

Discrimination of Rippled-Spectrum Noise from Flat-Spectrum Wideband Noise by Chinchillas

WILLIAM P. SHOFNER and WILLIAM A. YOST

Parmly Hearing Institute, Loyola University Chicago, 6525 N. Sheridan Rd., Chicago, IL 60626

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Chinchillas were trained to discriminate infinitely-iterated rippled noise from flat-spectrum wideband noise. Infinitely-iterated rippled noise is generated when a wideband noise is delayed and the delayed version of the noise is added to the undelayed noise through positive feedback. The pitch of the rippled noise is related to the delay and the pitch strength is related to the gain of the delayed noise. Psychometric functions for the discrimination of rippled noise from flat-spectrum wideband noise were generated for chinchillas and human subjects. The psychometric functions obtained for chinchillas are shifted to higher gains compared with those of human subjects, suggesting that, although chinchillas can discriminate the rippled-spectrum noise from the flat-spectrum noise, they are less sensitive than human subjects. However, the slopes of the psychometric functions are similar between chinchillas and human subjects, suggesting that there is no fundamental difference in the processing of the rippled noise between human subjects and chinchillas. The results obtained from chinchillas are consistent with recent results from human subjects, indicating that the discrimination is based on a simple temporal processing rule.

Key words: Rippled noise, chinchilla, pitch

PITCH IS AN IMPORTANT perception of many complex sounds, particularly in speech and music. A variety of sounds can produce the perception of the same pitch in human subjects (Fastl and Stoll, 1979), and it seems likely, therefore, that the neural mechanisms underlying pitch perception share some common proper-

ties for these various stimuli. One important class of complex sounds that produces the perception of pitch in human subjects is rippled noise. In contrast to tone complexes, which are periodic and have line spectra, rippled noises are aperiodic sounds having continuous spectra. An understanding of the processing of rippled noises is important for understanding pitch perception, because models and theories of pitch must be able to account for the pitches and pitch strengths of rippled noises.

Rippled noise is generated when a wideband noise is delayed, and the delayed repetition is then added back to the undelayed version (Fig. 1, top); this represents one iteration of the rippled noise. Rippled noise derives its name from its power spectrum. The power spectrum is given by:

$$|H(f)|^2 = 1 + g^2 + 2g\cos(2\pi fT) \quad (1)$$

(see Bilsen and Ritsma, 1970), where g is the gain and T is the delay, and has peaks that occur in a cosinusoidal manner at integer multiples of $1/T$ (Fig. 2). In the literature, this type of rippled noise has been referred to as ripple noise (Yost and Hill, 1978), repetition noise (Fay *et al.*, 1983), cosine-noise (Bilsen *et al.*, 1975), and comb-filtered-noise (Pick, 1980). For purposes of clarity, we will refer to this type of rippled noise as 1-iterated rippled noise. When the wideband noise is delayed, and the delayed repetition is added back to the undelayed noise through positive feedback, then the number of iterations is infinite (Fig. 1, bottom). This type of rippled noise has been referred to as comb-filtered noise (Raatgever and Bilsen, 1992) and peaked ripple noise (Fastl, 1988). We will refer to this type of rippled noise as infinitely-iterated rippled noise. The power spectrum of infinitely-iterated rippled noise is given by:

$$|H(f)|^2 = \frac{1}{1 + g^2 - 2g\cos(2\pi fT)} \quad (2)$$

(see Bilsen and Raatgever, 1983) and has sharper peaks at integer multiples of $1/T$ (Fig. 3). Thus, for both 1-iterated and infinitely-iterated rippled noises, in which

Corresponding author: Dr. William P. Shofner, Parmly Hearing Institute, Loyola University Chicago, 6525 N. Sheridan Road, Chicago, IL 60626, Telephone: (312) 508-2755; Fax: (312) 508-2719.

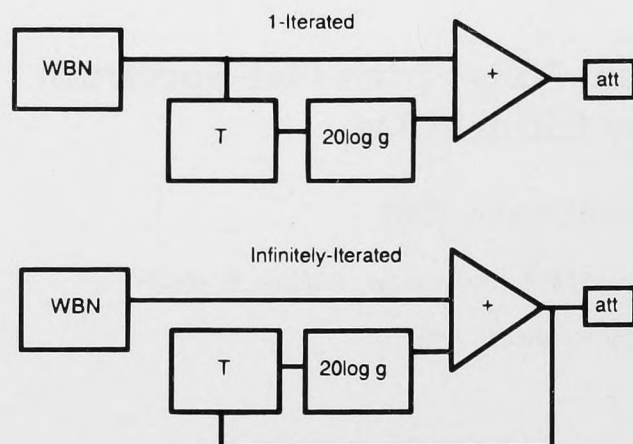


FIGURE 1 Schematic diagrams of circuits used to generate 1-iterated rippled noise (top) and infinitely-iterated rippled noise (bottom). WBN is wideband noise source, T is the delay, g is the gain, att is attenuation for overall level. The gain in dB is $20 \log g$.

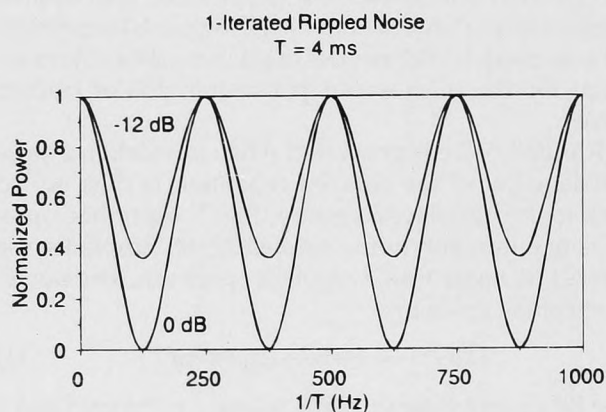


FIGURE 2 Spectra expressed in linear power units for 1-iterated rippled noise with a delay of 4 ms for gains of 0 dB and -12 dB.

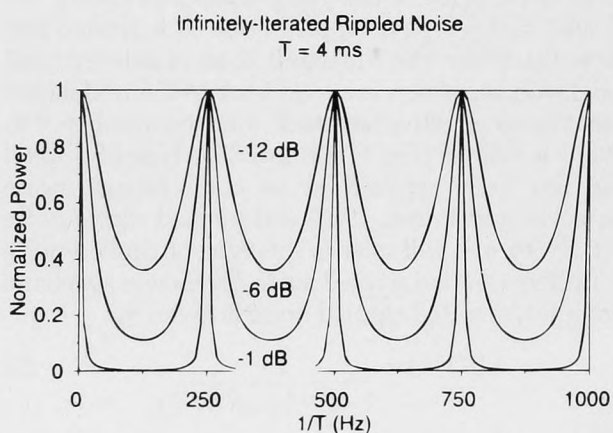


FIGURE 3 Spectra expressed in linear power units for infinitely-iterated rippled noise with a delay of 4 ms for gains of -1 dB, -6 dB, and -12 dB.

the delayed repetition of the noise is added to the undelayed noise, the spectral peaks are harmonically related. If the delayed repetition is inverted before being added back to the undelayed noise (i.e., subtracted), then the spectral valleys occur at integer multiples of $1/T$ and the inharmonic condition is produced. In this article we will only be concerned with the harmonic conditions of rippled noises.

The pitch of rippled noise is often referred to as repetition pitch. Pitch matching studies have shown that harmonic rippled noises have pitches equal to $1/T$ (Bilsen, 1970; Yost *et al.*, 1978). As the delayed repetition is attenuated ($g < 1$) relative to the undelayed noise, the spectral modulation depth decreases and the saliency of the repetition pitch weakens. The relationship between pitch strength and gain has been used to determine the sensitivity of human subjects for different repetition pitches. These studies have shown that human subjects are most sensitive to repetition pitches between 100 and 1000 Hz, which corresponds to delays of 10 to 1 ms, respectively (Bilsen and Ritsma, 1970; Yost and Hill, 1978). In addition, sensitivity is independent of overall level above about 20 dB sensation level (SL) (Bilsen and Ritsma, 1970; Yost and Hill, 1978). Pitch strength is also related to the number of iterations (Yost *et al.*, 1978) so that infinitely-iterated rippled noise has a much more salient pitch than 1-iterated rippled noise.

Animal psychophysical data not only provide a conceptual bridge between human psychophysical data and neurophysiological data, but also provide a biological context in which human psychophysical studies can be placed (see Fay, 1988a). Animal psychophysical studies using rippled noise signals have been carried out only for the goldfish (Fay *et al.*, 1983). Previous psychophysical studies in mammals have used rippled noises as maskers for tones in order to derive the shape and bandwidth of auditory filters (cat: Pickles, 1979; guinea pig: Evans *et al.*, 1992; chinchilla: Niemiec *et al.*, 1992), but have not used rippled noises as signals. In this article we describe psychophysical data obtained from the chinchilla using rippled noise signals. Chinchillas are an ideal animal model for these studies, because they can be readily trained using operant conditioning techniques, and a variety of psychophysical data suggest that they process sounds in a manner similar to human listeners (Salvi *et al.*, 1982; Heffner and Heffner, 1991; Niemiec *et al.*, 1992; Shofner *et al.*, 1993; Shofner and Sheft, 1994). Portions of the data in this article were presented in preliminary form (Shofner and Yost, 1994).

METHODS

Subjects

Six adult chinchillas (*Chinchilla lanigera*) served as subjects in these experiments. All chinchillas were in good

health throughout the period of data collection. Animals were housed in a room where the background noise level is 60 dBA sound pressure level (SPL); none of the chinchillas had a history of exposure to high noise levels. Chinchillas were maintained at a body weight of approximately 400 g. Chinchillas 3, 7, 8, 9, and 10 had served in previous psychophysical experiments (Niemic *et al.*, 1992; Shofner *et al.*, 1993; Shofner and Sheft, 1994) chinchilla 11 was a newly trained animal without previous experience. Although the primary focus of the present study was to obtain psychophysical data from the chinchilla, experiments using four human subjects were also carried out for a few select stimulus conditions. Three human listeners were undergraduate students who had previous experience as subjects in psychophysical experiments; the fourth human subject was the first author (subject BS). The data obtained from human subjects merely served as procedural controls.

Apparatus

Noise was generated with a Wavetek VCG/Noise generator (Model 132) where the sequence length was set to $2^{20} - 1$ at a sampling rate of 160 kHz. These parameters resulted in a noise having a 10 kHz bandwidth that repeated itself every 6.55 s. The output of the noise was divided into two channels, namely, channels A and B. For generating 1-iterated rippled noise, the outputs were fed into an Eventide Precision Delay Line (model PD 860) where channel B was delayed relative to channel A. This delay line uses a sampling rate of 62.5 kHz. The outputs of the two channels were then low-passed filtered separately at a cutoff frequency of 15 kHz. (FT5 Tucker-Davis Technologies). The gain of the delayed repetition (channel B) was varied using a programmable attenuator (PA4 Tucker-Davis Technologies), and these two channels were then added together (SM3 Tucker-Davis Technologies). For generating infinitely-iterated rippled noise, the delayed repetition was added to the wideband noise through a positive feedback circuit. In both of the above circuits, when the gain of channel B was at -100 dB attenuation, the summed output was a flat-spectrum wideband noise (i.e., essentially the input noise). The summed output was attenuated and amplified (Bryston Power Amplifier) and played through either a loudspeaker or headphones. In addition to generating a noise having a rippled spectrum, these two circuits also generate an increase in the overall level of the rippled noise relative to that of the original wideband noise. The increase in overall level was attenuated before the rippled noise was played to the subject, so that the wideband noise and rippled noise had equal root-mean-squared (rms) voltages. Thus, subjects could not use a loudness cue during the presentation of rippled noise. Since all rippled noises used in this study were generated by adding the delayed repetition

of the noise back to the undelayed noise, the resulting repetition pitches correspond to $1/T$. The delays used to generate rippled noises were 2, 4, and 8 ms. The sound level was monitored by placing a condenser microphone (Ivie 1133 free field microphone) in the approximate position of an animal's head and measuring the A-weighted sound pressure level with a sound level meter (Ivie IE-30A Audio Spectrum Analyzer). The overall levels of the wideband noise presented to the chinchillas were 64, 74, and 84 dB SPL. Data were obtained for human subjects for one level; the rms voltage to the headphones was equal to the rms voltage at the input to the loudspeaker that produced a sound level of 74 dB SPL.

Behavioral Paradigm

During a testing session, chinchillas were placed inside of a cage (16 inches long, 12 inches high and 10 inches wide) in a single-walled, sound-attenuating animal test chamber (Industrial Acoustics). Animals were not restrained and were free to roam around the cage. At one end of the cage was a pellet dispenser with a reward chute attached to a response lever. A loudspeaker (Realistic Minimus 7) was placed near the pellet dispenser approximately 6 inches in the front of the animal at approximately 30° to the right of center. The ceiling and walls of the sound-attenuating chamber were lined with acoustic foam (Azonic). Human listeners sat in a doubled-walled, sound-attenuating chamber (Tracoustics) and listened diotically through headphones (Stax SR-5).

Wideband noise bursts (500 ms with 10 ms rise/fall times) were presented continually once per second throughout the testing session regardless of whether the animal initiated a trial. The subject initiated a trial by pressing down on a response lever. After a trial was initiated, the noise bursts continued for 1 to 5 bursts for each trial. These additional 1 to 5 noise bursts resulted in a hold time of 1150 to 5150 ms. The number of noise bursts that continued after a trial was initiated varied randomly for each trial and was determined from a rectangular probability distribution. If the subject released the lever before the random hold time, the procedure was halted and the computer waited for the subject to reinitiate the trial by pressing the lever. If the subject held the response lever down for the duration of the hold time, then either a signal trial or a blank trial (nonsignal trial) was presented. A signal trial consisted of two bursts of rippled noise, and a blank trial consisted of two additional bursts of the flat-spectrum, wideband noise. The response window was coincident with the duration of the signal/blank trial, but began 150 ms after the onset of the first rippled/wideband noise burst and lasted until the onset of the next wideband noise burst; consequently, the duration of the response window was 1850 ms. Whenever the subject released the lever dur-

ing the response window, the release was scored as a "yes." If the subject released the lever during a signal trial, then this "yes" response was treated as a hit, whereas a lever release during a blank trial was treated as a false alarm. If the subject continued to hold the lever down for the duration of the response window, the response was treated as a correct rejection. Chinchillas were rewarded with food pellets (Noyes; Formula N) for hits and correct rejections, whereas human subjects received feedback through a red light-emitting diode for hits and correct rejections.

The method of constant stimuli was used to generate psychometric functions. Subjects ran in a block of 40 trials. A block consisted of nine different gain values: four trials each at eight different gain values, and eight trials at a gain of -100 dB. As previously described, the gain at -100 dB generated the flat-spectrum wideband noise, and these eight trials per block (20% of the trials) were the blank trials used to estimate false alarm rates. Of the eight different gain values, a gain of -1 dB was presented to all subjects; this gain produced an infinitely-iterated rippled noise having the largest spectral modulation depth that could be generated without causing the positive feedback circuit to oscillate. Preliminary observations were carried out to determine a range of gain values that would result in data points falling on the rising portion of the psychometric function in a monotonic fashion. The values of gain were presented randomly for each block. The final nine point psychometric functions were based on a minimum of 50 blocks, or 2000 total trials. These psychometric functions were fit with modified logistic functions having the form:

$$p(\text{yes}) = F + (H_o - F) \left(\frac{H_o}{H_o + \exp[-k(x - m)]} \right) \quad (3)$$

where $p(\text{yes})$ is the proportion of "yes" responses, F is the proportion of false alarms, H_o is the proportion of hits at the largest gain, k is the slope parameter, m is the mean of the function, and x is the gain in dB attenuation. The largest gain used for 1-iterated rippled noise experiments was 0 dB and was -1 dB for experiments using infinitely-iterated rippled noise.

RESULTS

Infinitely-Iterated Rippled Noise Experiments

Chinchillas were initially trained to discriminate infinitely-iterated rippled noise from flat-spectrum wideband noise. Infinitely-iterated rippled noise was used as a training stimulus, because it has a more salient repetition pitch than does 1-iterated rippled noise. Monotonic psychometric functions for the discrimination of infinitely-iterated rippled noise from wideband noise were obtained from chinchillas and human subjects for all conditions studied. Figures 4 and 5 show

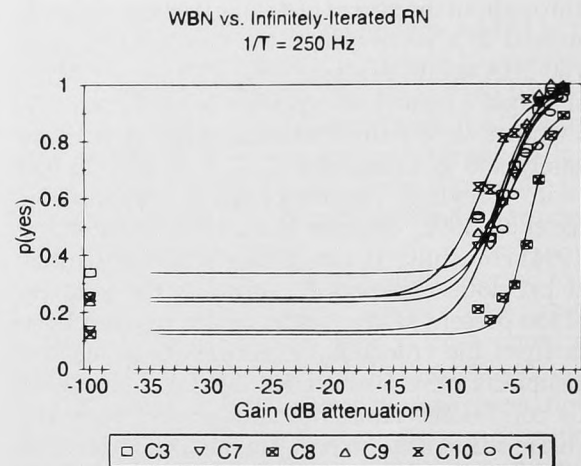


FIGURE 4 Psychometric functions for six chinchillas for the discrimination of infinitely-iterated rippled noise from flat-spectrum wideband noise. The delay of the rippled noise is 4 ms. The symbols show the proportion of "yes" responses obtained from the behavioral paradigm; the solid lines show the best fitting modified logistic functions. The $p(\text{yes})$ at -100 dB are estimates of the false alarm rate, and other values of $p(\text{yes})$ are estimates of hit rates.

psychometric functions obtained from six chinchillas and four human subjects, respectively, for infinitely-iterated rippled noise having a delay of 4 ms. The $p(\text{yes})$ at -100 dB is an estimate of a subject's false alarm rate, whereas $p(\text{yes})$ at all other gains are estimates of hit rates. The modified logistic functions provide excellent fits to the behavioral data; values of the coefficients of determination (R^2) are greater than 0.9. At a delay of 4 ms, the slope parameter, k , obtained from the best-fitting logistic functions ranged from 0.499 to 1.003 in chinchillas and from 0.379 to 0.755 in human subjects. The average k was 0.672 for the chinchillas and 0.564 for the human subjects; these average slopes are not significantly different ($t = 0.993$; $t < t_{0.05(2),8}$).

As described in Methods, chinchillas listened to the sound played through a loudspeaker, and human subjects listened over headphones. As a procedural control, a calibration microphone was placed in the animal test chamber at the position where a chinchilla's head would be during a test session. The output of the microphone was amplified and then played over the headphones to one human subject (subject BS). In this test condition, the subject "listened" to the sound field produced inside of the animal test chamber. The psychometric function for this condition was essentially identical to the subject's original psychometric function (Fig. 5).

The psychometric functions obtained from chinchillas at a delay of 4 ms are shifted to higher gains than those obtained from human subjects, suggesting that chinchillas are less sensitive than are human subjects. It can be observed in Figures 4 and 5 that human subjects tend to adopt more stringent criteria than do chinchillas, since the false alarm rates in human subjects are lower

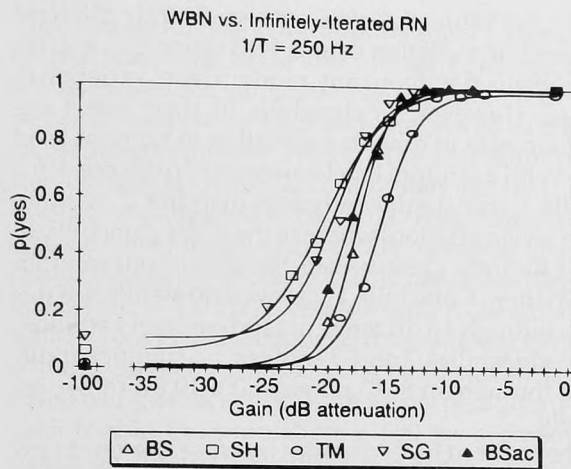


FIGURE 5 Psychometric functions for four human subjects for the discrimination of infinitely-iterated rippled noise from flat-spectrum wideband noise. The delay of the rippled noise is 4 ms. The symbols show the proportion of "yes" responses obtained from the behavioral paradigm; the solid lines show the best fitting modified logistic functions. The filled triangles show the $p(\text{yes})$ responses obtained when subject BS listened over headphones to the sound field produced by the loudspeaker in the animal test chamber (BSac). The output of the calibration microphone was amplified and adjusted so that the rms voltage into the headphones was equal to the rms voltage into the headphones that was used when the subject listened over headphones alone.

than those in chinchillas. To obtain an estimate of sensitivity that is independent of response bias or criterion, estimates of d' were obtained from the best-fitting modified logistic functions using $z(H)-z(F)$. The values of $z(H)$ and $z(F)$ were computed from an algorithm described by Macmillan and Creelman (1991). Figure 6 compares psychometric functions expressed as d' for chinchillas and human subjects. Sensitivity or "threshold" was defined as the gain where d' is 1. At a d' of 1, the gains for chinchillas ranged from -4.3 to -7.7 dB attenuation and ranged from -19.4 to -23.3 dB attenuation in human subjects. The average gains were -5.9 dB for chinchillas and -21.4 dB for human subjects; the average gain at 4 ms delay was significantly higher in chinchillas than in human subjects ($t = 16.859$; $t > t_{0.0005(1),8}$). Sensitivity appears to be independent of overall level from 64 to 84 dB SPL (Fig. 7). For the four chinchillas tested over a 20 dB range of overall levels, there is at most a change in "threshold" gain of 1.3 dB. Linear regressions through the average values for delays of 4 and 2 ms give slopes of 0.032 and -0.068, respectively. These slopes are not significantly different from a slope of 0 ($t(4 \text{ ms}) = 0.731$; $t < t_{0.05(1),1}$ and $t(2 \text{ ms}) = -1.199$; $t < t_{0.05(1),1}$). Figure 8 shows the gain in dB attenuation at d' of 1 as a function of delay for chinchillas and human subjects for delays of 2, 4, and 8 ms. Sensitivity also appears to be independent of the delay (i.e., of the repetition pitch, $1/T$); the slope of the linear regression through the av-

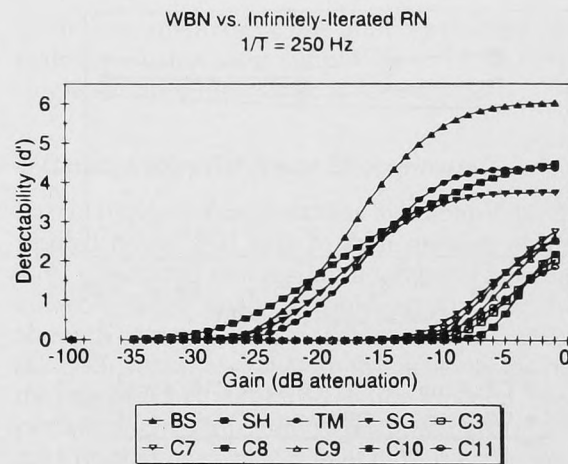


FIGURE 6 Comparison of psychometric functions for the discrimination of infinitely-iterated rippled noise from flat-spectrum wideband noise for chinchillas (open symbols) and human subjects (filled symbols). Symbols do not indicate actual data points, but are used only to differentiate curves among subjects. Behavioral performance is expressed as d' .

erage gain values is -0.01 and is not significantly different from a slope of 0 ($t = -4.200$; $t < t_{0.05(1),1}$). Human subjects are more sensitive than chinchillas by approximately 15 dB at all three delays.

Effects of Random Overall Level

As previously described in the Methods, the increase in the overall level of the infinitely-iterated rippled noise that is produced during the generation of the rippled noise was eliminated by attenuating the rippled noise by an appropriate amount so that a loudness cue could not be used by the chinchillas during a signal trial. However, this does not eliminate the possibility that the chinchilla could monitor a single auditory filter having a center frequency corresponding to one of the spectral peaks of the rippled noise and "listen" for intensity increases within that auditory channel. In an effort to reduce the possibility of monitoring intensity increases within a single auditory channel, psychometric functions were obtained for the discrimination of infinitely-iterated rippled noise from wideband noise for five chinchillas in which the overall level during the signal/blank trial varied randomly for each trial. The attenuation for a given signal trial was equal to the attenuation required to eliminate the overall level increase produced during the rippled noise generation plus or minus some additional attenuation to produce a random change in overall level. For a blank trial, there was no overall level increase to eliminate, so the random change in level was just the additional plus or minus attenuation. The range of random overall level variation was 0 to 10 dB. A range of 4 dB in overall level corresponds to random level variations of ± 2 dB after elimination of the increase in overall level produced during

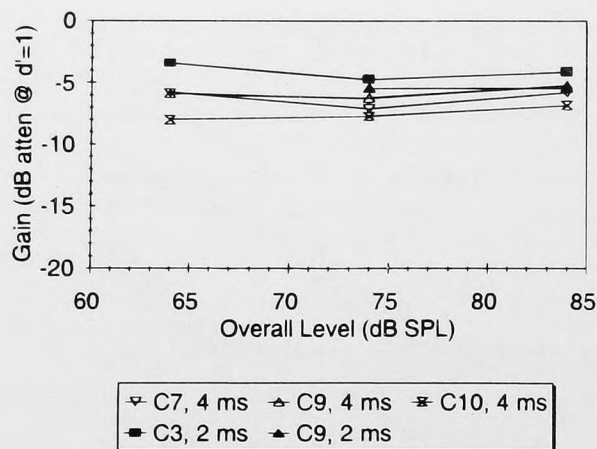


FIGURE 7 Sensitivity at d' of 1 as a function of overall level for four chinchillas for the discrimination of infinitely-iterated rippled noise from flat-spectrum wideband noise. Open symbols are for a 4 ms delay, and closed symbols are for a 2 ms delay.

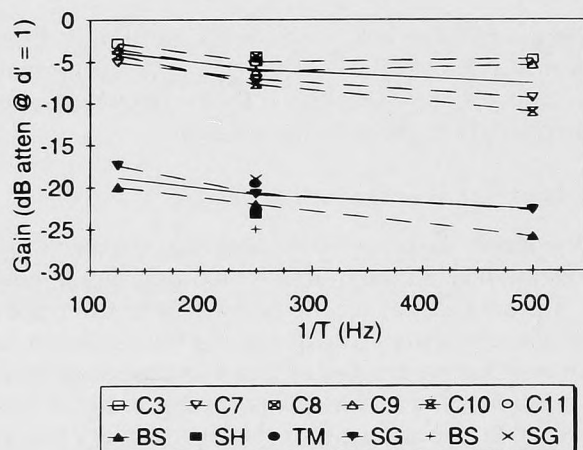


FIGURE 8 Sensitivity at d' of 1 for the discrimination of infinitely-iterated rippled noise from flat-spectrum wideband noise as a function of repetition pitch ($1/T$) for six chinchillas (open symbols, dashed lines) and four human subjects (filled symbols, solid lines). The upper solid line shows the average gains for the chinchillas, and the lower solid line shows the chinchilla average gains displaced 15 dB. The \times and $+$ symbols are sensitivity estimates from two human subjects for the discrimination of 1-iterated rippled noise from wideband noise.

rippled noise generation. The attenuation used to produce the random level variations was determined from a rectangular probability distribution.

Figure 9 shows the behavioral performances of five chinchillas for infinitely-iterated rippled noise with a gain of -6 dB attenuation (i.e., gain in the rippled noise network) and a delay of 4 ms. A change in behavioral performance was determined using the test of significance of d' values as described by Gourevitch and Galanter (1967). Figure 9 shows that, for chinchillas 3, 7,

9, and 11, the value of d' was not significantly different with a random variation over a 4 dB range (i.e., ± 2 dB) from d' obtained without any random level variation (0 dB range). However, for chinchilla 10, there was a significant increase in d' with a variation in random level of 4 dB. With a random level variation of 6 dB, the d' for chinchilla 3 was significantly less than the d' with no random level variation, whereas the d' for chinchilla 10 was significantly greater than the d' without random level variation. Chinchilla 11 showed no significant differences through a 6 dB range of random level variation, whereas chinchillas 7 and 9 showed no significant differences through an 8 dB range and a 10 dB range, respectively.

As the random level changes increase, we might expect the false alarm rates ($p(\text{FA})$) and the hit rates ($p(\text{H})$) of the animals to increase, if the animals respond to the change in level from the hold time noise bursts. Table I shows the values of $p(\text{H})$ at a gain of -6 dB and $p(\text{FA})$ that were used to compute the d' s shown in Figure 9. These data show that chinchilla 11 was the only animal in which both the $p(\text{H})$ and $p(\text{FA})$ increased when random level variations were introduced. The decline in behavioral performance with random level variations for chinchilla 3 is attributed to a decline in $p(\text{H})$, whereas the $p(\text{FA})$ remained relatively constant. The increase in performance observed for chinchilla 10 with random level variations is attributed to a decrease in $p(\text{FA})$, whereas $p(\text{H})$ increased slightly. The relatively constant behavioral performances of chinchillas 7 and 9 reflects relatively constant $p(\text{FA})$ and $p(\text{H})$ across random level ranges.

To gain some insight into how much random level variation is necessary to reduce the performance of an ideal observer that is monitoring a single auditory channel for increases in the intensity, the behavioral proce-

TABLE I
 $p(\text{Hits})$ at -6 dB Gain and $p(\text{False Alarms})$
Obtained with Random Variations in Overall Level

Chinchilla	Range of Random Level Variation (dB)				
	0	4	6	8	10
C3					
$p(\text{FA})$	0.3382	0.3135	0.3442		
$p(\text{H})$	0.6097	0.5472	0.5153		
C7					
$p(\text{FA})$	0.1373	0.1563	0.2264	0.1898	0.1875
$p(\text{H})$	0.6078	0.7309	0.6402	0.6123	0.5299
C9					
$p(\text{FA})$	0.2377	0.1648	0.2014	0.2105	0.2754
$p(\text{H})$	0.6403	0.4623	0.5846	0.6173	0.6171
C10					
$p(\text{FA})$	0.2524	0.0900	0.1851		
$p(\text{H})$	0.7872	0.8348	0.8550		
C11					
$p(\text{FA})$	0.2524	0.4159	0.4150		
$p(\text{H})$	0.5651	0.7340	0.7935		

ture was simulated in a computer model. Five seconds each of wideband noise and infinitely-iterated rippled noises of various gains that were generated in the behavioral setup were digitized and stored as files on a MassComp computer system. The rms amplitudes of the wideband noise and infinitely-iterated rippled noises were adjusted to be equal. These equal rms amplitude waveforms were digitally bandpass filtered at a center frequency of 500 Hz. This bandpass filter had a 60 Hz (470 to 530 Hz) passband with rectangular skirts, which is equal to the equivalent rectangular bandwidth of the average chinchilla auditory filter at 500 Hz as measured using a notched-noise masking paradigm [15]. For each trial in the simulation, a 500 ms segment of the bandpass filtered wideband noise was obtained randomly from the 5 s sample, and a random 500 ms segment of a bandpass filtered infinitely-iterated rippled noise was also obtained from the 5 s sample. The presentation of stimuli in the simulation was analogous to that in the behavioral task in that a wideband noise was presented and followed by either a signal or a blank trial. A signal trial was an infinitely-iterated rippled noise, whereas a blank trial was another random segment of wideband noise. The first segment of filtered wideband noise was analogous to the wideband noise bursts during the random hold time. For a given trial, the rms amplitudes were computed for the first wideband noise and for the signal or blank trial. If the rms amplitude of the signal/blank trial was larger than the rms amplitude of the first wideband noise segment, then a "yes" response was scored. As in the behavioral procedure, "yes" responses for a signal trial were treated as hits, and "yes" responses for a blank trial were treated as false alarms. Nine point psychometric functions were generated having a total of 200 trials at each point corresponding to signal trials and 400 trials for the blank trials. This psychometric function is equivalent to a behaviorally generated psychometric function based on 50 blocks (see Methods). The $p(\text{yes})$ responses obtained from the model were first fit with the modified logistic function, and then this psychometric function was converted into estimates of d' . That is, the data obtained from the simulation were treated identically to the behavioral data.

Figure 9 also shows the performance of the above model as measured by d' for the same conditions described for the chinchillas. As the amount of random level variation is increased from a range of 0 to 8 dB, there is a systematic decrease in d' . The decrease in d' for a variation in random level of 4 dB is not statistically significant from the d' with no random level variation. However, the decrease in d' for variations in random level of 6 and 8 dB are both significantly less than the d' obtained for no random level variation. Thus, in the model, a significant decrease in performance is reached with a 6 dB variation in random level. Since only chinchilla 3 showed this pattern of change in d' with amount

of random attenuation, it is unlikely that the other animals were using some simple aspect of the output of a single auditory filter as a cue for detection.

1-Iterated Rippled Noise Experiments

Recent psychophysical studies in human subjects using rippled noises that vary in their number of iterations have concluded that a simple temporal rule based on autocorrelation analysis could account for the pitch strength of rippled noise (Patterson *et al.*, 1993; Yost *et al.*, 1993; Yost *et al.*, 1994). In this scheme, the height of the first peak in the autocorrelation function determines pitch strength. If the autocorrelation function for 1-iterated rippled noise at a gain of 0 dB is compared to the autocorrelation function of infinitely-iterated rippled noise with a gain of -6 dB, it can be observed that the peaks at the delay, T , are equal in height, suggesting that the pitch strengths of these two rippled noises are equal. Two rippled noises, generated with the same delay and yielding the same first autocorrelation functions peak heights, are almost impossible to discriminate from each other by human listeners (Yost *et al.*, 1994). To provide some insight into whether the height of the first peak in the autocorrelation function could also account for behavioral sensitivity in the chinchilla, we compared the sensitivity of chinchillas for 1-iterated rippled noise with a gain of 0 dB to their sensitivity for infinitely-iterated rippled noise with a gain of -6 dB. If the height of the first peak in the autocorrelation function is an important parameter for pitch strength in chinchillas, then we would expect behavioral sensitivities to be equal for 1-iterated rippled noise with a gain of 0 dB and infinitely-iterated rippled noise with a gain of -6 dB. Rather than having chinchillas attempt to discriminate between two sounds (1-iterated and infinitely-iterated rippled noises) that are probably very difficult to discriminate from each other, the rippled noise versus flat-spectrum noise discrimination experiments were conducted using 1-iterated rippled noise with a gain of 0 dB and compared to the behavioral performance previously observed using infinitely-iterated rippled noise with a gain of -6 dB. If for each chinchilla tested, the discrimination between flat-spectrum noise and 1-iterated rippled noise with a gain of 0 dB produced the same level of performance as that between flat-spectrum noise and infinitely-iterated rippled noise with a gain of -6 dB, then it seems reasonable to assume that the chinchillas might have difficulty discriminating the 1-iterated rippled noise from the infinitely-iterated rippled noise as human listeners do.

Four animals were tested in blocks of 40 trials in which half of the trials were wideband noise and half of the trials were 1-iterated rippled noise with a gain of 0 dB. Thus, half of the trials estimated hit rates, and half of the trials estimated false alarm rates. The gain of 0 dB produces the strongest repetition pitch for 1-iterated rip-

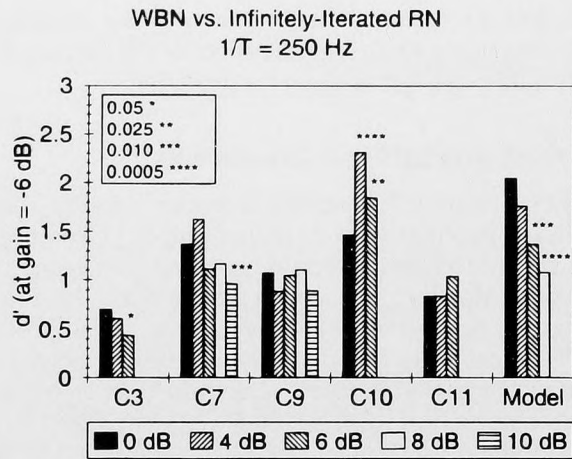


FIGURE 9 Behavioral performance as measured by d' for the discrimination of infinitely-iterated rippled noise at a gain of -6 dB from flat-spectrum wideband noise for five chinchillas and a computer simulation (see text for explanation). Random variations in overall level ranged from 0 dB (no random level variations) to 10 dB (random level variations of ± 5 dB). The d' at -6 dB was computed from the best fitting logistic functions. The delay was 4 ms. Significance levels are shown.

TABLE II
 d' for the Discrimination of 1-Iterated Rippled Noise from Wideband Noise*

Delay (ms)	2	4
Chinchilla	d'^{\dagger}	d'^{\dagger}
C3	0.271 (880)	0.213 (1080)
C7	1.964 (600)	1.505 (680)
C9	0.678 (520)	0.692 (760)
C10	3.126 (640)	1.823 (600)

*Gain of the delayed repetition = 0 dB.

\dagger The numbers in parentheses show the total number of trials used to estimate d' .

pled noise. The overall level increase produced by the generation of the rippled noise was eliminated as previously described, but no random variations in overall level were introduced. Table II shows the behavioral performances of the four chinchillas for delays of 2 and 4 ms as measured by d' . The numbers in parentheses indicate the total number of trials used to compute d' . It can be seen that C3 essentially cannot discriminate the 1-iterated rippled noise from wideband noise; the behavioral performance of C9 is below d' of 1; the behavioral performances of C7 and C10 are above d' of 1.

Figure 10 shows the d' obtained for the 1-iterated rippled noise at a gain of 0 dB as a function of the d' obtained from the psychometric functions for the infinitely-iterated rippled noise at a gain of -6 dB. The open symbols are data for a delay of 4 ms, and the filled symbols are for a delay of 2 ms. Each data point at a given delay is from one of the four animals. The solid line has a slope of 1 and a y-intercept through the ori-

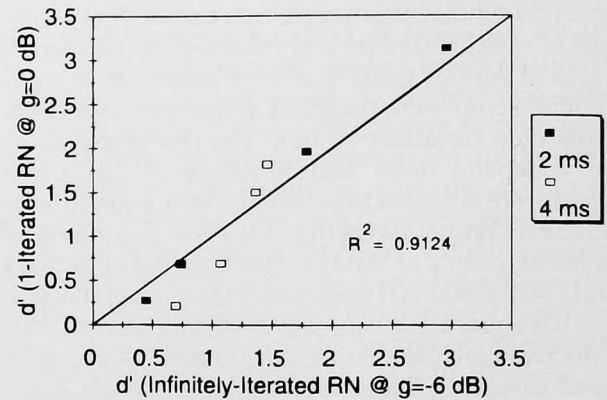


FIGURE 10 Comparison of the behavioral performance of four chinchillas for the discrimination of 1-iterated rippled noise with a gain of 0 dB from wideband noise and the discrimination of infinitely-iterated rippled noise at a gain of -6 dB from wideband noise. Filled squares are data points for a 2 ms delay; open squares are for a 4 ms delay. Each data point for a given delay is from one animal. The diagonal line has a slope of 1 and a y-intercept of 0 and indicates equal behavioral performance for the two rippled noises. The coefficient of determination (R^2) of the scatter of data points around this line is 0.9124.

gin. This line represents equal behavioral performance, that is, the line indicates that the behavioral performance for the discrimination of 1-iterated rippled noise from wideband noise is the same as the performance for the discrimination of infinitely-iterated rippled noise from wideband noise. The empirical values of d' are closely scattered around this line (Fig. 10). Although this line is not a linear regression to the data points, the R^2 is 0.9124, that is, this line accounts for 91.24% of the variance of the data points. Plots similar to Figure 10 were also made using infinitely-iterated rippled noises at gains of -8 , -7 , -5 , and -4 dB. Table III summarizes the values of R^2 for a line of unity slope for these conditions. It can be seen that the stimulus condition in which the data are most highly correlated around a line representing equal behavioral performance is for infinitely-iterated rippled noise at a gain of -6 dB.

DISCUSSION

Previous psychophysical experiments in mammals have not used rippled noises as signals per se, but instead have used rippled noises as maskers for the detection of tonal signals (Pickles, 1979; Evans *et al.*, 1992; Niemiec *et al.*, 1992). Psychophysical experiments have been carried out investigating the ability of the goldfish to discriminate different rippled noises (Fay *et al.*, 1983). The present results describe the ability of the chinchilla to discriminate various rippled-spectrum noises from flat-spectrum wideband noise. However, before we discuss the psychophysical performance of the chinchilla, a discussion of the validity of the behavioral paradigm is beneficial.

TABLE III

Coefficients of Determination for a Line Showing Equal Behavioral Performance for the Discrimination of Infinitely-Iterated Rippled Noises from Wideband Noise and the Discrimination of 1-Iterated Rippled Noise at a Gain of 0 dB from Wideband Noise

Gain (dB) of Infinitely-Iterated Rippled Noise	R ²
-4	0.3590
-5	0.7600
-6	0.9124
-7	0.8456
-8	0.6259

In the behavioral paradigm, wideband noise bursts were continually presented, and a trial was initiated by the subject by pressing down on a response lever. A variable random hold time occurred before a signal or blank trial was presented. Consequently, the signal trial was not marked or defined. Moreover, a signal trial did not consist of one burst of rippled noise, but consisted of two bursts of rippled noise; a blank trial consisted of two additional bursts of wideband noise. A "yes" response (i.e., release of the lever) had to occur within a specified time window. Although hits and false alarms were estimated from this paradigm and d' was computed, the above paradigm is not a single-interval, forced-choice design in which the listening interval is marked. Therefore, in the strictest sense the underlying assumptions for computing d' have been violated. To test the validity of the above behavioral paradigm, two human subjects were also tested in the same behavioral procedure using 1-iterated rippled noise with a delay of 4 ms (repetition pitch of 250 Hz). The sensitivity for the discrimination of 1-iterated rippled noise from wideband noise for these two subjects (see Fig. 8) falls within the ranges of sensitivity reported for human subjects using same-different or forced-choice paradigms (Bilsen and Ritsma, 1970; Buunen, 1980; Yost and Moore, 1987). Thus, the present behavioral paradigm appears to produce valid estimates of sensitivity.

Another difference in the present study and previous human psychophysical studies is that the sounds are presented to the chinchillas through a loudspeaker in the free field, whereas stimulus presentation in human subjects is over headphones. Concerns over comparisons of animal psychophysical data obtained using free-field stimulus presentation with human psychophysical data obtained using headphones have recently been raised by Long (1994). To control for these differences, psychometric functions for infinitely-iterated rippled noise at a delay of 4 ms were obtained for one human subject under headphones alone and then under conditions in which the subject listened over headphones to the sound field produced in the animal test chamber. These two psychometric functions were

essentially identical, suggesting that the higher gains obtained for the chinchillas do reflect their sensitivity for the repetition pitch of infinitely-iterated rippled noise and are not attributed merely to a difference in the sound fields produced by the headphones and loudspeaker. There is a binaural difference in the above comparison in that dichotic cues from pinna filtering were available to the chinchillas, whereas the human subject was still receiving diotic input. However, any binaural cues would be present for both wideband noise and rippled noise; it is not at all clear what kind of dichotic cues due to pinna filtering would be present for rippled noise but not present for wideband noise.

Another potential difference that could account for the discrepancy in sensitivity between the human and chinchilla psychophysical data is that the human subjects were more motivated to attend to the rippled noise stimuli than were the chinchillas. In the behavioral procedure, the animal initiates a trial by pressing down and holding a response lever. That is, the animal makes an operant response when it is ready to begin "listening" for the signal. Thus, it seems that the attention levels of the chinchillas should be high. However, if there are other variables that may have led to a lower motivational state, then these variables would probably apply to all conditions tested. That is, such variables may have led to poorer discrimination performance in general, but could not explain differences among the many conditions.

The results of this study show that chinchillas are able to discriminate a rippled-spectrum noise from a flat-spectrum noise. Individual differences in sensitivity exist across chinchillas. These differences in sensitivity are also observed for human subjects (see Fig. 6; also see Figure 5 of Yost and Hill (1978)). It is interesting to note, that in the present study, C3 is consistently insensitive compared to the other animals, whereas C10 is consistently more sensitive. This lack of sensitivity of C3 presumably reflects this animal's perception of repetition pitch rather than a general hearing loss, because when behavioral performances for C3 and C10 are compared for noise intensity discrimination, it is C3 that is consistently more sensitive than C10 (Shofner *et al.*, 1993; Shofner and Sheft, 1994).

The present study shows that chinchillas are less sensitive in discriminating rippled noise from flat-spectrum noise than are human subjects. For example, for infinitely-iterated rippled noise with a repetition pitch of 250 Hz (i.e., a delay of 4 ms), the average gain at d' of 1 for chinchillas is -5.9 dB attenuation, whereas in human subjects, the average gain is -21.4 dB. The spectral modulation depth as described as the peak-to-valley (P/V) ratio (see Bilsen and Raatgever, 1983) in the power spectrum, P/V in dB, is given by:

$$\frac{P}{V} \text{ (dB)} = 10 \log \left(\frac{(1+g)^2}{(1-g)^2} \right) \quad (4)$$

The peak-to-valley ratios that correspond to these average gains are 9.4 dB for chinchillas and 1.5 dB for human subjects. That is, human subjects can just discriminate a 1.5 dB ripple from a flat-spectrum, whereas chinchillas can just discriminate a spectral ripple of 9.4 dB. Discrimination thresholds are often higher in chinchillas than in human subjects (Fay, 1988b). It is interesting to note, however, that the slopes of the psychometric functions for the discrimination of infinitely-iterated rippled noise from flat-spectrum noise are the same in chinchillas and human subjects, suggesting that the neural processing mechanisms underlying the discrimination of rippled noise from wideband noise are fundamentally the same in chinchillas and human subjects. There appears to be a relatively constant difference in sensitivity between chinchillas and human subjects of about 15 dB (see Fig. 8). An upward shift in the psychometric function from the ideal observer is often attributed to internal noise (Green, 1960a; Green, 1960b). Thus, the amount of internal noise present in the processing of rippled noise is presumably higher in chinchillas than in human subjects; in other words, the human auditory system is more efficient than the chinchilla auditory system in extracting the signal from this internal noise.

There are several possibilities in terms of how the chinchilla auditory system processes the rippled noise. One possibility is that the chinchilla auditory system monitors the output of a single auditory filter that is centered on a spectral peak of the rippled noise. If the stimulus intensity at the output of the filter is larger for the rippled noise than for the flat-spectrum noise, the behavioral response would be "yes the signal is rippled noise." The results of the computer simulation of discrimination of infinitely-iterated rippled noise from flat-spectrum noise showed that the performance of a detector, which monitors the output of a single auditory filter for intensity increases, declines as the range of random level variation is increased. The decline in performance became statistically significant when the range of random level variation was 6 dB. With the exception of chinchilla 3, the behavioral performances of the other four chinchillas do not follow the predictions of this model. Thus, we argue that it is unlikely that the chinchillas discriminate the rippled noise from the flat-spectrum noise based on the output of a single auditory filter. That is, some form of across-channel listening is presumably involved.

One type of across-channel listening in the spectral domain is to measure the peak-to-valley ratio found in the excitation pattern. If the auditory filters of chinchillas are broad in comparison to those in human subjects, then one might predict that the peak-to-valley ratio for a given rippled noise excitation pattern would be less in chinchillas than in human subjects. However, recent evidence suggests that the shapes and bandwidths of chinchilla auditory filters are approximately the same as those for human subjects (Niemic *et al.*, 1992), sug-

gesting that the excitation patterns for a given rippled noise should be similar for chinchillas and human subjects. If this is the case, then the predicted performance for the discrimination of rippled noise from flat-spectrum noise should be similar in chinchillas and human subjects. Based simply on the shape and bandwidth of the auditory filters, it is not clear how the internal noise in chinchillas manifests itself to be greater than the internal noise in human subjects.

Across-channel listening in the temporal domain has been described in models based on autocorrelation analysis (Wightman, 1973; Yost and Hill, 1979; Yost, 1982; Patterson, 1987; Meddis and Hewitt, 1991). In this scheme autocorrelation functions are based on the wideband spectrum of the stimulus. Recent psychophysical studies in human subjects using rippled noises that vary in their number of iterations and gains have concluded that pitch strength can be accounted for by a simple temporal rule based on autocorrelation analysis (Patterson *et al.*, 1993; Yost *et al.*, 1993; Yost *et al.*, 1994). Comparison of the behavioral performances of the chinchillas for the discrimination of 1-iterated rippled noise from wideband noise with the discrimination of infinitely-iterated rippled noise from wideband noise may give some insights into whether a similar temporal rule based on autocorrelation is viable in chinchillas. We found to a first approximation that the behavioral performances of the chinchillas for the discrimination of infinitely-iterated rippled noise with a gain of -6 dB from wideband noise was similar to the discrimination of 1-iterated rippled noise with a gain of 0 dB from wideband noise (Fig. 10, Table III). Figure 11 shows the spectra and autocorrelation functions for these two rippled noises and a wideband noise. There are differences in the shapes of the two rippled noise spectra in that the peaks are sharper in the spectrum of the infinitely-iterated rippled noise than for the 1-iterated rippled noise, whereas the peak-to-valley ratio of the 1-iterated rippled noise is larger than that of the infinitely-iterated rippled noise. There is not an obvious common feature in the spectral domain for these two rippled noises that could account for the equal discriminability from the wideband noise. However, there is an obvious common feature in the autocorrelation functions; namely, the height of the first peak at the delay of 4 ms is about equal in both cases. The only condition in which the heights of the peaks in the autocorrelation function for 1-iterated rippled noise and infinitely-iterated rippled noise are the same is when the infinitely-iterated noise is generated with a gain of -6 dB. Yost *et al.* (1994) showed that for human subjects, when iterated rippled noises were generated with the same heights for the first peak in the autocorrelation functions, the noises were very difficult to discriminate from each other. Given the data in Figure 11, one would make the prediction that chinchillas would have similar difficulties discriminating 1-iterated rippled noise

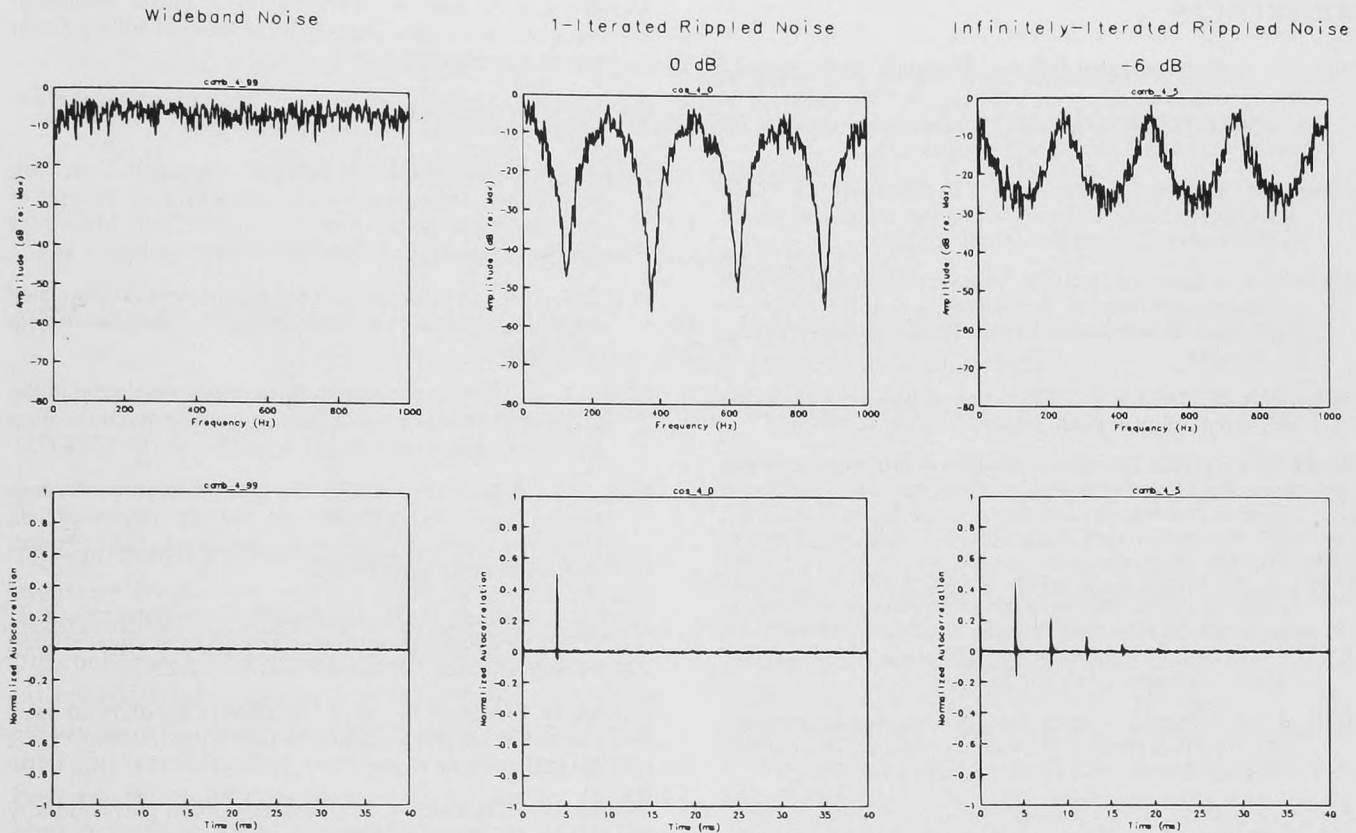


FIGURE 11 Comparison of the amplitude spectra (top panels) and autocorrelation functions (bottom panels) for a wideband noise, 1-iterated rippled noise at 0 dB gain, and infinitely-iterated rippled noise at -6 dB gain. The delay for both rippled noises is 4 ms. The amplitude spectra are expressed in dB rather than in linear power units as shown in Figures 2 and 3.

with a gain of 0 dB from infinitely-iterated rippled noise with a gain of -6 dB.

The height of the first peak in the autocorrelation function of rippled noise indicates the proportion of intervals in the fine structure of the rippled noise that have a period equal to the delay, T . For instance, the height of the first peak in the autocorrelation function for 1-iterated rippled noise generated with a delay T and a gain of 0 dB is 0.5; in this case, half of the intervals in the fine structure are T ms. Yost *et al.* (1994) argued that discrimination between different iterated rippled noises is based on processing this interval information. If chinchillas are less sensitive to temporal variables than are human subjects, they might be expected to process iterated rippled noise less well also. There is some evidence for poor temporal processing in chinchillas, since the thresholds for the detection of a change in modulation rate of a sinusoidally amplitude modulated noise are higher in chinchillas than in human subjects (Long and Clark, 1984). This modulation rate discrimination is interpreted as reflecting how accurately temporal intervals are represented in the auditory nervous system (Fay, 1988b). Thus, the higher modulation rate discrim-

ination thresholds in chinchillas suggests that their neural representation of the temporal information in rippled noise is less accurate than that in human subjects. In other words, there may be more internal noise in the temporal representation in chinchillas than in human subjects.

In summary, chinchillas can discriminate rippled-spectrum noise from flat-spectrum noise, but are less sensitive than human subjects. The discrimination in chinchillas appears to be based on some form of across-channel listening, regardless of whether it takes place in the spectral or temporal domain. However, the present results seem to be more consistent with a temporal processing rule.

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