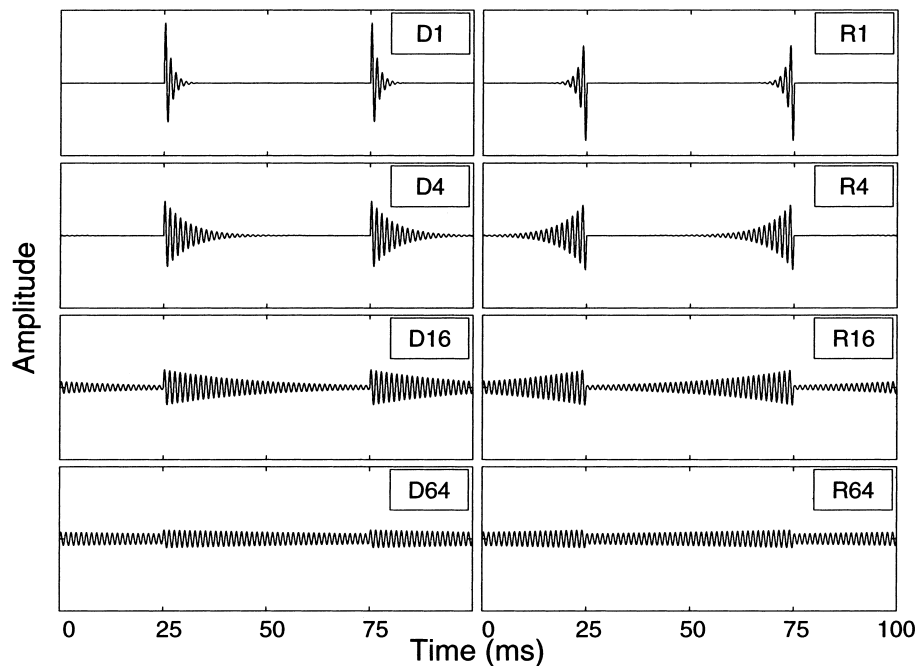
Fig. 1. Waveforms of damped and ramped sinusoids. Damped sinusoids (D) are in the left column, ramped sinusoids (R) in the right column. The half-lives used in the experiments are displayed: 1, 4, 16 and 64 ms, as identified by the top-right insert on each panel. The carrier frequency in this example is 0.8 kHz. Carrier frequency was always adjusted to equal the unit's BF. The modulation period was chosen to be the largest integer number of carrier periods less than or equal to 50 ms. Ten modulation periods were constructed, giving a duration of approximately 500 ms.

section of the input–output function of the unit (Pressnitzer et al., 2000). We did not systematically study the influence of sound pressure level. Note however that Lu et al. (2001) found that temporal asymmetry coding was largely independent from stimulus intensity at the level of cortical neurones, which is consistent with the perception. The different conditions were presented in random order with a repetition rate of 1/s and a sampling rate of 50 kHz. Each condition had 25 repetitions resulting in 250 modulation periods.

The responses to the ramped or damped stimuli were analysed with PSTHs, tsc and the p/t, a measure of the 'peakiness' of the response to each modulation. For this measure the PSTHs were transformed into modulation period histograms (MPHs), which are period histograms with a period equal to the modulation period, $1/f_m$. Because the first period of the PSTH was often distinctly different from the others and would therefore distort the asymmetry measure, it was omitted from the MPH. Thus there is a total of 225 modulation periods in one MPH. Provided the total number of spikes was greater than 50, the number of spikes in the highest MPH bin (binwidth, 1 ms) was divided by the total number of spikes in the MPH. In cases where the activity was evenly spread throughout the modulation cycle, the p/t is close to 0; if activity was restricted to a single bin, the p/t would be 1.

For visual purposes, period histograms were computed based on the modulation period, but with a two-period length. The two-period length ensures that at least one uninterrupted cycle of modulation is visible in the figure.

Visual inspection of the responses indicated that, in contrast to the VCN results (Pressnitzer et al., 2000), MPHs often did not follow the stimulus envelope (see Fig. 6, ramped 4-ms condition). To quantify this observation, a new measure was introduced. The similarity between the shape of the response and the shape of the stimulus envelope was estimated by calculating a form of derivative for each bin of the MPH over one period. This was done by subtracting the value in one bin of the MPH from the value in the following bin. If the total number of negative values exceeded the total number of positive values, the MPH decreased longer than it increased and was classified as having a damped shape. If the opposite was true, the response was classified as having a ramped shape. The response shape was then compared to the type of stimulus envelope. This measure was preferred to a correlation between the neural responses and the stimuli's envelopes as it is not sensitive to properties of the response other than shape.

Differences in the responses to damped and ramped sinusoids for different unit types were evaluated by applying the 'sign test of the median' to the p/t and the tsc. The test determines whether the median ratio of a particular damped/ramped response type differed signif-
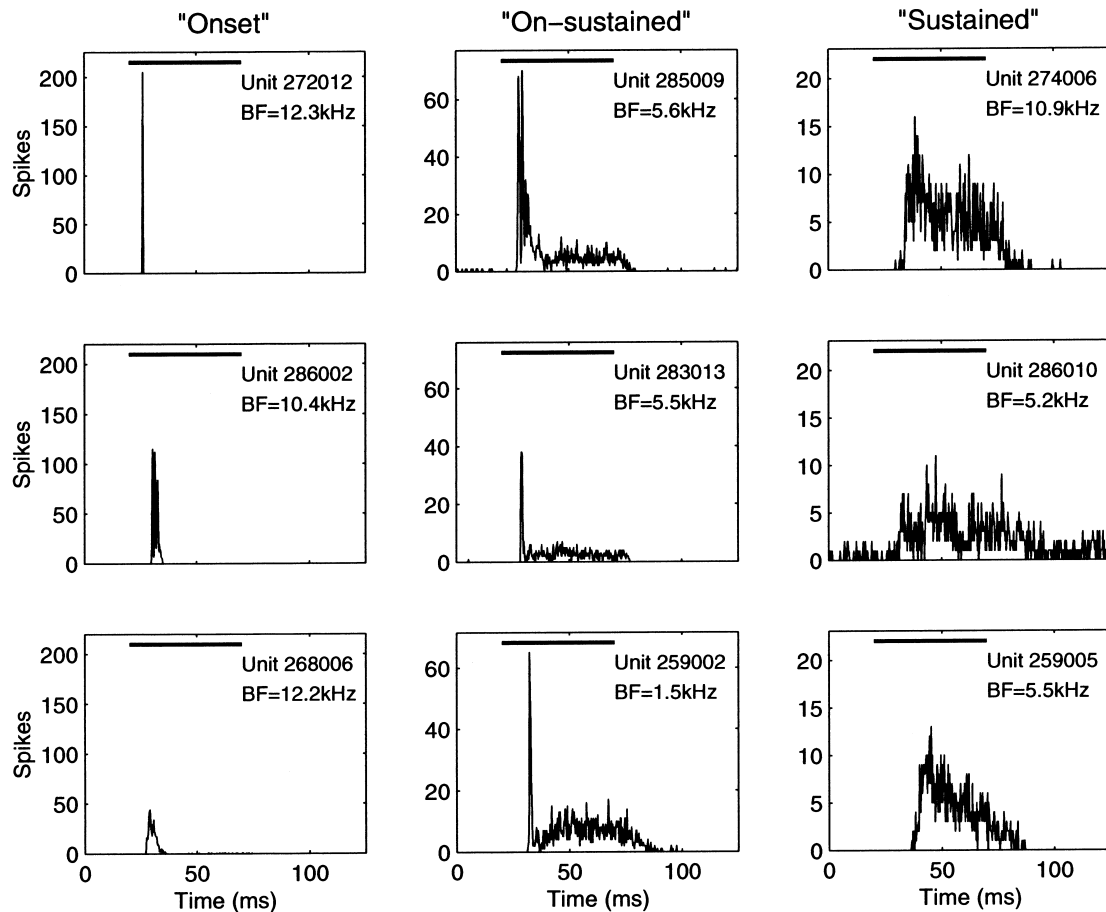
Fig. 2. Responses of single units in the IC to 250 repetitions of a 50-ms tone burst at the BF of the unit. Example PSTHs are shown, which illustrate the grouping in 'Onset', 'On-sustained' and 'Sustained' units (left, middle and right columns, respectively). The unit number and BF are specified at the top right corner of each panel. The black bar indicates the time the stimulus was on.

icantly from unity. Each individual ratio was subtracted from the hypothesised median. The number of positive and negative differences is then compared, to determine whether the population median differed significantly from the hypothesised median.

We have adopted a summary population analysis introduced by Lu et al. (2001). In this analysis the number of spikes obtained in response to the damped sinusoid was compared on a trial-by-trial basis to the number of spikes to the ramped sinusoids for each half-life. The presence of a significant asymmetry ($P < 0.05$) was tested using the Wilcoxon rank sum test (Ferguson, 1976) on the tsc distributions.

3. Results

The data presented in this paper are based on the responses of 92 units from the IC with BFs ranging from 0.226 to 14.4 kHz. The PSTHs recorded in this study are similar to the PSTHs reported in previous studies (e.g. Le Beau et al., 1996; Rees et al., 1997;

Nuding et al., 1999) and the BF increased during dorsal-to-ventral electrode penetration. For 4 of the 14 experiments the electrode tracks were examined under the microscope. All of these tracks coursed their way through the central nucleus of the IC, however, this does not rule out the possibility that some of the units might have been located in the dorsal or lateral nucleus.

Initially, the units were classified based on the scheme of Le Beau et al. (1996) into narrow onsets, broad onsets, onset-choppers, pausers, choppers, on-sustained and sustained units. In addition, three further categories were used, 'long-latency', 'build-up' and 'off-response'. Classification was based on the PSTHs collected at 20 and 50 dB suprathreshold, and on the interspike interval histograms. After reviewing the PSTHs, three groups were formed, namely onset, on-sustained and sustained units. In the on-sustained group, pauser, chopper and on-sustained units were combined, as their responses to ramped and damped sinusoids did not differ markedly. All of these units showed a pure tone response consisting of a clear onset response followed by sustained activity of more than 10
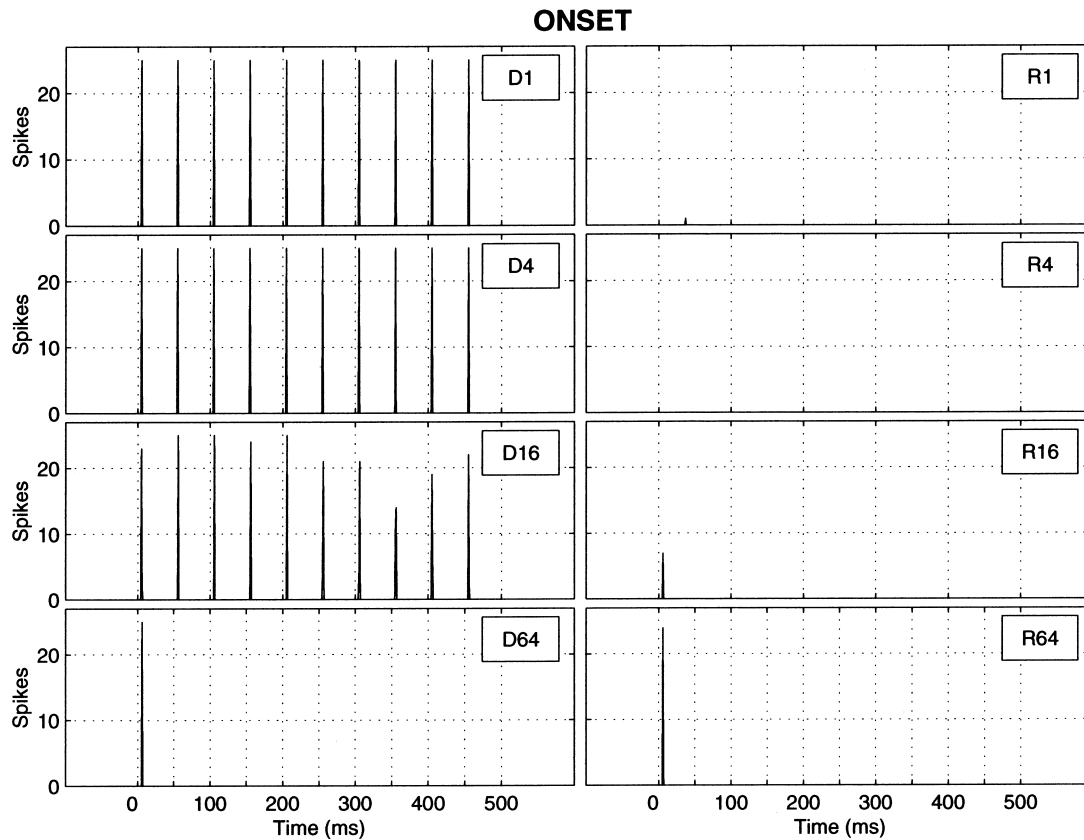
ONSET

Fig. 3. Post-stimulus–time histograms in response to damped and ramped sinusoids. Unit 0272012003, BF = 12.3 kHz, 25 repeats. Stimulus level was 15 dB above pure-tone threshold. This unit was classified as an Onset. Bin width is 1 ms. There is a very precise response to each modulation cycle of the damped sinusoids with half-lives of 1, 4 and 16 ms but only to the first modulation cycle of stimuli with a 64 ms half-life. The unit fails to respond to ramped stimuli with half-lives of 1, 4 and 16 ms but it does respond at the onset of the stimulus when the half-life is 64 ms.

spikes/s. The sustained group consisted of sustained units, build-up units and long-latency units, which showed a sustained response. These units did not exhibit a pronounced onset response and they could fire throughout the duration of the stimulus. Examples of the PSTHs are presented in Fig. 2.

Ten units did not fit into any of the above groups and were excluded from further analysis. These units were either of the type long-latency, off-response or they could not be classified.

3.1. Responses of single units

3.1.1. Onsets

The onset group ($n = 19$) consisted of narrow onset (10), broad onset (5) and onset-chopper (4) units (see Le Beau et al., 1996 for details of the classification). Fig. 3 shows the post-stimulus–time histograms of the responses to damped and ramped sinusoids of a narrow onset unit. The bottom panels show the responses to damped and ramped sinusoids with a 64-ms half-life. As one would expect for an onset unit, the unit fires at the onset of both stimuli. However, the responses to

damped and ramped stimuli with half-lives between 1 and 16 ms are different. The unit responds to each cycle of the damped stimulus, as if the beginning of each cycle were a new stimulus. In contrast, the unit does not respond to the corresponding ramped stimuli.

MPHs for the same unit are presented in Fig. 4, together with the p/t and tsc statistics. Fig. 5 shows a summary of the statistics of all onset units. The individual values in response to damped stimuli are plotted against the corresponding values in response to ramped stimuli with the p/t values on the left-hand side and tsc values on the right-hand side of the figure. Each half-life is shown in a different sub-figure. The p/t value was set to zero if there were 50 spikes or less in the MPH. Onsets typically produced a very precise response (high p/t) at the onset of each cycle of the damped and ramped stimuli with a 1-ms half-life, and to damped stimuli with 4- and 16-ms half-lives. In contrast, they produced a very low response to damped and ramped stimuli with a half-life of 64 ms, and to ramped stimuli with 4- and 16-ms half-lives. Thus a large asymmetry is observed when comparing responses to damped and ramped sinusoids. Note however that this asymmetry
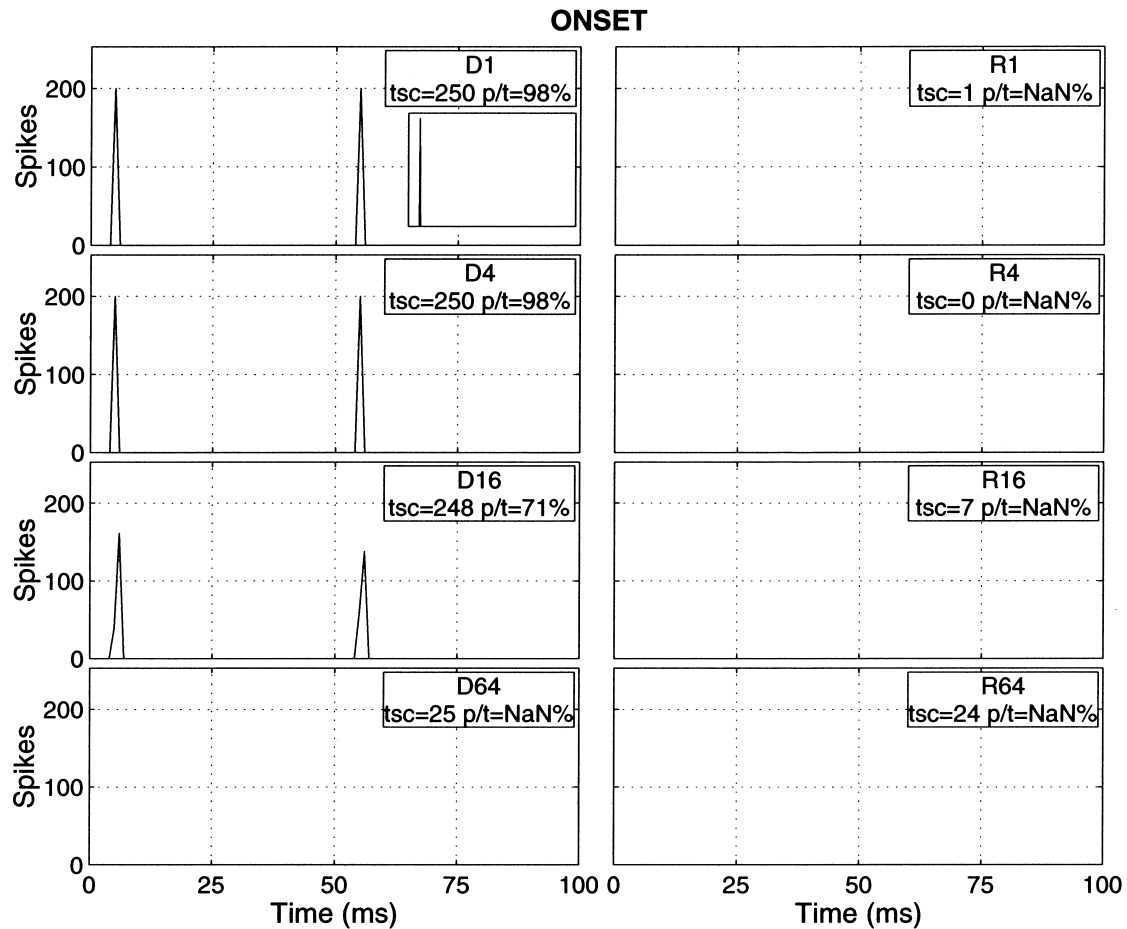
ONSET

Fig. 4. MPHs for the onset unit, shown in Fig. 3, in response to damped and ramped sinusoids. Two periods of the MPH are displayed for visual purposes (bin width is 1 ms). The stimulus conditions (damped or ramped and half-life) and the corresponding MPH statistics (tsc and p/t) are shown in the top right insert. The additional insert in the top left panel shows the PSTH of the unit in response to a 20-dB suprathreshold BF tone burst. Bin width is 250 μs.

cannot be simply related to the perceptual encoding of damped and ramped stimuli, as most of the units are silent in response to almost half of the stimulus set.

With regard to the tsc measure, responses are quite diverse at the 1-ms half-life; nearly half of the units (47%) responded more to ramped than to damped stimuli including one unit that did not respond to the damped version of the stimulus at all. However, there were also three units that responded exclusively to damped stimuli. At 4 ms and 16 ms the majority of units (79% and 89% respectively) responded more to damped than to ramped stimuli. Responses at 64 ms are very weak in both conditions. Post-stimulus–time histograms for stimuli with a 64-ms half-life, revealed that 17 units (89%) only responded to the very onset of the stimulus (as shown in Fig. 3) while two (11%) units did not respond to the stimulus at all.

3.1.2. On-sustained

There were 43 on-sustained units consisting of the unit types described above. The general response pat-

tern to damped and ramped sinusoids observed within this group can be seen in Fig. 6, which shows a characteristic two-period MPH. Fig. 7 shows the statistics for individual units with the p/t on the left and tsc on the right. The response to the 1-ms half-life provided typically high p/ts for both types of stimuli, although the p/t was less than for onset units. The number of on-sustained units with greater p/t values in response to damped stimuli at 1 ms is only slightly larger than the number of units with greater p/t values in response to ramped stimuli (Fig. 7, top of left column). In contrast, the p/t-values at 4 and 16 ms are much larger in response to damped than to ramped stimuli. At 64 ms, the p/t was very low, but still significantly higher for damped than for ramped stimuli ($P < 0.01$, sign test of median). A relatively high proportion of units (13%) elicited too few spikes in response to damped 1-ms sinusoids to calculate p/t.

For the tsc measure, nearly all points lie below the dashed line of unity in the 1-ms condition, indicating that the units responded more to ramped than to
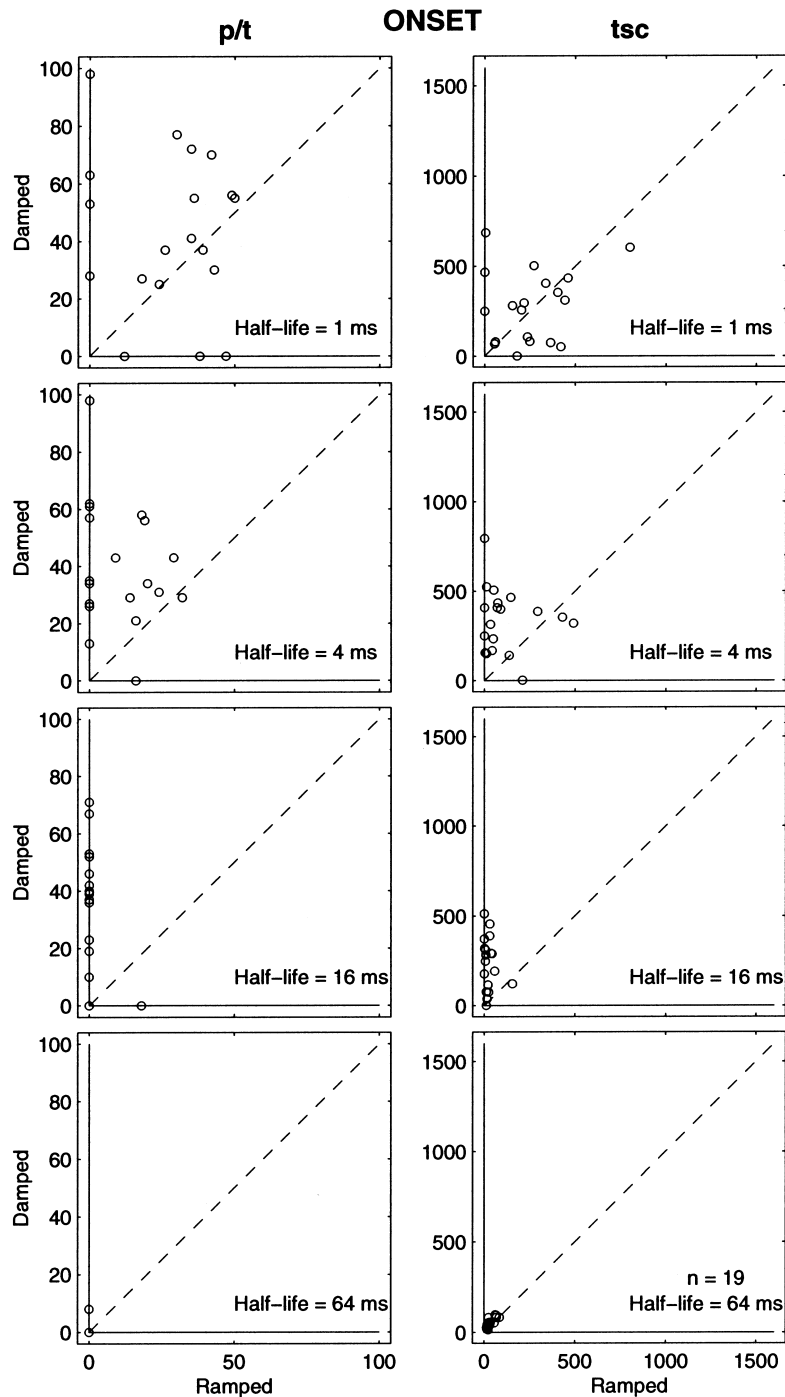
Fig. 5. Individual tsc (right column) and p/t (left column) values in response to damped sinusoids, plotted against the corresponding values in response to ramped sinusoid for the onset group. The half-lives were 1, 4, 16, and 64 ms. The dashed line indicates a ratio of unity. For visual purposes the p/t value was set to zero if it could not be calculated due to a lack of spikes. The number of units in the group is displayed in the bottom right panel.

damped 1-ms tones. The points are more evenly distributed in the 4- and 16-ms condition and they lie on or near the line of unity at a half-life of 64 ms. The tsc increased significantly with half-lives up to 16 ms and then decreased in both conditions. In the 1-ms half-life condition, significantly more spikes were elicited to

ramped than to damped stimuli ($P < 0.001$, sign test of median). At 4 ms, 31% of the units discharged significantly more to ramped sinusoids, whereas 51% of the units preferred damped sinusoids. At 16 ms, the numbers are 49 and 33% respectively (Wilcoxon rank sum test, $P < 0.05$).
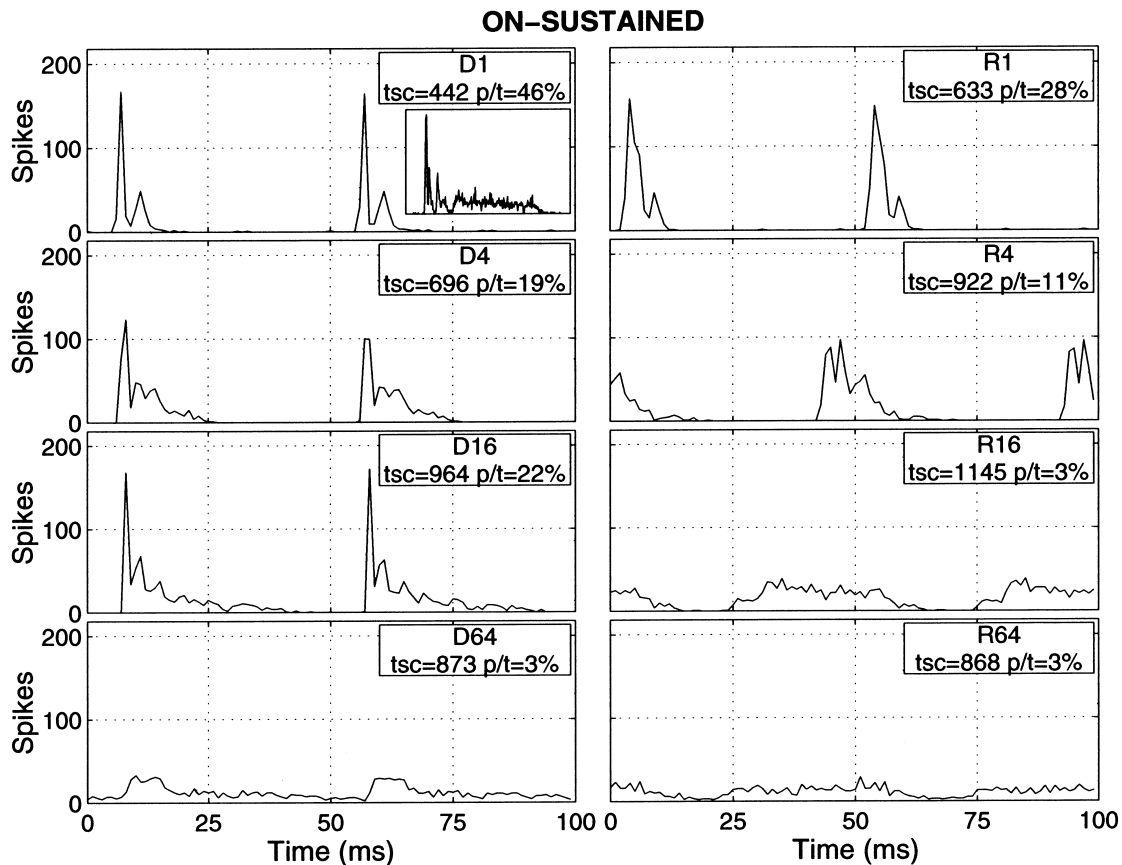
ON–SUSTAINED

Fig. 6. MPHs for an on-sustained unit in response to damped and ramped sinusoids. Unit 0274020003, BF = 4.4 kHz. The format is the same as in Fig. 4.

If one compares the shapes of the MPHs in response to damped and ramped sinusoids with the envelopes of the stimuli, it is noticeable that in many cases the MPHs in response to damped sinusoids resemble the envelopes of the damped stimuli, whereas the MPHs in response to ramped sinusoids do not resemble the envelopes of the ramped stimuli. Rather, they are more similar to the envelopes of the damped stimuli (compare Figs. 1 and 6). In the VCN, Pressnitzer et al. (2000) found that the MPHs resembled the stimulus-waveform for both damped and ramped sinusoids (their figures 4–6). To quantify this observation, we compared the neural response shape with the stimuli's envelope, as described in Section 2. The calculations were made for the present data and the VCN data at the 4-ms half-life, where the effect was particularly pronounced. The statistics are shown in Table 1. In the VCN, responses to damped sinusoids almost always have a damped shape and responses to ramped sinusoids have a ramped shape. In the IC, on the other hand, a high percentage of the damped MPHs had a damped shape, whereas only very few responses to ramped sinusoids had a ramped shape. Thus, for on-sustained units in the IC, the envelopes of the neural responses were often different from the envelope of the physical stimulation.

3.1.3. Sustained

There were 20 sustained units. The results for a typical unit can be seen in Figs. 8 and 9. Compared with the other groups, p/t is much lower in response to both, damped and ramped sinusoids. Also, in contrast to the other groups, the p/t values are similar for 1- and 4-ms half-lives and there is no significant difference between ramped and damped p/t values at any half-life.

The tsc values are distributed around the line of unity, but there seems to be a preference for ramped stimuli in the 1-, 4- and 16-ms conditions; however, this effect is only significant at 4 ms ($P < 0.05$, sign test of median). Overall, very little asymmetry is observed in sustained units.

3.2. Population analyses

3.2.1. Asymmetry ratios

In order to quantify the temporal asymmetry across the population of neurones, ratios were computed for each of the asymmetry measurements, p/t and tsc. In
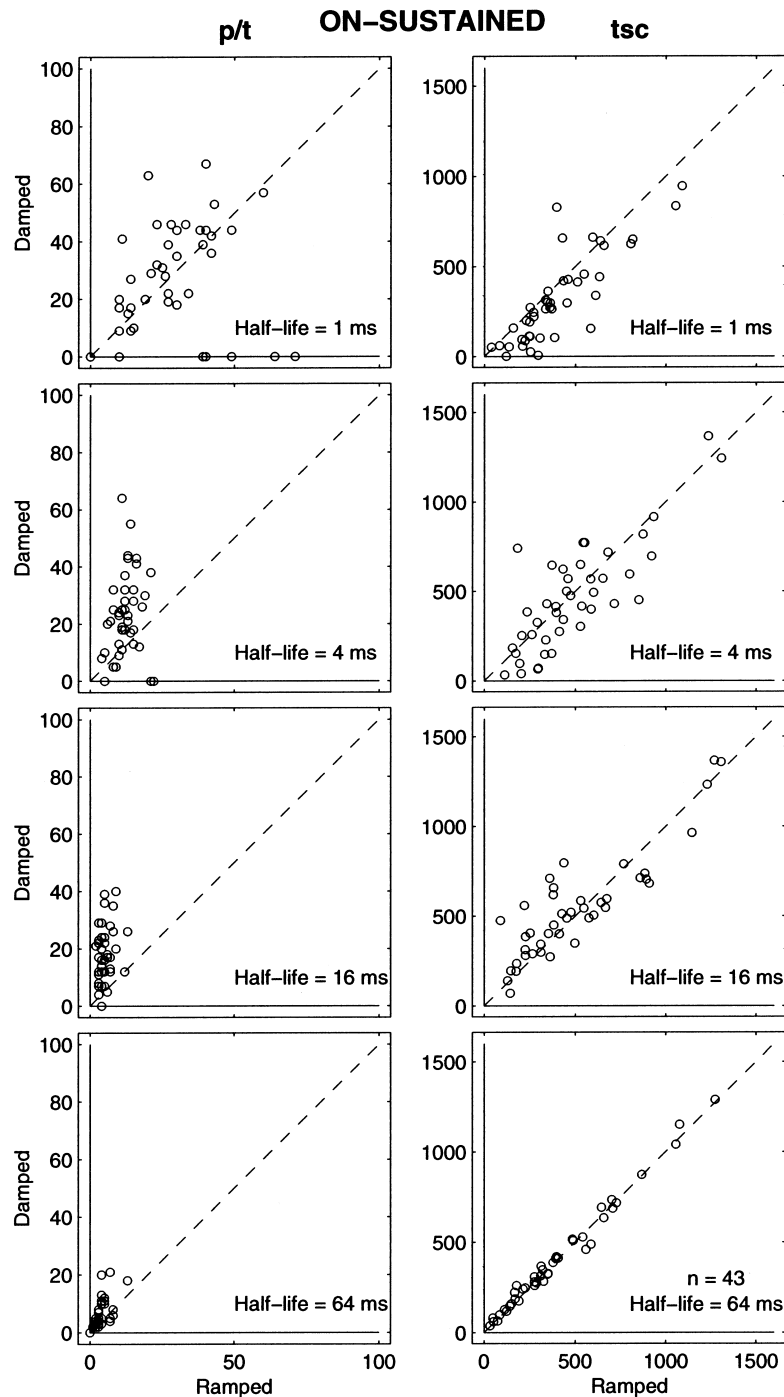
Fig. 7. Individual tsc (right column) and p/t (left column) values for on-sustained units in response to damped sinusoids plotted against the corresponding values in response to ramped sinusoid for the on-sustained group. Half-lives were 1, 4, 16, and 64 ms. The dashed line indicates a ratio of unity. For visual purposes the p/t value was set to zero if it could not be calculated due to a lack of spikes. The number of units in the group is displayed in the bottom right panel.

the case when the response to ramped and damped stimuli is equal (no asymmetry), the ratio is one and the data would fall on a horizontal line. The onset group was excluded from the population comparison, since p/t could not be calculated for the majority of units due to the lack of spikes in response to ramped

stimuli. Moreover, although tsc ratios could typically be calculated, the values were highly variable.

The median p/t for the remaining two groups are shown in the upper panel of Fig. 10 as a function of half-life. A sign test of the median was performed to determine whether the values were significantly different

Table 1
Comparison of MPH shapes in response to ramped and damped sinusoids in the CN and IC of the guinea pig

Unit type	VCN				IC
	All VCN	PL	C	O	OS
Damped	96	94	97	96	86
Ramped	90	87	97	85	12

Percentages of responses with the same shape as the corresponding stimulus.
PL: primary-like; C: chopper; O: onset (VCN); OS: on-sustained.

from unity. On-sustained units showed significant asymmetry in all conditions except the 1-ms condition. For this group the asymmetry is largest at 16 ms and relatively small at 1 and 64 ms. There was no significant asymmetry for the sustained type.

The lower panel of Fig. 10 shows the median tsc ratios as a function of half-life for the two groups. In accordance with the previous sections, the only significant tsc ratio is for the on-sustained group at 1 ms and the sustained group at 4 ms. At 4 and 16 ms, the majority of on-sustained units exhibited asymmetry, but about half of the units responded with more spikes to damped and the other half with more spikes to ramped

stimuli. There was no correlation between the tsc ratio and the spontaneous rate or BF.

3.2.2. Summary population analysis

A cortical correlate of temporal asymmetry has been proposed by Lu et al. (2001). It is based on the proportion of units showing significant asymmetry as a function of stimulus half-life (see Section 2.3 for calculation of asymmetry). Note that this correlate does not distinguish the direction of the asymmetry, i.e. whether the response to damped was greater than the response to ramped or vice versa. Fig. 11 shows a comparison between the results of this analysis for the IC units (filled diamonds) and psychophysical performance (open circles). The IC unit population includes the units classified as onset, on-sustained and sustained. The psychophysical data were taken from Patterson (1994a; figure 11) and were averaged across carrier frequencies and listeners. In Patterson (1994a) the psychophysical task was to choose the sound with the stronger sinusoidal quality and the results were the proportion of trials where subjects chose the damped sinusoid. In our Fig. 11, we plotted the proportion of trials that subjects chose the ramped sinusoid (1-damped). There is a close match between the physiological and the psychophysi-
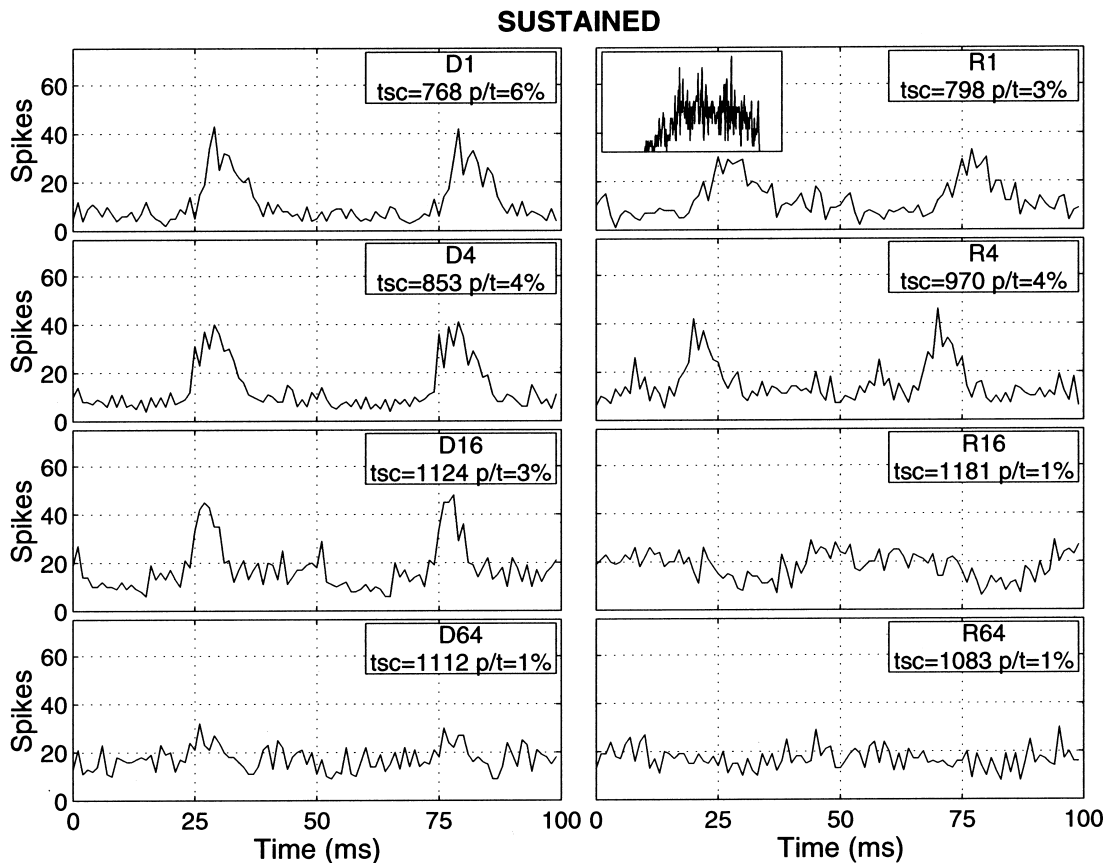
SUSTAINED

Fig. 8. MPHs for a sustained unit in response to damped and ramped sinusoids. Unit 0284022003. Format is the same as for Fig. 4, except that the PSTH is shown in the top right panel.
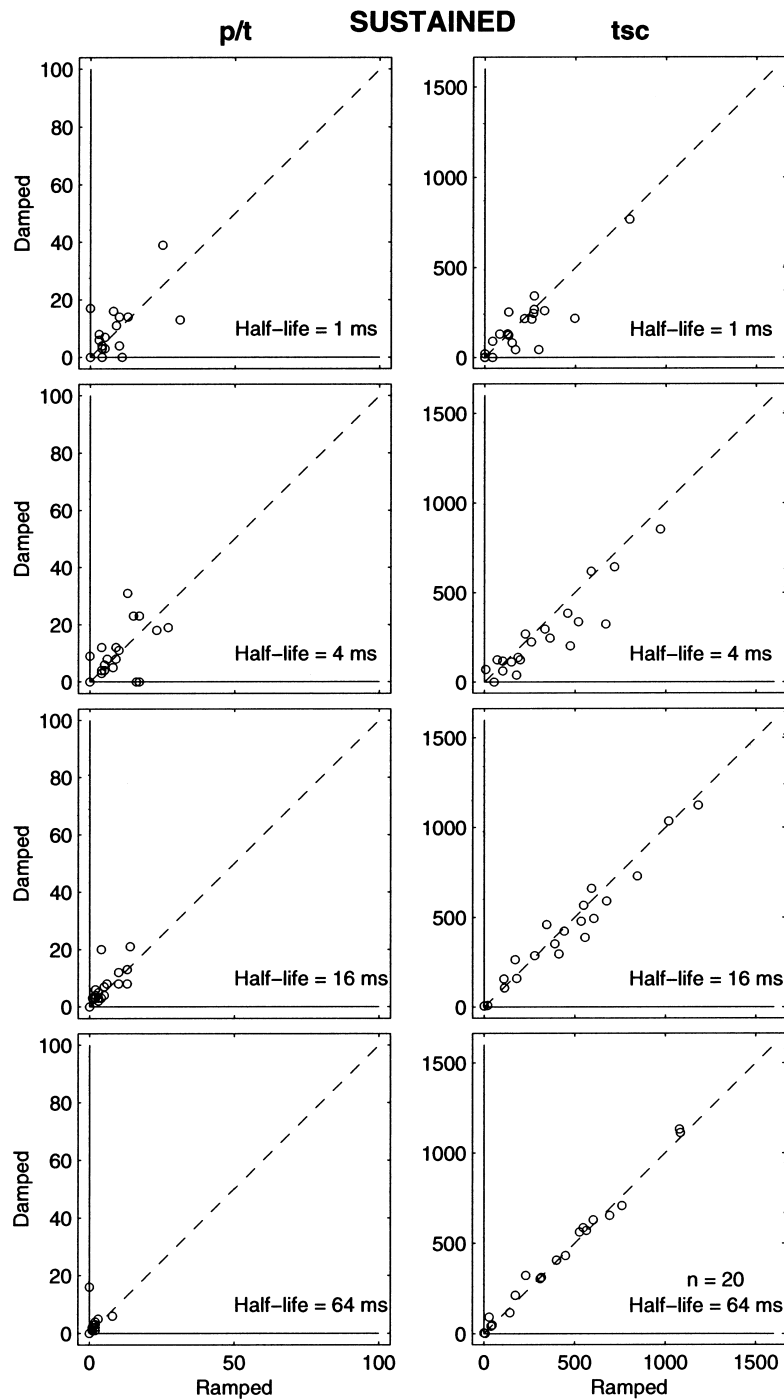
Fig. 9. Individual tsc (right column) and p/t (left column) values in response to damped sinusoids plotted against the corresponding values in response to ramped sinusoid for the sustained group. Half-lives were 1, 4, 16, and 64 ms. The dashed line indicates a ratio of unity. For visual purposes the p/t value was set to zero if it could not be calculated due to a lack of spikes. The number of units in the group is displayed in the bottom right panel.

cal data, both with regard to the pattern of results and the actual proportions.

In addition we performed the physiological population analysis on the VCN data of Pressnitzer et al. (2000). We plotted the results for the whole population of units (onsets, choppers, primary-like; filled squares) and the results for the sub-population of primary-like neurones (asterisks). The pattern of results matches the psychophysics in all cases. If one assumes that the primary-like sub-population reflects the activity at the lev-

el of the auditory nerve, then there is an increase in the proportion of neurones that show an asymmetry as we go up the auditory pathway.

4. Discussion

This paper shows that asymmetry is encoded, albeit diversely, in the responses of single units at the level of the mammalian IC. Onset units show an extreme asymmetry as in many cases they do not respond to the ramped stimuli. On-sustained units show significant asymmetry in p/t and tsc – the p/t is significantly higher for damped sinusoids than for ramped sinusoids at all

Fig. 11. The proportion of neurones showing a significant asymmetry as a function of half-life for the IC (filled diamonds), the VCN (filled squares) and the sub-population of primary-like units in the VCN (asterisks). The psychophysical data (open circles) were taken from Patterson (1994a; Fig. 11) and were averaged across carrier frequencies and listeners. In Patterson (1994a) the psychophysical task was to choose the sound with the stronger sinusoidal quality and the results were a proportion of trials where subjects chose the damped sinusoid. In this figure we plot the proportion of trials that subjects chose ramped (1-damped).
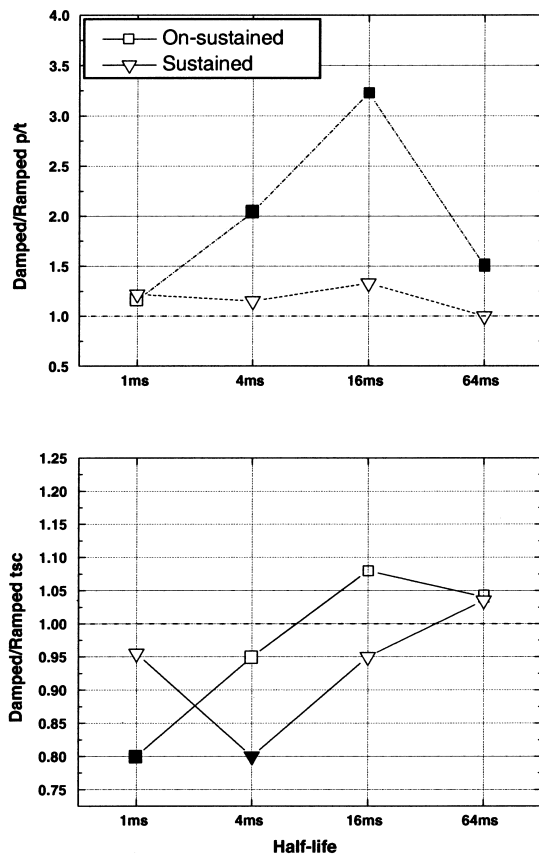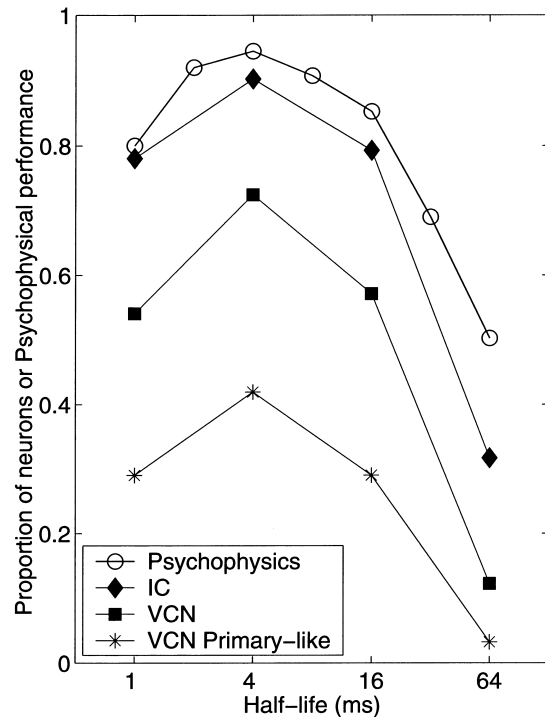

Fig. 10. Population analysis of p/t (top) and tsc (bottom) asymmetry. For each half-life the ratio between the value obtained in response to the damped sinusoid was divided by the value obtained in response to the ramped sinusoid. The analysis was done within the on-sustained and the sustained group – the onset group was excluded from the population comparison, because p/t could not be calculated in many instances due to the lack of spikes and although tsc ratios could be calculated, the values often were highly variable. Median results for each unit type and half-life are displayed. If no asymmetry was present in the statistics, all points would fall on the horizontal line of unity. Filled symbols indicate a significant asymmetry ($P < 0.05$, sign test of median). The number of units included in the calculation of the p/t medians varied in each condition, as p/t could not always be calculated.

half-lives apart from 1 ms; a consistent preference in the tsc is only found at 1 ms. At 4 and 16 ms, some units prefer damped, and some ramped, sinusoids. The sustained units show no asymmetry in p/t but discharge significantly more to the ramped stimuli with a 4-ms half-life.

In the following, we will first discuss the different unit types separately, comparing our results to the results published in Pressnitzer et al. (2000). We will then compare our results to the results in the cortex (Lu et al., 2001) and discuss the population asymmetry measure for VCN, IC and cortex with respect to the psychophysical results obtained by Patterson (1994a).

4.1. Onset units

When comparing the data from the onset group with the responses of onset units in the VCN (Pressnitzer et al., 2000), the main difference is that onset units in the IC often fail to respond to ramped stimuli with half-lives longer than 1 ms. This was never observed in the VCN. As a result, the p/t is very large for onset units in

the IC. With regard to Irino and Patterson's (1998) hypothesis that asymmetry would be enhanced in the IC, it is the case that the p/t is greater for onset units in the IC than it was for onset units in the VCN. It is not clear, however, that this increase in p/t is relevant for the perceptual encoding of the stimuli, as onset units remain silent for half of the stimulus set, which is not what Irino and Patterson (1996) meant by asymmetry. Nevertheless, the lack of response to ramped sinusoids by onset units is intriguing.

Onsets units show the greatest adaptation, often only firing at the beginning of a sound, so it might be expected that they would elicit spikes at the beginning of each damped modulation cycle and not fire elsewhere in the period. The absence of response to ramped stimuli with reasonably long half-lives can be explained with models of temporal coincidence detection. If an IC onset unit acts as a temporal coincidence neurone, which gets input from an array of CN units with the same BFs (Hewitt and Meddis, 1994), this unit only elicits spikes if the inputs are simultaneous. In the case of damped stimuli, the probability of firing precisely at the onset of a modulation cycle is high in the VCN. For ramped stimuli, in contrast, the probability of neurones in the VCN firing at exactly the same point in the modulation cycle is relatively low. This difference could explain why some onset units in the IC failed to respond to ramped sinusoids even at 1 ms.

4.2. On-sustained units

The number of spikes elicited to ramped and damped stimuli with the same half-life showed that ramped stimuli produced consistently more spikes than damped stimuli only at 1 ms (see Fig. 7). In the other conditions, units responded either more to ramped or more to damped stimuli, or they elicited about the same number of spikes to both stimuli. In contrast, chopper units in the VCN reliably preferred ramped sinusoids. The diverse results for on-sustained units may indicate that, at the level of the IC, classification based on the PSTH in response to pure tones is not appropriate when the issue is the response to complex stimuli. The p/t values of on-sustained units are similar to the p/t values of chopper units in the VCN (Pressnitzer et al., 2000).

On-sustained units in the IC exhibited response properties that none of the units in the VCN exhibited. The shapes of the MPHs in response to ramped stimuli looked more like those produced in response to a damped stimulus, whereas in the VCN, the shape of the MPH almost always resembled the envelope of the stimulus. The transformation of the response may take place at the level of the dorsal cochlear nucleus (DCN). It is possible that pauser units in the DCN,

which resemble pauser units in the IC, behave similarly. It should be noted that anaesthesia might play a role in shaping the responses reported in this paper, particularly if the responses of the IC are influenced by direct input from the DCN. For instance, responses of DCN units are influenced by anaesthesia (Young and Brownell, 1976; Rhode and Kettner, 1987) and Davis (1999) has shown that some unit responses in the central nucleus of the IC (resembling type IV units of the DCN – Young and Brownell, 1976) are abolished by manipulation of the fibre tracts that convey information from the DCN to the IC.

4.3. Sustained units

Sustained units showed least asymmetry of all units studied and did not show significant asymmetry in any of the p/t ratios. This lack of asymmetry in the temporal shape of the neural responses is noteworthy, since all of the units investigated in the VCN displayed an asymmetry. The asymmetry observed in all VCN units must be transformed to obtain the sustained response but the reason is obscure at this juncture.

4.4. Comparison of population analysis at different levels of the auditory pathway

The responses of single units in the auditory cortex to damped and ramped sinusoids in the awake marmoset (Lu et al., 2001) show that the temporal asymmetry of the stimuli is preserved at the level of the cortex, but it is primarily reflected in the discharge rate rather than the firing pattern. Lu et al. (2001) reported that 77% of the units responded with significant asymmetry in discharge rate to at least one of the half-lives tested (0.5–32 ms). Of these units, 20% showed significant asymmetry at all half-lives, with the majority of units preferring ramped sinusoids. In the IC, 100% of units showed significant asymmetry in tsc to at least one of the half-lives and 20% showed significant asymmetry at all half-lives (1–64 ms).

A noticeable difference between the responses in the IC with those in the cortex is the pronounced temporal structure in the MPHs for single units in the IC (e.g. Fig. 6). However, the lack of temporal structure in the cortical responses might be attributable in part to the fact that Lu et al. (2001) used a period of 25 ms. When longer modulation periods were used, Lu et al. (2001) found that synchrony to the modulation period increased with modulation period. Nevertheless, the asymmetry in discharge rate exists independent of modulation period.

Comparing the population responses of IC (Fig. 11) and auditory cortex (figure 15 in Lu et al., 2001) with the psychophysical results of Patterson (1994a) reveals a

similar pattern of results. In fact, the population measure of asymmetry shows the same pattern in the IC, the VCN, the sub-population of primary-like units in the VCN and in the cortex. The difference between the different levels of the auditory pathway lies in the absolute proportion of units displaying the asymmetry. If the primary-like units are considered to reflect the activity at the level of the auditory nerve, there is an increase in the proportion of neurones showing asymmetry at a given half-life up to the level of the IC, where the actual proportions are very similar to the psychophysical performance (Fig. 11). The proportion of units displaying asymmetry in the cortex is considerably lower than in the IC. Units in the primary auditory cortex are more diverse in their spectro-temporal characteristics than units in the IC. It is conceivable that whereas virtually all units in the IC are sensitive to the temporal asymmetry of the stimuli, cortical units are more specialised and only a subset of all units serves to process temporal asymmetry.

The population asymmetry measure summarises asymmetry in discharge rate, irrespective of unit type and direction. It may serve as a relative measure of the difference between the tonal components of damped and ramped sinusoids, but it does not provide a quantitative physiological correlate, e.g. spike rate, to the actual strength of the tonal component. The physiological correlate of the 'sound of a sinusoid' still remains elusive at the level of the IC. It is likely that temporal information (differences in p/t values), differences in spike rate and different subsets of stimulated units (some units prefer damped, some ramped sounds) all contribute to the perception of the tonal component.

5. Summary and conclusions

Units classified as onset in the IC often failed to respond to ramped sinusoids with half-lives greater than 1 ms. This extreme form of asymmetry was never observed from onset units in the VCN (Pressnitzer et al., 2000). The temporal response of all unit types in the VCN resembled the shape of the stimulus envelope, however, for on-sustained units in the IC the temporal response to ramped stimuli more closely resembled the envelope of the damped stimuli. Sustained units showed less asymmetry than observed in the VCN.

There is an increase in the proportion of units showing an asymmetry in terms of discharge rate as one ascends the lower auditory pathway. Primary-like units (which can be regarded as reflecting the activity of the primary afferent input to the cochlear nucleus) show the lowest proportion of units displaying significant asymmetry as a function of half-life. A higher proportion of units showing asymmetry is found if the responses of

VCN primary-like, onset and chopper units are pooled and this proportion increases still further when looking at the population of IC units reported here. The pattern of results is the same in the cortex, but the proportion of units showing asymmetry is lower (Lu et al., 2001). Although the population responses in IC, VCN and auditory cortex demonstrate a degree of asymmetry in keeping with the psychophysics, the results do not suggest a simple physiological correlate of the strength of the tonal component in damped and ramped sinusoids.

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