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Cochlear nerve responses to waveform singularities and envelope corners

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One way that discrete acoustic events may be signaled to the central nervous system is through spike synchrony over a subpopulation of cochlear axons. Each of the four corners of a trapezoidally modulated tone burst is such an event. Ordinarily, each corner comprises both an abrupt change in envelope slope and a singularity in the modulated waveform. In this study, in addition to stimuli of this sort, we employed a stimulus waveform in which a corner occurred without a waveform singularity. We obtained masker tuning curves for the CAPs corresponding to both kinds of corners and single-unit responses to both kinds of corners. The results suggest that the subpopulation of cochlear axons excited by the singularity component of a corner is distinct from that excited by the abrupt change in envelope slope.

Onset response; Offset response; Compound action potentials; Masking tuning curves; Gerbil auditory nerve

Introduction

The cochlear-nerve compound action potential (CAP) in response to the onset of a tone appears to result from the summation of extracellular currents from multiple cochlear axons firing in near synchrony (Ozdamar and Dallos, 1978). This conclusion is consistent with the observation that, when recording from single cochlear axons, one typically observes spikes synchronized to the onset of the tone burst. This is particularly evident in peristimulus time histograms, which typically show the highest probability of spike production in the time bins just following the tone-burst onset (Kiang et al., 1965; Westerman and Smith, 1984). When a second ('masker') tone of appropriate frequency and intensity is applied either just before the tone burst or during it, the CAP at the onset of the tone burst is reduced in amplitude ('masked'). When the amplitude of the tone burst is relatively low, and one plots the effectiveness of

the masker in reducing the CAP amplitude as a function of the frequency of the masker tone, the resulting 'masker tuning curve' (MTC) typically exhibits a sharp, narrow tip and strongly resembles the frequency-threshold tuning curve of a single axon whose characteristic frequency (CF) is that of the tone burst (the 'probe tone') (Dallos and Cheatham, 1976). This normally is interpreted under the assumption that the reduction in CAP amplitude is a consequence of reduction of the number of axons with spikes synchronized to the tone-burst onset, and that such reduction is accomplished by pre-emptive excitation of the axons that would have participated in spike synchrony. Thus the sharp tip of the typical MTC is taken to imply that axons whose synchronous spikes are being eliminated are those with CFs close to the probe-tone (tone burst) frequency.

The CAP also has been observed in response to the sudden termination ('offset') of a probe tone (Onishi and Davis, 1968; Eggermont and Odenthal, 1974). In terms of the interpretations commonly applied to onset responses, this observation implies that cochlear axons can fire in synchrony to tone offsets as well as to tone onsets.

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This conclusion has been confirmed by peristimulus time histograms, in which synchrony of spike activity with tone offset often is clearly visible (Geisler and Sinex, 1982; Rhode and Smith, 1985). However, because the offset of a tone necessarily must be preceded by the tone itself, one must consider the possibility that masking has occurred, and therefore that the population of axons participating in generation of the offset CAP is different from that participating in the onset CAP. This possibility is given strong support by masker tuning curves for offset CAPs (Henry, 1987). For forward masking with mid-frequency probe stimuli with intensities of 65 dB SPL or greater, those MTCs typically exhibit one sharp tip well below the probe-tone frequency. This could be interpreted to imply that the axons whose offset synchrony is being eliminated have CFs in a narrow range well below the probe-tone frequency. With simultaneous masking, a second sharp tip appears in the MTC, above the probe-tone frequency. This tip typically is centered at a frequency, f_2 , at which $2f_1 - f_2 = f_0$, where f_1 is the probe-tone frequency and f_0 is the frequency at the center of the sharp MTC tip below the probe-tone frequency. Thus, both tips of the MTC for simultaneous masking may reflect elimination of offset synchrony in the same population of axons – in one case by direct excitation by the masker alone, in the other case by cubic difference tone excitation by the masker and probe tone together.

When either a pulse-modulated sinusoid or a trapezoidally-modulated sinusoid is used as the probe tone, as is typically the case, then the probe tone begins and ends with a singularity (e.g., a discontinuity in the stimulus waveform itself or in its first or second time derivative, depending upon the phases of the modulated sinusoid at the beginning and end of the tone burst). If such a tone burst is applied to an analog filter structure, such as the cochlear filter associated with an individual auditory afferent axon, the waveform singularities will produce transient excitations of that structure (Lewis and Henry, 1988). When the frequency of the modulated tone falls within the pass band of the filter, the transient excitations elicited by the waveform singularities will be completely overwhelmed by the response to the tone itself. On the other hand, when the edge of the pass band is

steep (as is the case for the high-frequency edge of cochlear filters), and the frequency of the modulated tone falls beyond that edge but close to it, then the transient excitations will stand alone, distinctly marking the times of the singularities. This phenomenon commonly is classified as a form of spectral splatter. With its primary tip at a frequency well below the probe stimulus frequency, the masking tuning curve described in the previous paragraph for probe-tone offsets suggest that the spike synchrony eliminated by the masker was a consequence of excitation by waveform singularity. On the other hand, with its tip close to the frequency of the probe stimulus, the MTC for probe-tone onsets suggests that the spike synchrony eliminated by the masker in that case was a consequence of some phenomenon other than waveform singularity.

There are several methods by which identical singularities can be made to have drastically different effects on the shape of the envelope of a tone burst. For example, the same singularities that turn the tone burst off can be made to double the amplitude of the burst instead. In other words, what was an offset becomes a second onset. If a large, maskable component of the CAP at the offset of a probe tone is the consequence of the corresponding waveform singularities, per se, then that component should be elicited by the same singularities whether they lead to the offset or to a further onset. One purpose of the research reported here was to test this idea. Basically, we have two putative classes of stimuli: (1) sudden change of shape in the tone-burst envelope, and (2) waveform singularity. Another purpose of this project was to seek distinctions between the cochlear nerve responses to these two classes.

Methods

Mongolian gerbils (*Meriones unguiculatus*) were bred and reared in acoustically controlled quarters; the animals used in these experiments were 60 to 180 days old. Each candidate subject was pre-tranquilized with chlorprothixene (5 mg/kg, i.m.) and anesthetized 30 to 160 min later with ketamine (40 mg/kg, i.p.). Supplemental doses of ketamine (10 mg/kg, i.p.) were administered as needed. Only subjects showing no visible signs of

middle or outer-ear disease were used. All physiological measurements were carried out with the animal placed inside a lab-built acoustic barrier: a 0.7 m by 0.8 m by 1.0 m box constructed of 2.0 cm thick plywood, with tightly glued joints and a gasket-sealed door of the same material as the walls, all lined with 2 cm thick fiberboard and 7 cm thick Sonex foam. This box rested on a vibration isolation table comprising three second-order mechanical filter stages constructed from lightly inflated rubber inner tubes and approximately 700 kg of bricks. The entire structure resided within a shielded 2.35 m by 2.4 m by 2.25 m Industrial Acoustics model 403A acoustic room, lined with 10 cm thick Sonex acoustic foam. In the frequency range from 1 kHz to 20 kHz, this combination provided attenuation greater than 52 dB. Integrated over the same frequency range, the ambient noise outside the outer chamber was less than 40 dB SPL. No effort was made to control for the cardiovascular, respiratory, gastric, and other sounds emitted by the animal subject itself. An Etymotic ER7C microphone probe (1 mm o.d.) was positioned with its orifice within 1 mm of the vertex of the tympanic membrane. The output of the probe microphone was calibrated with a Bruel and Kjaer sound pressure level meter and analyzed on-line with a Hewlett-Packard 3561A Dynamic Signal Analyzer. Both instruments were used to evaluate the stimulus over the entire frequency range employed in the experiment. Throughout the experiments, the stimuli all were well within the linear operating ranges of the acoustic drivers; thus the Dynamic Signal Analyzer revealed no amplitude-dependence in the normalized shape of the spectral profile of the acoustic driver outputs. Also, throughout the experiment, the core temperature of the animal (sensed by rectal probe) was maintained between 36 and 39°C; and anesthesia was maintained at a level sufficient to eliminate reflexive movement to tail pinch.

For observation of the cochlear nerve compound action potential (CAP), the recording electrode was a silver wire, insulated except for its looped tip. It was placed in contact with the ventrolateral wall of the antrum of the round window of the left ear. The indifferent electrode was attached to a bar pressed against the soft

palate, or to the jaw muscles adjacent to the bulla. In order to eliminate the need for removal of the pinna and associated muscles, and thus to open the possibility of using the same animal subject for more than one session, the ear was stimulated with a quasi-free field arrangement. The acoustic source for the probe stimulus was either a 1-inch Bruel and Kjaer (B and K) microphone rewired to operate as a driver or a Yamaha piezoelectric acoustic driver. The source for the masker stimulus in all experiments was a Yamaha piezoelectric driver.

For CAP observations, we used two classes of probe-stimulus waveforms. In one class the envelope rise and fall times (1 ms) were comparable to those used by us in previous studies. With such short rise and fall times, each onset and offset of the envelope elicited at most a single CAP, in spite of the fact that each onset and offset actually was accompanied by a pair of singularities in rapid succession (Lewis and Henry, 1988). One member of this class consisted of a trapezoidal tone burst, 30-ms in duration, with an 8-ms trapezoidal tone burst subtracted from its center; the other consisted of a 30-ms trapezoidal tone burst with an 8-ms trapezoidal tone burst added to its center (see Fig. 2). Although it was produced by an analog oscillator and analog gates, each of these probe stimuli comprised the equivalent of a sum of four pairs of ramp-modulated sinusoids of identical frequencies: The first member of each pair introduced either a positive or a negative slope into the modulation envelope. One ms later, the second member of the pair came into action and counteracted the first, bringing the slope of the envelope back to zero. Associated with each pair of ramp-modulated sinusoids was a corresponding pair of stimulus-waveform singularities. These probe-tones were presented with the Bruel and Kjaer driver; the amplitude of the harmonic distortion (measured with the probe microphone) was equal to or less than -40 dB relative to the stimulus fundamental frequency.

For each CAP, the probe stimulus was presented 64 times, with the phase of the modulated tone at the stimulus onset varying randomly from one presentation to the next – with a uniform distribution over the entire 360-degree range. Thus, for each sample of 64 stimuli, the phases of all

four pairs of ramp-modulated sinusoids were uniformly distributed over the same range (360 deg). In that sense, the four pairs of singularities in each waveform were identical, and each pair in either waveform in Fig. 2 was identical to every pair in the other. The only differences among the paired singularities in each waveform and between the paired singularities in either waveform and those in the other were the contexts in which they were presented.

In waveforms belonging to the second class, rise and fall times were sufficiently long to allow responses to individual singularities to be distinguished. The simplest member of this class was an 18-ms trapezoidal tone burst with 6 ms rise and fall times (see Fig. 5). This probe waveform also was presented with the Bruel and Kjaer driver; the amplitude of the harmonic distortion (measured with the probe microphone) was equal to or less than -40 dB relative to the amplitude of the stimulus fundamental frequency. The other two members of the second stimulus class had identical envelopes, each comprising a trapezoid with a notch at its center – leading to zero amplitude at that point. In each waveform, the notch (Fig. 1) was initiated and terminated by a pair of singularities that were identical except for their contexts. In one of the waveforms, however, there was another singularity at the center of the notch – where the envelope reached zero amplitude. The form of that singularity was identical to that of the other two, but its amplitude was doubled. This singularity was absent from the second stimulus waveform. The difference was accomplished by digitally synthesizing the first waveform as a summed sequence of seven ramp-modulated sinusoids and digitally synthesizing the second as a summed sequence of six (see Appendix A). All of the modulated sinusoids were identical in frequency; and all of the ramp onsets occurred when the modulated sinusoid was in positive cosine phase. Thus, all of the singularities had the same form, comprising stepwise discontinuities in the first time derivative of the stimulus waveform (Lewis and Henry, 1988). These probe waveforms were presented with the Yamaha driver.

To test for the presence or absence of the singularity at the center of the notch in the acoustic waveform that was actually presented to the

animal, that waveform (as transduced by the probe microphone) was passed through a low-pass filter with a corner frequency approximately $1/2$ Octave below the probe-stimulus frequency and with high-frequency rolloff at 96 dB/Oct. In this way, the sinusoidal component of the probe-stimulus was sufficiently attenuated to allow the filter's response to the singularity to be observed (see Lewis and Henry, 1988). Since this response normally was very weak, we often added a high-pass filter with a corner frequency of approximately 100 Hz, in cascade with the low-pass filter. This reduced low-frequency drift of the baseline on which the singularity response rested. All waveforms designed to possess singularities at the center of the notch did so; those designed not to have such singularities did not.

For each CAP, the simple trapezoid with 6-ms rise and fall times was presented 64 times, with the phase of the modulated tone at the stimulus onset varying randomly from one presentation to the next – again with a uniform distribution over the entire 360-degree range. Thus the neural responses to all four corners were averaged over sets of singularities that were essentially identical except for the contexts in which they were presented.

Ideally, one would obtain tuning curves for both simultaneous and forward masking. However, each probe-stimulus presentation generated a sequence of four CAPs, and attempting to obtain similar conditions of forward masking for all of these would have been problematic. Therefore, at least 2 s before the beginning of the series of 64 probe stimuli used to estimate a single CAP amplitude, a masker stimulus was begun. The masker then was continued at constant amplitude for the duration of the 64 stimulus presentations. Probe and masker frequencies were monitored with digital frequency meters. Masker frequencies were varied in 1 kHz steps from approximately 5 to 24 kHz. In order to avoid harmonic relationships between masker and probe stimuli, the masker frequencies were deliberately set approximately 0.5% above or below integral kHz values. Masker intensities were varied in 5 dB steps; and each masked or unmasked CAP was produced by averaging the responses to 64 stimulus presentations. The averaged data were stored on magnetic tape and examined off-line. Tuning curves for the ef-

fectiveness of masking (masker TCs) were obtained by plotting, as a function of frequency, the amplitude of the masker that reduced the CAP to 50% of its unmasked value. For each of the twenty masker frequencies employed, that amplitude was estimated by interpolation. After presentation of a high-intensity masker, depression of the CAP often persisted for several to many minutes. After each presentation, the subject was allowed to rest until each CAP returned to its original amplitude. This greatly prolonged the experimental procedure, making it impossible to take more than a few masker tuning curves in a day. Occasionally, depression of the CAP was so persistent that the experiment had to be terminated before an MTC series could be completed.

For observations of single cochlear axon activity, we employed the surgical approach first published by Chamberlain, 1977. The left pinna and associated muscles were removed, leaving the left ear canal exposed and unimpeded. The left bulla was opened, exposing the round-window antrum; and part of the floor of the antrum was removed to expose the cochlear nerve of the left ear. Single cochlear afferent axons within 0.25 mm of the surface of the nerve were penetrated with glass micropipettes filled with 3 M NaCl and having impedances greater than 50 megohm. Spike activity was recorded simultaneously with the stimulus and stimulus trigger. Stimuli were presented with a closed-field system with a Yamaha piezoelectric acoustic driver serving as the source. The characteristic frequency (CF) of each unit was estimated from on-line auditory presentations of spike responses to trapezoidal tone bursts 20 ms in duration and presented at a rate of 5/s. The CF was bracketed increasingly narrowly as the amplitude of the stimulus was reduced in steps, beginning at approximately 60 dB SPL. The threshold in each case was taken to be the minimum sound pressure level at CF at which the experimenter could hear clear spike responses to each tone burst. Once CF and threshold had been estimated in this manner, a test stimulus was selected at a frequency equal to or above CF and an amplitude level well above threshold.

For single-axon observations, the notched waveforms similar to those of Fig. 1 were employed. A four-channel analog tape recorder was

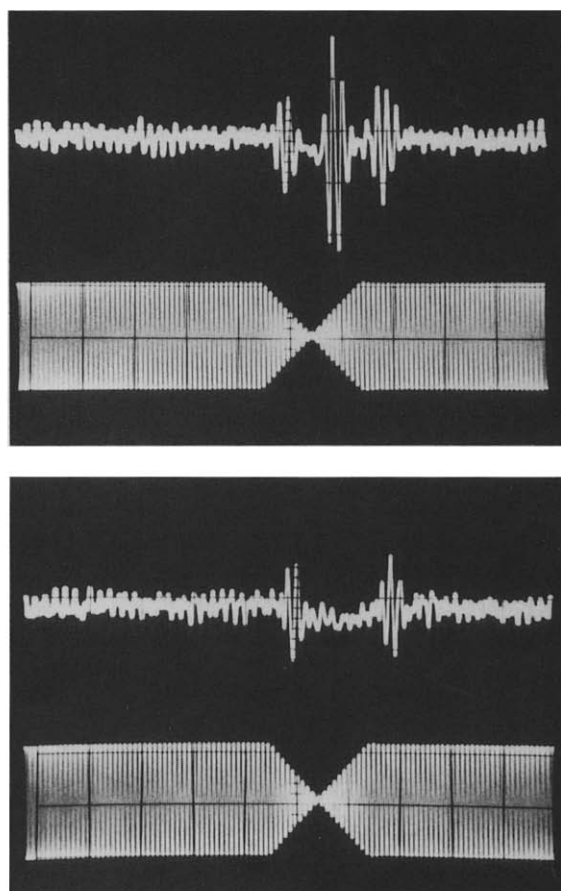


Fig. 1. Oscilloscope tracings of envelope notches and the transient excitations they produce in a linear filter with a steep band edge. The notch in the upper photograph was produced with a waveform singularity at the center of the notch, that in the lower photograph was produced without the singularity. The frequency of the modulated sinusoid was 10 kHz. The filter was a 16-pole, low-pass Butterworth realization, with its corner frequency at 7 kHz.

used to record the stimulus waveform, the trigger that initiated it, the spikes from the axon, and a voice record. The data were analyzed off-line and displayed in peristimulus time histograms. The latter were examined for responses to the stimulus corner at the center of the notch and elsewhere.

Results

CAP responses

Fig. 2 displays CAP responses to a pair of test waveforms comprising four pairs of ramp-mod-

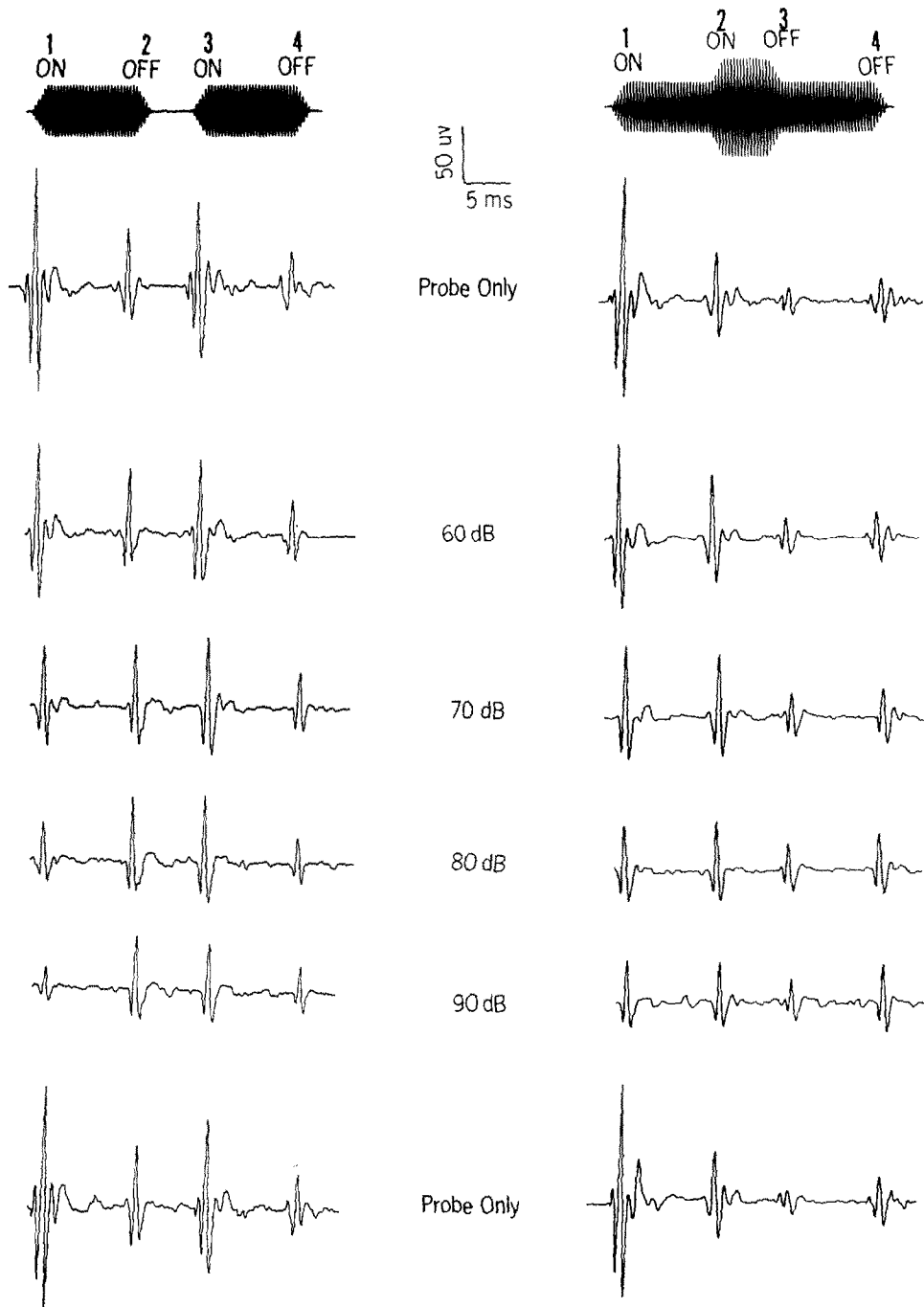


Fig. 2. Two 16-kHz probe stimulus waveforms each with four tone-burst edges ('onsets' and 'offsets'). Each edge, in turn, comprised a pair of ramp modulated, 16 kHz sine waves. With respect to transient excitation of a linearly-responding filter, all eight edges are identical. The plateau amplitude (between edges 1 and 2) of each probe stimulus was 70 dB SPL. Beneath each waveform are six sets of CAP responses to the various edges. The top and bottom sets show responses to the probe stimulus alone, at the beginning and end of the experiment. The other four sets show the effects of masking with a continuous, 15.9 kHz tone at the intensities listed (dB SPL). For estimating the 50% masking level, the amplitude of the CAP was measured from the large positive peak to the subsequent negative peak. The 50% masking level was determined by interpolation with data taken at 5 dB intervals. With the 10 dB interval data shown here, the 50% masking level for edge number 1 would be estimated at approximately 68 dB from the left-hand column, 70 dB from the right-hand column. For edge number 3 in the right-hand column it would be estimated at approximately 90 dB. For the remaining edges in this figure, the 50% masking level was not reached (i.e., the notch in the masker tuning curve reached beyond 90 dB in this subject).

ulated sinusoids. In this case, the stimulus frequency was 16 kHz and the plateau amplitude (between edges 1 and 2) was 70 dB SPL. Here we observed a distinct CAP corresponding to the waveform edge formed by each of the four pairs. In response to the unmasked waveform, the amplitudes of the CAPs were consistently greatest for the first pair of ramp-modulated sinusoids (edge 1). The relative amplitudes of the CAP responses at the remaining three edges were different for the two waveforms. The effects of a simultaneous, 15.9 kHz masker stimulus on the various CAPs were markedly different (middle traces in Fig. 2). As the masker stimulus intensity was increased, the amplitude of the CAP at the first edge (the onset of overall-waveform) diminished monotonically. The CAPs at the other three edges in the stimulus with the subtracted 8-ms trapezoid remained relatively unchanged, diminishing in am-

plitude slightly when the masker intensity reached 90 dB SPL. The amplitudes of the CAPs at the other three edges of the stimulus with the added 8-ms trapezoid increased slightly in the presence of the masker stimulus. The effects of the masker stimulus were reversible, all CAPs eventually returning to their original amplitudes when the masker was removed (bottom traces of Fig. 2).

Figs. 3 and 4 show a masker tuning curve (MTC) for the CAP at each of the four edges of the two 16-kHz waveforms, at several probe-stimulus plateau amplitudes. The data were taken from different subjects from that used for Fig. 2, with the data for Fig. 3 being obtained from one subject, and those for Fig. 4 being obtained from another. The maximum masker-stimulus amplitude employed in each case was 90 dB SPL. Therefore none of the MTCs extend above that level. The general shapes of the MTCs for CAPs

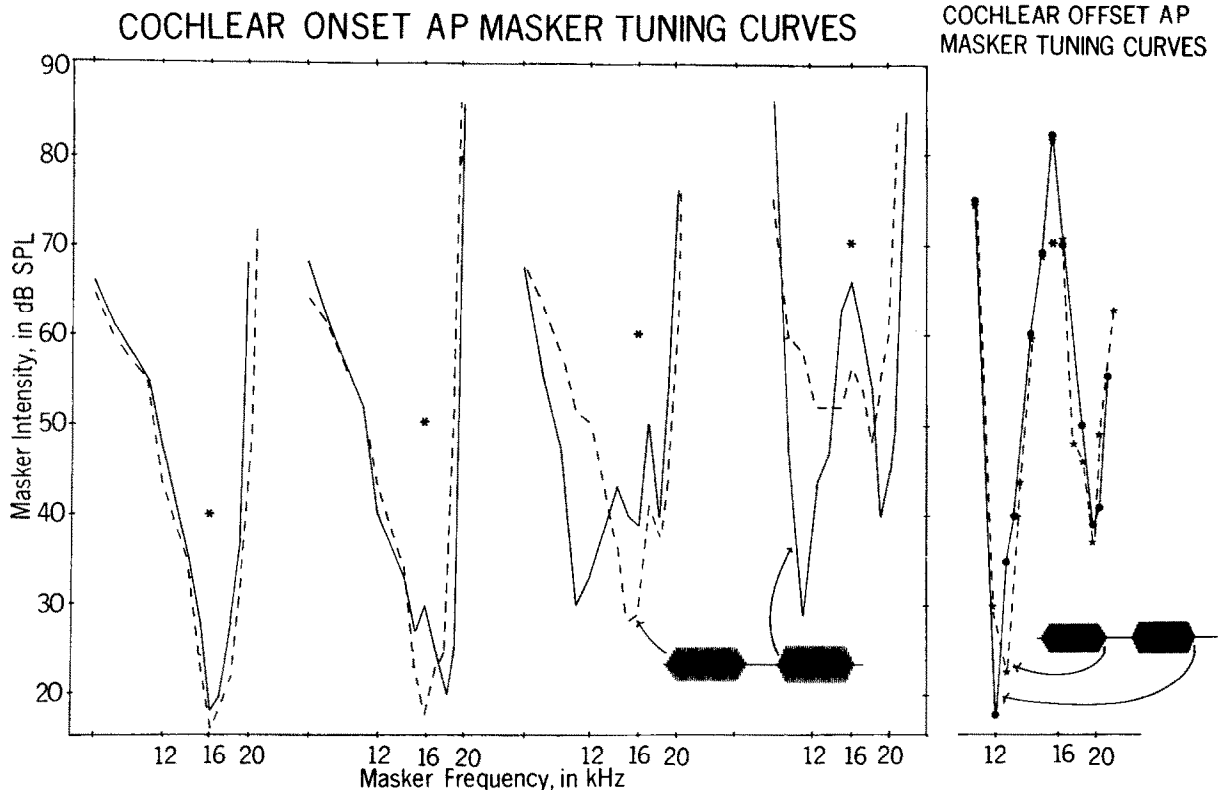


Fig. 3. Masker tuning curves for CAPs of the type shown on the left side of Fig. 2, but taken from a different subject. Each asterisk depicts the frequency and intensity of the probe stimulus. Arrows show the edge corresponding to each MTC. In the left panel, the four MTCs with dashed lines are for the CAP at stimulus edge number 1 in Fig. 2; the four MTCs with solid lines are for the CAP at edge number 3. In the right panel, the dashed MTC is for edge 2 and the solid corner is for edge 4.

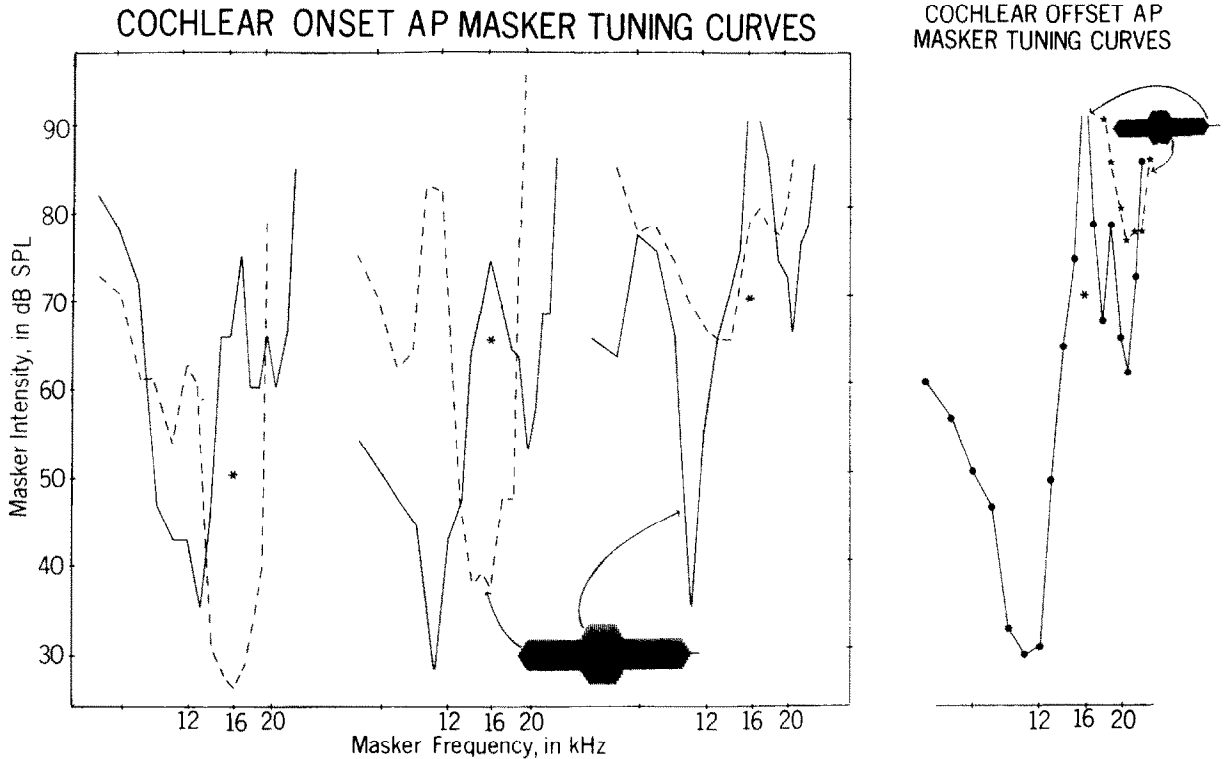


Fig. 4. Masker tuning curves for CAPs of the type shown on the right side of Fig. 2, taken from a third subject (different from those of Figs. 2 and 3). Each asterisk depicts the frequency and intensity of the probe stimulus. Arrows show the edge corresponding to each MTC. In the left panel, the four MTCs with dashed lines are for the CAP at stimulus edge number 1 in Fig. 2; the four MTCs with solid lines are for the CAP at edge number 2. In the right panel, the dashed MTC is for edge 3 and the solid corner is for edge 4.

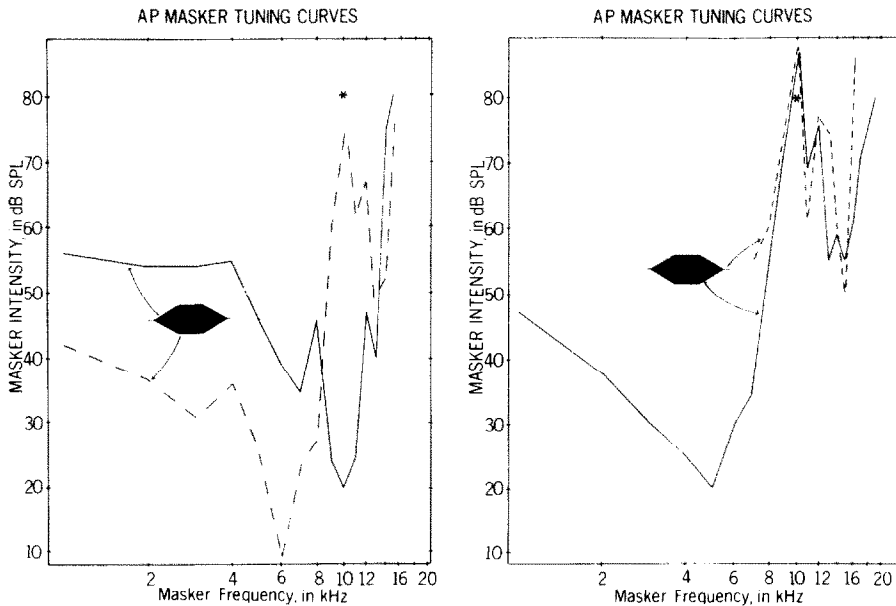


Fig. 5. Masker tuning curves for CAPs occurring at the four corners of a trapezoidally-modulated, 10 kHz probe tone. Each corner corresponds to the onset of one of the four ramp-modulated, 10-kHz sinusoids composing the total probe stimulus. With respect to its excitation of a linearly-operating filter, each of the four corners is identical to the others. Arrows show the corner corresponding to each MTC.

at the edges corresponding to negative envelope slopes did not change with probe-stimulus intensity. For the CAPs at three of the four edges corresponding to positive envelope slopes, on the other hand, the general shapes of the MTCs changed conspicuously. For the probe stimulus in Fig. 3 (with the 8-ms trapezoid subtracted) at low probe-stimulus intensities, the MTCs for the CAP at edges 1 and 3 were essentially identical, with relatively sharp tips at the probe-stimulus frequency. At higher probe-stimulus intensities, the general shape of the MTC for the CAP at edge 3 became very similar to that for CAPs at edges with negative slopes, i.e., W-shaped, with sharp tips at 12 kHz and 20 kHz, separated by a deep notch at the probe-stimulus frequency (16 kHz). For the probe stimulus in Fig. 4 (with the 8-ms trapezoid added), the MTCs for the CAP at the second positively-sloped edge (edge 2) were W-shaped at all probe-stimulus intensities that we

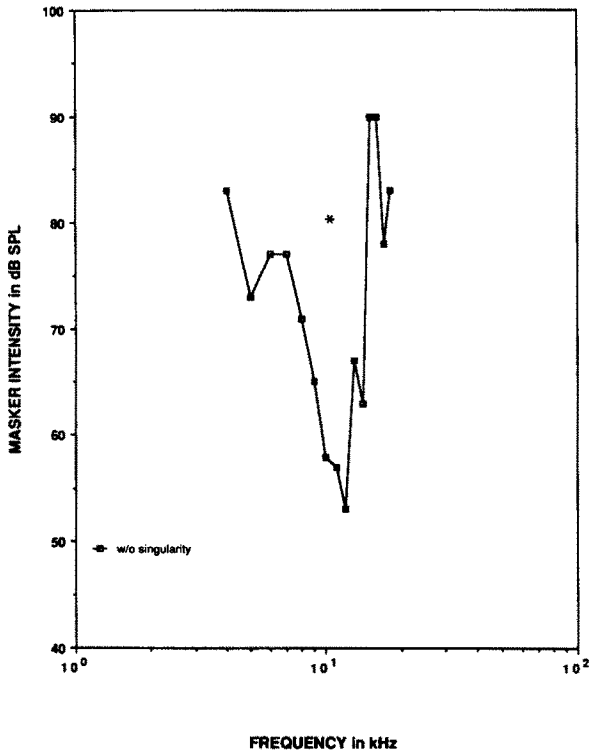


Fig. 6. Masker tuning curve for the CAP produced at the center of a notch (i.e., the envelope zero-crossing) similar to that in the lower photograph in Fig. 1 (no singularity present). The probe-stimulus frequency was 11.1 kHz.

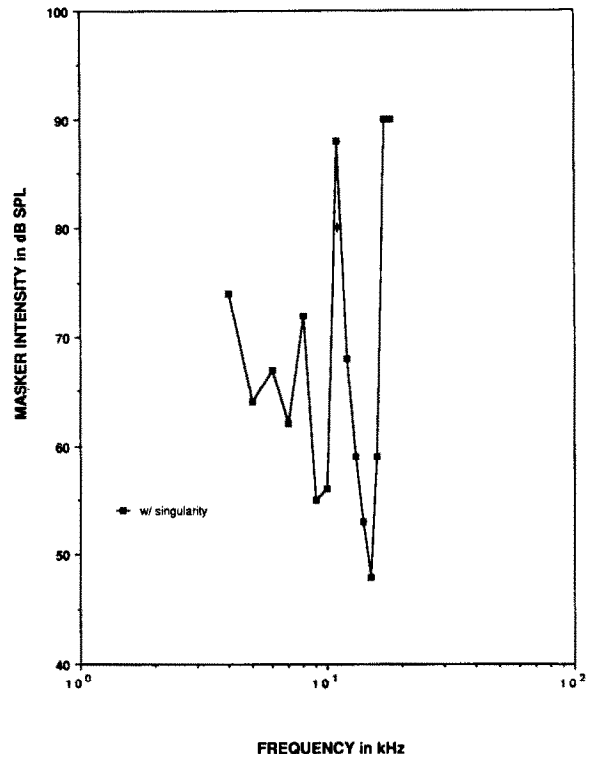


Fig. 7. Masker tuning curve for the CAP produced at the center of a notch similar to that in the upper photograph in Fig. 1 (singularity present). The probe-stimulus frequency was 11.1 kHz.

used. For the CAP at edge 3 of the same probe stimulus, the only part of the MTC that was visible below 90 dB SPL was a single tip at 20 kHz. At the highest probe-tone intensity (70 dB SPL in Fig. 3, 75 dB SPL in Fig. 4), the MTC for the CAP at edge 1 in each waveform exhibited a broad tip, with a very slight notch at the probe-stimulus frequency.

Fig. 5 shows MTCs for CAPs at each of the four corners of a simple trapezoidal tone burst with 6-ms rise and decay times. The data used here were obtained from a different subject than those used for Figs. 2 through 4. In this case, the probe-stimulus frequency was 10 kHz. For the CAP at the first corner, at the very beginning of the trapezoidal stimulus, the MTC exhibited a sharp tip at the probe stimulus frequency. For the CAPs at the second and third corners, the MTCs were W-shaped, with deep notches at the probe-stimulus frequency. For the CAP at the fourth

corner, the low-frequency portions of the MTC were not visible below 75 dB SPL (the maximum masking intensity used at masker frequencies below 9 kHz).

Figs. 6 and 7 were obtained from a single subject and show MTCs for CAPs at the centers of notches similar to those of Fig. 1. The probe-tone frequency in this case was 11-kHz. When the

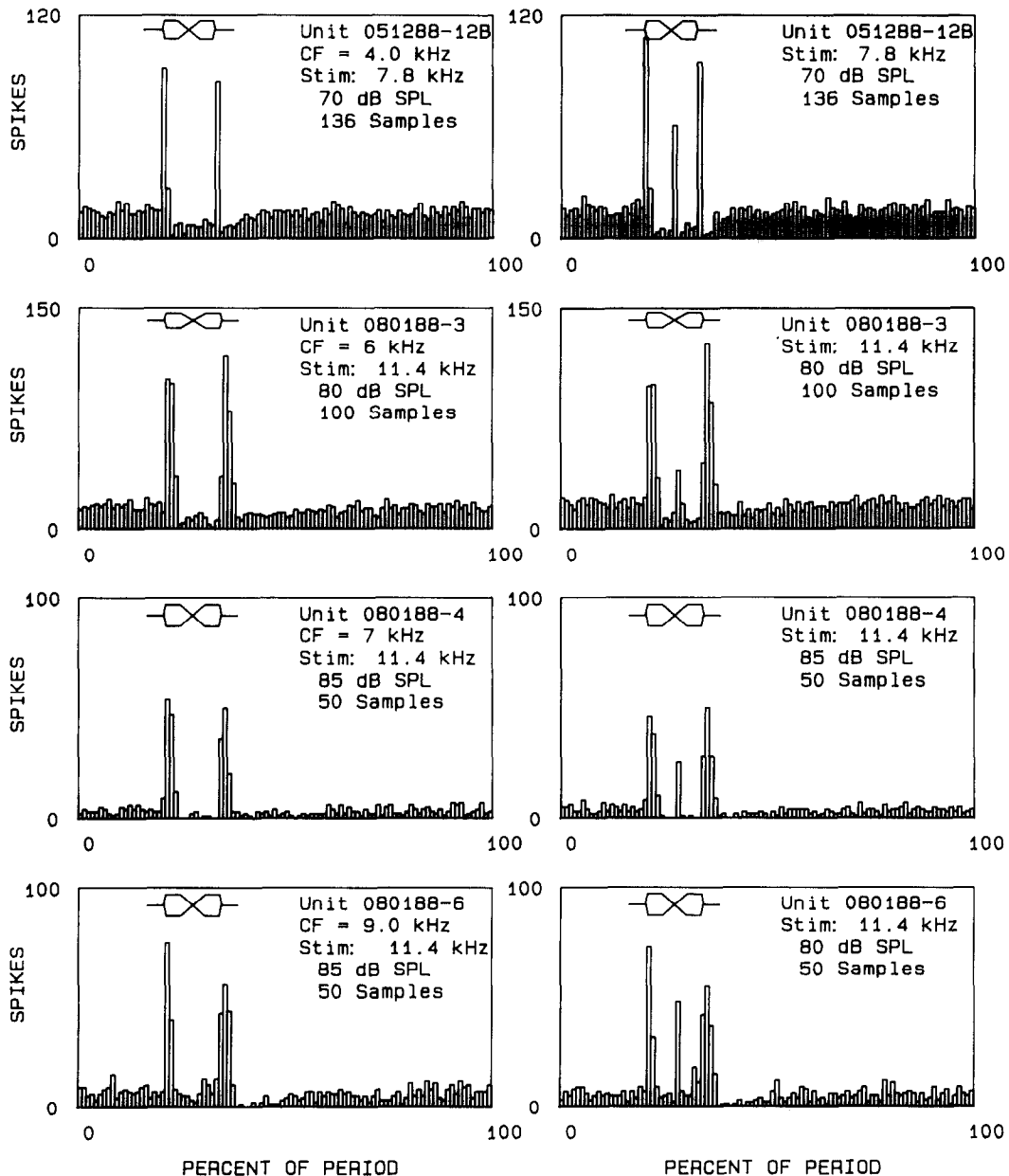


Fig. 8. Peristimulus time histograms representative of the axons showing spike synchrony in response to the singularity at the center of the notch. In each pair of histograms, the left-hand member shows the response in the absence of a singularity at the center of the notch; the right-hand member shows the response in the presence of a singularity at that point. Double singularities occurred at the beginning and end of each probe stimulus. None of the 21 axons tested showed spike synchrony to the center of the notch when the singularity was not present there.

center of the notch was not associated with a waveform singularity (Fig. 6), the MTC was approximately V-shaped, with a sharp tip at the probe-stimulus frequency. When the center of the notch was associated with a waveform singularity (Fig. 7), the MTC was approximately W-shaped, with a deep notch at the probe-stimulus frequency.

Single-unit responses

To date we have recorded the responses of 21 axons to the two trapezoidal tone bursts with notches. The plateau amplitudes of the tone bursts ranged from 70 to 90 dB SPL. Although the size of this sample is small, the results are compellingly consistent. The peristimulus time histograms of 12 axons showed strong spike synchrony at the center of the notch when the singularity was present at that point; no peristimulus time histograms showed spike synchrony at that point when there was not a singularity there. The CFs of the axons ranged from approximately 4 kHz to 16 kHz, with thresholds at CF ranging from less than 0 dB SPL to approximately 35 dB SPL. The spontaneous spike rates of the axons ranged from 0.01 to 114 spikes/s. The 12 axons showing strong spike synchrony to the singularity at the center of the notch spanned essentially the same ranges (spontaneous rates from 1.2 to 82 spikes/s, CFs from approximately 4 kHz to approximately 11 kHz, and thresholds at CF from less than 0 dB to approximately 35 dB). In each case, the probe-stimulus frequencies used were above the CF of the axon. Representative peristimulus time histograms for these units are displayed in Fig. 8.

Discussion

CAP studies

If we interpret masker tuning curves for CAPs under the common assumption that masking is accomplished by pre-emptive stimulation of the axons in which spike synchrony would otherwise have occurred, then the MTCs of Figs. 3 and 4 would imply that two separate populations of axons are involved in the production of CAPs in response to the four-edged stimuli. One population evidently comprises axons with CFs close to the probe-stimulus frequency. The other popula-

tion evidently comprises axons with CFs approximately 1/2 Oct below the probe-stimulus frequency (and possibly some axons with CFs above the probe-stimulus frequency). Because the MTCs of Figs. 4 and 5 were based on > 50% reduction in the CAP amplitude, one must keep the remaining < 50% in mind when interpreting them. Thus, for example, the tuning curves at the far left of Fig. 3 imply (under the assumption cited above) that the > 50% of the (CAP) spike synchrony that was most easily eliminated by the masker was contributed by units with CFs close to the probe-stimulus frequency. The MTCs tell us nothing about the axons contributing the other < 50%. Thus, we can interpret the MTCs as follows:

1. At the initial onset of the stimuli (i.e., the first envelope edge, contributed by the first pair of ramp-modulated sinusoids), the majority of the axons contributing spike synchrony had CFs close to the probe-stimulus frequency.

2. Assuming that each axon has only one CF, it is impossible for a majority of the axon population contributing spike synchrony to have CFs 1/2 Oct below the probe-stimulus frequency and for a majority of the same population to have CFs above the probe-stimulus frequency. Therefore, the most reasonable interpretation of the W-shaped tuning curves seems to be the one given in the introduction – namely that the lower-frequency tip reflects the CFs of the axons contributing spike synchrony, while the higher-frequency tip reflects elimination of synchrony in those same axons by a cubic-difference tone (generated by interaction of the masker stimulus and the probe stimulus).

3. At the third edge of the waveform in which the 8-ms trapezoid was subtracted (Fig. 3), the majority contribution to spike synchrony shifted as the probe-stimulus amplitude was increased. At low amplitudes it came from axons with CFs close to the probe-stimulus frequency; and at high amplitudes it came from axons with CFs approximately 1/2 Oct below the probe-stimulus frequency. At one intermediate amplitude (third pair of MTCs from the left), the source of the majority contribution to spike synchrony was not cleanly delineated by the experiment; and we evidently see the effects of two populations – one

with CFs close to the probe-stimulus frequency and one with CFs $1/2$ Oct below it.

4. At edges 2 and 4 in both Fig. 3 and Fig. 4, the majority contribution to spike synchrony came from axons with CFs close to $1/2$ Oct below the probe-stimulus frequency.

5. At edge 3 in Fig. 4, the majority contribution may have come from a population with CFs above the probe-tone frequency. However, the possibility of cubic-difference tone involvement is suggested by the similarity of the MTC for the CAP at that edge and the high-frequency branches of the W-shaped MTCs for corners 2 and 4.

None of these conclusions is inconsistent with the many MTCs published to date for onset and offset CAPs in gerbils or other animals (Dallos and Cheatham, 1976; Henry, 1987). However, they allow us to refine the interpretation of these earlier results. Previously, sharply-tuned, W-shaped MTCs have been reported only for stimulus 'offsets' (i.e., edges with negative slopes). The results reported here imply that sharply-tuned W-shaped MTCs do not depend on whether the slope of an edge is positive or negative (e.g., compare the MTCs for edge 2 in Figs. 3 and 4). The sharply-tuned W-shaped MTC evidently occurs for an edge (with either positive or negative slopes) preceded by a part of the probe stimulus with sufficient amplitude. Thus the presence of the tone itself appears to pre-empt synchronous response in axons with CFs close to the probe stimulus frequency, leaving another population of axons to participate in the CAP. For the CAPs at edges 2 and 4 in Fig. 3 and edges 2, 3 and 4 in Fig. 4, this pre-emption would be simultaneous masking. For the CAP at edge 3 in Fig. 3, it would be forward masking; and its impact clearly increases with the amplitude of the masking stimulus.

The question that arises next is whether the two ramp-modulated sinusoids that make up an edge are capable of generating separate CAPs, and if so, what shapes would the corresponding MTCs assume. The results in Fig. 5 imply that the V-shaped MTC (with sharp tip at probe stimulus frequency) typical of CAPs at probe-tone 'onsets' actually is associated with the first of the two ramp-modulated sinusoids composing the onset. For the CAP at the second corner of the onset (i.e., at the beginning of the ramp-modulated

sinusoid that ends the onset edge and brings the slope of the envelope back to zero), the MTC exhibits the sharply-tuned W-shape (with deep notch at the probe stimulus frequency) previously thought to be typical of 'offsets.'

The next question that arises is whether or not the singularity associated with the initiation of a ramp-modulated sinusoid (i.e., the singularity that occurs at each of the envelope corners of the stimuli of Figs. 3, 4 and 5) is necessary to elicit a CAP at that corner. Using notches similar to those in the waveforms of Fig. 1, we found that the answer is no; CAPs occur whether the singularity is present or not. However, the CAP in response to a notch without a singularity normally is smaller in amplitude than that in response to a notch with a singularity. The typical ratio of amplitudes is approximately 2:1.

Next, we would like to know whether different axon populations are involved in the synchronous responses (CAPs) with and without singularities. The results in Figs. 6 and 7 imply that the answer is yes: the notch without singularity leads to a V-shaped tuning curve with a sharp tip at the probe stimulus frequency; and the notch with singularity leads to a W-shaped tuning curve with a notch at the probe stimulus frequency.

The results to date thus suggest that there are two classes of synchronous response leading to CAPs in response to rapid modulations of tones. For one class the effective stimulus is simply a rapid increase of tone amplitude from a very low level. For the other class, the effective stimulus is a waveform singularity. We choose to label members of the first class 'envelope responses' and members of the second class 'singularity responses.' The MTCs derived for a particular CAP thus would depend upon the class to which the majority of axons participating in the underlying synchrony belong.

Single-unit studies

The final questions addressed in this study were whether or not one can distinguish between envelope and singularity responses at the single-unit level and, if so, whether the properties of those responses at that level conform to our conclusions drawn from the CAP results. For envelope responses, we evidently should be using stimuli with

frequencies close to CF. Whenever we tried that with the notch stimulus, the axon responded with more-or-less continuous spike train. If there was a tendency toward synchronization of spikes with the center of the stimulus notch, it was not visible against this background activity in our peristimulus time histograms. However, at frequencies sufficiently higher than CF, this background activity was not present. In fact, for sufficiently intense stimuli the spike rate during the tone burst often was reduced to levels below the spontaneous rate, as has been previously reported (Lewis and Henry, 1988). Against this background, singularity responses were readily seen; but envelope responses were neither seen nor expected (owing to the stimulus frequencies relative to CF).

Envelope effects

Post-stimulus and peristimulus time histograms often reveal a tendency for auditory axons to produce spikes in synchrony with the onsets of tone-bursts (Kiang et al., 1965; Rhode and Smith, 1985; Geisler and Sinex, 1982). For tones well within the spectral pass-band of an axon, it evidently is not reasonable to attribute this tendency to singularity response, since the effects of the waveform singularity in that case should be completely overwhelmed by the effects of the tone itself (Lewis and Henry, 1988). However, the tendency toward onset synchrony might be attributable to at least two other phenomena. One possibility is a rapid decline of the responsiveness ('adaptation') of the axon after the onset of the tone (Westerman and Smith, 1984). The other possibility is rectification of the tone burst by the transduction process, and dominance by the pulse-like rectified response over the unrectified response component in the generator potential that reaches the spike initiator of the afferent axon. Given the frequencies of the probe-stimuli used in this project, dominance by the rectified component is very likely (Kiang et al., 1965; Rose et al., 1967; Russell and Sellick, 1978). In response to pulsatile stimuli, spike initiators typically produce spikes in near synchrony with the onset of the pulse and more-or-less aperiodically throughout the rest of the pulse (Stein 1967; Chapman, 1980). Thus the pulse-like dc response to a tone burst envelope could lead to a tendency

toward onset synchrony and subsequent asynchrony, even without adaptation.

As a consequence of their extremely steep rolloff at frequencies above CF (Kiang et al., 1965), the tuning curves of mammalian cochlear axons suggest that the rectified response components for probe tones at frequencies well above CF will be extremely small. In such cases, the singularity responses at the onset and other edges of a tone burst should be much larger than the envelope responses and therefore dominate (Lewis and Henry, 1988). This would explain the shapes of the peristimulus time histograms obtained from single axons in this study. It also would explain, in part, the fact that one population of axons contributing to spike synchrony in the CAPs of this project seemed to have CFs well below the probe-stimulus frequency. On the other hand, it does not explain the sharpness of the tip on the corresponding masker tuning curve (i.e., the low-frequency tip of the W-shaped MTC). Theoretically, for the singularity at the onset of a ramp-modulated sinusoid, the ability to excite a cochlear axon should decrease between 12 and 18 dB per Octave (relative to CF) as the frequency of the modulated sinusoid is increased above CF (the slope depends on the phase of the modulated sinusoid at the onset of the ramp modulation). The single-unit data are consistent with the theory; singularity responses are commonly found with probe-stimulus frequencies an Octave or more above CF (e.g., see Fig. 8). Why then should the majority of axons participating in singularity CAP responses (according to the MTCs of Fig. 3, 4 and 5) evidently have their CFs confined to such narrow regions?

Significance of waveform singularities

Taylor's theorem tells us that any waveform that begins in finite time (i.e., has not existed forever) must exhibit a waveform singularity at the moment it begins. Thus, in principle, all natural acoustic stimuli must possess waveform singularities. To convince ourselves that this implication of Taylor's theorem is correct, we used the method described in conjunction with Fig. 1 to look for waveform singularities among the calls and songs of birds and frogs. For that purpose, we used frog calls recorded by one of us (ERL) at

various field sites in the United States, Puerto Rico, and Costa Rica; and we used bird songs and calls from *A Field Guide to Western Bird Songs* published by Houghton Mifflin Company. We found that waveform singularities are indeed ubiquitous. Many calls and songs are punctuated with such singularities not only at their onsets, as expected, but at several other places during their time courses.

Given the relative ease with which spike coincidence detectors can be realized with neural circuitry, discrete acoustic events that produce sufficient spike synchrony to yield CAPs should be especially easy to extract from sensor noise (e.g., signal contamination by Brownian motion in the cochlea) and from ambient acoustic noise or interference. Such events also should be useful for refining and tracking acoustic images – as in the cocktail party phenomenon.

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Appendix A

The synthesis of the notched stimulus waveforms can be described as follows: Let x_s be the stimulus waveform comprising seven ramps, x'_s be the waveform comprising six, and f_s be the frequency of the modulated tone. Then, for x_s we have

$$x_s = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 \quad (1)$$

$$x_1 = 0 \quad t < t_1$$

$$x_1 = A(t - t_1) \cos[w(t - t_1)] \quad t \geq t_1$$

$$x_2 = 0 \quad t < t_2$$

$$x_2 = A(t - t_2) \cos[w(t - t_2)] \quad t \geq t_2$$

$$x_3 = 0 \quad t < t_3$$

$$x_3 = B(t - t_3) \cos[w(t - t_3)] \quad t \geq t_3$$

$$x_4 = 0 \quad t < t_4$$

$$x_4 = 2B(t - t_4) \cos[w(t - t_4)] \quad t \geq t_4$$

$$x_5 = 0 \quad t < t_5$$

$$x_5 = B(t - t_5) \cos[w(t - t_5)] \quad t \geq t_5$$

$$x_6 = 0 \quad t < t_6$$

$$x_6 = A(t - t_6) \cos[w(t - t_6)] \quad t \geq t_6$$

$$x_7 = 0 \quad t < t_7$$

$$x_7 = A(t - t_7) \cos[w(t - t_7)] \quad t \geq t_7$$

where

$$w = 2\pi f_s$$

and

$$t_7 - t_6 = t_2 - t_1 = K_1/2f_s$$

$$t_4 - t_3 = t_5 - t_4 = K_2/2f_s$$

$$t_3 - t_2 = t_6 - t_5 = K_3/2f_s$$

$$K_1, K_2 = \text{odd integers}$$

$$K_3 = \text{even integer}$$

$$2A(t_2 - t_1) = B(t_5 - t_3)$$

For x'_s , we have

$$x'_s = x'_1 + x'_2 + x'_3 + x'_4 + x'_5 + x'_6 + x'_7 \quad (2)$$

$$x'_1 = 0 \quad t < t_1$$

$$x'_1 = A(t - t_1) \cos[w(t - t_1)] \quad t \geq t_1$$

$$x'_2 = 0 \quad t < t_2$$

$$x'_2 = A(t - t_2) \cos[w(t - t_2)] \quad t \geq t_2$$

$$x'_3 = 0 \quad t < t_3$$

$$x'_3 = B'(t - t_3) \cos[w(t - t_3)] \quad t \geq t_3$$

$$x'_4 = 0 \text{ for all time}$$

$$x'_5 = 0 \quad t < t_5$$

$$x'_5 = B'(t - t_5) \cos[w(t - t_5)] \quad t \geq t_5$$

$$x'_6 = 0 \quad t < t_6$$

$$x'_6 = A(t - t_6) \cos[w(t - t_6)] \quad t \geq t_6$$

$$x'_7 = 0 \quad t < t_7$$

$$x'_7 = A(t - t_7) \cos[w(t - t_7)] \quad t \geq t_7$$

where

$$w = 2\pi f_s$$

and

$$t_7 - t_6 = t_2 - t_1 = K_1/2f_s$$

$$t_5 - t_3 = 2K_2/f_s + 1/2f_s$$

$$t_3 - t_2 = t_6 - t_5 = K_3/2f_s$$

$$K_1, K_2 = \text{odd integers}$$

$$K_3 = \text{even integer}$$

$$2A(t_2 - t_1) = B'(t_5 - t_3)$$

With these constraints on the constants K_1 , K_2 and K_3 , the sinusoids in x_1 , x_4 and x_7 are in phase with each other and 180 deg out of phase with those in x_2 , x_3 , x_5 and x_6 ; and the sinusoids in x'_1 , x'_5 and x'_6 are in phase with each other and 180 deg out of phase with those in x'_2 , x'_3 and x'_7 . In this way, x_1 and x'_1 create positive slopes at the beginning of the waveform envelopes (at t_1); x_2 and x'_2 subtract from those functions and thus bring the slopes of the envelopes to zero (beginning at t_2); and x_3 and x'_3 also subtract, making the slopes of the envelopes negative (beginning at t_3). With the specified relationships between A and B and B', both envelopes reach zero at a time (t_4) precisely halfway between t_3 and t_5 . However, the function x'_3 continues past t_4 , to t_5 , bringing the envelope of x'_s through zero and back to its full amplitude. x'_5 is additive rather than subtractive, and therefore brings the slope of the envelope of x'_s to zero (beginning at t_5). The envelope of x'_s is completed by the addition of x'_6 and subtraction of x'_7 . In the function x_s , x_3 is interrupted just as it brings the envelope to zero. At that point, the addition of x_4 , with twice the amplitude of x_3 , makes the slope of the envelope positive (beginning at t_4). The subtraction of x_5 brings the slope to zero again; and x_6 and x_7 complete the envelope.

The durations of the linear rise at the beginning of each waveform and the linear fall at the end were set to within 1/2 cycle (of f_s) of 1.0 ms. The width of the notch at the center of each waveform was set to within 1/2 cycle of 12 ms; but the notch width for x_s differed from that for x'_s by 1/2 cycle. The durations of the plateau portions were identical in the two waveforms, and were set

to within 1 cycle of 7 ms. The 6 ms rise and fall times on either side of t_4 provided a compromise between the need for steep ramps in order to produce a response to the envelope corner or waveform singularity at that point, and the need for wide separation of t_3 , t_4 , and t_5 in order to distinguish the responses from those three corners of the stimulus waveform. The slopes of the notches and the amplitudes of the singularities at their beginnings and ends were very slightly different, owing to the half-cycle difference in notch width (required to achieve cosine phase).

The magnitude of this difference was ap-

proximately the ratio of half the stimulus-tone period divided by 12 ms. For the nominal 8, 11 and 16 kHz tones used in the experiments reported here, this amounted to approximately 1/2 to 1 percent. Each stimulus frequency was chosen so that 1/2 period was equal to an integral number of cycles of the clock in the digital signal synthesizer. The paired singularities on each end of the waveform had approximately six times the amplitude of those beginning and ending the notches, approximately three times the amplitude of the singularity at the center of the notch in x_s .