Binaural detection with narrowband and wideband reproducible noise maskers: II. Results for rabbit

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Binaural detection with narrowband and wideband noise maskers was examined by using a Pavlovian-conditioned eyeblink response in rabbits. The target was a tone at 500 Hz, and the maskers were ten individual noise samples having one of two bandwidths, 200 Hz (410 Hz to 610 Hz) or 2900 Hz (100 Hz to 3 kHz). The narrowband noise maskers were created by filtering the wideband noise maskers such that the two sets of maskers had identical spectra in the 200-Hz frequency region surrounding the tone. The responses across the set of noise maskers were compared across bandwidths and across interaural configurations (N_0S_0 and N_0S_π). Responses across the set of noise waveforms were not strongly correlated across bandwidths; this result is inconsistent with models for binaural detection that depend only upon the narrow band of energy centered at the frequency of the target tone. Responses were correlated across interaural configurations for the wideband masker condition, but not for the narrowband masker. All of these results were consistent with the companion study of human listeners [Evilsizer *et al.*, J. Acoust. Soc. Am. **111**, 336–345 (2002)] and with the results of human studies of binaural detection that used only wideband [Gilkey *et al.*, J. Acoust. Soc. Am. **78**, 1207–1219 (1985)] or narrowband [Isabelle and Colburn, J. Acoust. Soc. Am. **89**, 352–259 (1991)] individual noise maskers. © *2002 Acoustical Society of America.* [DOI: 10.1121/1.1423930]

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I. INTRODUCTION

Understanding the psychophysics and neurophysiology of the detection of a tone in a noise masker is one of the classic problems in auditory science. In the current study, a behavioral paradigm for the rabbit was used to investigate the detection of tones in wideband and narrowband maskers, and the correlation of detection results across bandwidths for a set of individual masker noise waveforms was investigated. These experiments were designed in parallel with a companion study on human subjects by Evilsizer *et al.* (2002). In both studies, narrowband maskers were derived from a set of individual wideband maskers such that the sets of stimuli had identical spectra in the narrow frequency band surrounding the target tone. Noise waveforms that were digitally stored, and were therefore reproducible, were used so that the details of responses across a set of masker waveforms could be investigated. Comparisons of results across bandwidths and across interaural configurations at each bandwidth provided information concerning the effect of masker frequencies outside the narrow frequency band that surrounds the tone frequency.

Two interaural configurations are frequently tested in studies of binaural detection with human listeners: a diotic N_0S_0 condition (in-phase masker and tone to the two ears) and a dichotic N_0S_π condition (in-phase masker and out-of-phase tone to the two ears). Several studies have measured binaural detection in animals (e.g., cat: Geesa and Langford, 1976; Wakeford and Robinson, 1974; budgerigar: Dent *et al.*, 1997; ferret: Hine *et al.*, 1994; rabbit: Early *et al.*, 2001). Most studies in other species have used free-field or near-field stimuli and have investigated binaural unmasking by changing the phase of the stimulus to one speaker placed near the animal. Studies in the rabbit allow the use of earmolds sealed into the ear canal, such that N_0S_0 and N_0S_π stimuli can be presented (Early *et al.*, 2001). Using this preparation, stimuli can be carefully controlled, allowing differences in performance across reproducible noise samples to be studied. Early *et al.* (2001) reported that responses were significantly different across reproducible noise samples and were correlated between N_0S_0 and N_0S_π; that study was limited to wideband noise maskers and tested only one tone phase for the N_0S_0 condition. In the current study, the set of stimulus conditions was expanded to provide responses that

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[a)] Author to whom correspondence should be addressed. Present address: Department of Bioengineering and Neuroscience, Institute for Sensory Research, Syracuse University, 621 Skytop Rd., Syracuse, NY 13244; electronic mail: laurel_carney@isr.syr.edu can be studied in parallel with results for human listeners (Evilsizer *et al.*, 2002); both studies were focused on comparing the responses across reproducible noise maskers at two bandwidths.

These studies were designed to address a discrepancy that exists in the human psychophysical literature concerning binaural detection studied with reproducible noise maskers. Gilkey *et al.* (1985) investigated detection of a 500-Hz tone using wideband (2900 Hz bandwidth, from 100 Hz to 3 kHz) reproducible noise maskers. They found significant differences in responses across noise samples and significant correlation of the responses between the N_0S_0 and the N_0S_π conditions. Isabelle and Colburn (1991) studied detection of 500-Hz tones using narrowband reproducible noise maskers (116 Hz bandwidth, from 445 to 561 Hz). They also found that there were significant differences in responses across narrowband noise samples; however, unlike the Gilkey *et al.* (1985) study, results were not significantly correlated between the N_0S_0 and N_0S_π conditions. The importance of this discrepancy lies in its implications for predictions of classical models for detection (reviewed by Colburn *et al.*, 1997), because the results for wideband and narrowband maskers should be identical if detection is influenced only by energy at frequencies within a critical band of the target frequency.

To address this discrepancy, the current study tested rabbits with a Pavlovian-conditioned eyeblink response in a detection task with 500-ms duration 500-Hz tones and narrowband and wideband noise maskers. Where possible, the parameters of this study were chosen to parallel those of the companion human study (Evilsizer *et al.*, 2002); due to the difference in species and test paradigms, there were differences between the studies. One such difference was the bandwidth of the narrowband maskers: the narrowband maskers in the companion study had a bandwidth of 100 Hz, whereas the narrowband maskers in the current study had a 200-Hz bandwidth (410 to 610 Hz). These stimuli were chosen based on preliminary results which suggested that performance in the rabbit was considerably more stable for the 200-Hz bandwidth than for 100 Hz, and performance levels differed between these bandwidths (Carney *et al.*, 2000). In addition, detection performance was found to be similar for 200-Hz and 3-kHz bandwidths in the current study, suggesting that the critical band of the rabbit is less than or equal to 200 Hz. The broader critical band of the rabbit is not surprising based on the fact that peripheral tuning is relatively broad in this species (Borg *et al.*, 1988).

As in the companion study, the wideband and the narrowband maskers in the current study were created with the same spectra in the 200-Hz band surrounding the tone frequency; the set of wideband maskers was filtered to obtain the set of narrowband maskers. The companion study used 25 reproducible noises; a subset of 10 of these noises was used in the current study, due to the limited number of tone-plus-noise trials that could be delivered in each behavioral test session. The total duration of stimuli differed between the two studies, but durations were chosen in an effort to study detection based on comparable effective stimulus durations (see later in this work). Finally, a tracking paradigm was used for most of the measurements in the current study, whereas most human studies of detection with reproducible noise maskers have used a fixed-level task (including the companion study Evilsizer *et al.*, 2002). In both the companion study and in the current study, a limited number of measurements were made to allow the comparison of results for the two stimulus-level-selection paradigms.

The aim of this study was to compare results for a tone-detection task with reproducible noise maskers for rabbit detection across bandwidths and interaural configurations and to test the hypothesis that rabbits exhibit the same trends in responses across conditions as human listeners. The use of reproducible noise maskers in psychophysical experiments such as these, as well as physiological experiments, provide data that are critical for testing models of binaural detection. Models of detection typically focus on the interactions of the target and masker in the response of a single auditory filter (or critical band). The responses presented here and in the companion article indicate that these models must be extended in future studies to include the influence of energy outside the critical band centered on the target in order to explain results for reproducible noises.

II. GENERAL METHODS

All experimental methods were approved by the Charles River Campus Institutional Animal Care and Use Committee at Boston University. The behavioral methods are similar to those reported by Early *et al.* (2001), and the ten wideband reproducible noise maskers were the same as in that study.

Three female Dutch-Belted rabbits (2.0–3.5 kg), with clean ear canals and normal distortion-product otoacoustic emissions (Lonsbury-Martin *et al.*, 1987), were the subjects in this study. The experiments were conducted in an IAC (Industrial Acoustics Co., Bronx, NY) double-walled sound-attenuating booth. Two-hour sessions were run daily. The animal sat in a custom-made open box and was wrapped in a towel. Stable positioning of the head was achieved with a bar surgically mounted on the skull using screws and dental acrylic. Each rabbit had earmolds that were custom-molded using a soft plastic material (Per-form H/H, Hal-Hen, Long Island City, NY).

A. Pavlovian eyeblink conditioning

Pavlovian eyeblink conditioning (reviewed in Gormezano *et al.*, 1983) was used to study binaural detection. The conditioned stimulus (CS) was a 500-Hz tone, and the unconditioned stimulus (US) was an electrical shock (0.9 mA, 60 Hz) delivered to electrodes positioned posterior to the orbit by a Med Associates (St. Albans, VT) constant-current shocker (ENV-410A). The shock occurred during the last 100 ms of the 500-ms duration tone. The choice of 500-ms duration for the tones and noise maskers and of a 400-ms delay to the onset of the US was based on previous studies of Pavlovian conditioning of the eyeblink response (e.g., Frey and Ross, 1968).

The onset of an eyeblink in the presence of the tone-plus-noise stimulus (CS) before the onset of the shock constituted a conditioned response (CR). Onset of the eyeblink after the shock constituted an unconditioned response (UR). The CS was always accompanied by the US.

An eyeblink on a tone-plus-noise trial with latency shorter than 400 ms was designated a CR. Allowing 100 ms for the execution of the eyeblink response, it was estimated that the first 300 ms of the tone-plus-masker stimulus determined the animal's response. The stimulus duration for the human study was set at 300 ms (Evilsizer *et al.*, 2002), thus providing roughly comparable effective stimulus durations across the studies.

Eyeblink responses to noise-alone trials were also recorded and analyzed. The eyeblink was monitored by a photodiode-phototransistor pair that was aimed at the edge of a small piece of white paper taped to the animal's eyelid to contrast with the animal's dark eye. The photodiode–phototransistor pair converted eyelid position into voltage. The onset of an eyeblink was determined automatically based on a criterion for the slope of the photodiode voltage.

Individual animals were initially trained with tones in quiet, and the level of the CS was fixed at a relatively high level (70 dB SPL) until the animal had CRs for 80% of the trials in a session. Two of the animals (R4 and R6) were subjects in a previous study (Early *et al.*, 2001) and had extensive experience in binaural detection with wideband maskers. All three animals were tested for about 30 sessions on a binaural detection task using noise maskers with several bandwidths (50 Hz, 200 Hz, 800 Hz, and 3 kHz) before being tested at the two bandwidths used in the current study. These 30 sessions were the only prior experience for R7 on the tone-plus-noise detection task.

B. Acoustic stimuli

A Tucker-Davis Technologies (Gainesville, FL) System II was used to generate, low-pass filter (with corner frequency equal to 20 kHz), and present stimuli, record waveforms in the ear canal, and record eyeblink responses. Beyerdynamic DT-48 (Heilbronn, Germany) earphones were used to present the stimuli to the ear canals through the custom-made earmolds. The frequency response of the acoustic system (including the properties of the earphone, earmold, and ear canal) was characterized and used to create a prefilter that was applied to the stimuli. Each calibration was based on 64 500-ms duration white-noise samples that were presented and recorded using a probe-tube microphone (Etymotic ER-7, Elk Grove Village, IL) attached to the earmold. The amplitude spectra of the 64 noise recordings were averaged for each calibration curve.

The prefilter used to digitally compensate the reproducible noise waveforms for the shape of the frequency response was computed once for each rabbit on the basis of an average of several calibration curves that were obtained before data collection for this study began. This averaged calibration curve for each rabbit was calculated by averaging 16 to 20 calibration curves from both ears (8–10 from each ear) for that rabbit. The calibration curves included in the average calibrations varied by ±5 dB between 200 Hz and 3 kHz, and varied slightly more (±10 dB) at frequencies below 200 Hz. The repeatability of the calibrations across days is illustrated in Fig. 1.

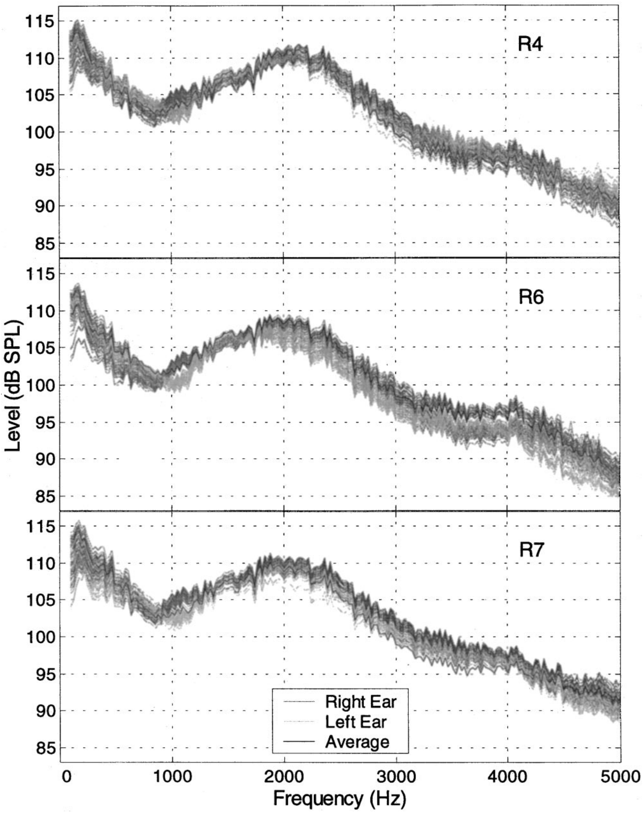

FIG. 1. Calibration curves for each ear of each animal (panels) for the 64 sessions in this study. Each curve is plotted as level in dB SPL as a function of frequency in Hz for the range 100–5000 Hz. The dark gray lines are the daily in-the-ear calibration curves for the right ear and the light gray lines are for the left ear. The black curve in each panel is the average calibration for that animal which was used to prefilter the stimuli delivered to both ears during the course of this study. See text for details of the acoustic calibration.

The average calibration curve was used as the prefilter to ensure that identical waveforms were presented daily (Early *et al.*, 2001). However, the calibration curve of the acoustic system was still checked daily to ensure that there were no significant changes in the acoustics (e.g., related to position of the earmold) that could have introduced variability into the reproducible waveforms from day to day. Any significant difference between the daily calibration and the average calibration was investigated and resolved before daily testing began, typically by reseating the earmold within the ear canal. The set of ten reproducible noise maskers was created using digitized Gaussian noise samples that were pregenerated on the array processor of the TDT-II system at a sampling rate of 50 kHz. Band-limited noise maskers were obtained by applying a rectangular window in the frequency domain to the reproducible noise waveforms. The frequency window for the 200-Hz bandwidth noise maskers was geometrically centered at 500 Hz (410 to 610 Hz). The frequency window for the wideband maskers was 2900 Hz wide (100 Hz to 3 kHz). To create noises that had a flat spectrum in the ear canal, the amplitude spectrum of each band-limited white noise sample was divided by the averaged calibration curve for each rabbit. The mean spectrum level across all noises was fixed at 40 dB SPL.

A 500-Hz tone was the target stimulus. The tone level was set based on the averaged calibration curve. Both the tone and the masker had 500-ms durations, with 10-ms cosine-squared onset/offset ramps. Between tone-plus-noise trials there were many noise-alone trials (see later in this work); these stimuli were drawn from the same set of reproducible noises as the maskers in the tone-plus-noise trials. A 1-s interval followed each 500-ms trial.

The noise waveforms to the two ears were identical in all conditions (N_0). The tones presented to the two ears were either diotic (S_0) or were 180° out of phase (S_π). Previous studies that explored the phase-dependence of binaural detection (e.g., Gilkey *et al.*, 1985; Isabelle and Colburn, 1991) showed that N_0S_0 responses depend upon the starting phase of the tone. Therefore, half of the N_0S_0 stimuli in this study were created using tones with 0° starting phase [referred to as $N_0S_0(0°)$] and half were created with 180° starting phase [referred to as $N_0S_0(180°)$]. In addition to providing estimates of performance based on starting phases, these starting phases are the two components of the N_0S_π stimulus and are thus useful for analyses that compare responses across interaural configurations.

III. EXPERIMENT 1

The first experiment included tests of responses for narrowband and wideband maskers for both interaural configurations. In the companion study with human listeners (Evilsizer *et al.*, 2002), a fixed-level task was used to test performance across noise samples with the tone level fixed. A previous animal study (Early *et al.*, 2001) demonstrated that, with rabbits, a one-down–one-up track yielded results that were more stable over time as compared to testing at a fixed tone level (Carney *et al.*, 1998). Therefore, a tracking procedure was used for experiment 1 in the current study. The use of tracking versus fixed-level testing was further investigated in experiment 2.

A. Methods

Animals were tested with two masker bandwidths, 200 and 2900 Hz, and two binaural configurations, N_0S_π and N_0S_0; half of the N_0S_0 trials were $N_0S_0(0°)$ and half were $N_0S_0(180°)$. Only one condition was tested during a 2-h experimental session. Sixty-four sessions were run for each animal in eight sets. A set comprised eight sessions, with four sessions at each bandwidth. For each bandwidth there were two N_0S_0 sessions (one at each starting phase) and two N_0S_π sessions to match the number of sessions across the diotic and dichotic conditions. The eight sessions in each set were organized such that N_0S_0 conditions were tested in four consecutive sessions with bandwidth (narrowband and wideband) and tone starting phase (0° or 180° for N_0S_0) randomized, followed by four N_0S_π sessions. A new random sequence was determined for each odd-numbered test set, and the test order was reversed for the subsequent even-numbered set. Each rabbit had a different testing order. This strategy of changing interaural configurations only every few days was adopted after preliminary tests suggested that changing the interaural configuration (N_0S_0 vs. N_0S_π) on a daily basis resulted in performance that was less consistent over time. This method of ordering sessions allowed testing of all of the interaural configurations in a partially interleaved manner while still maintaining consistent performance over time.

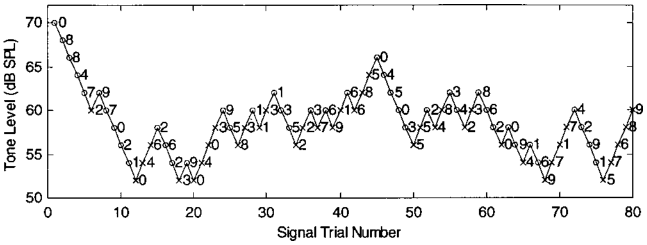

FIG. 2. A one-down–one-up track (R4, session 375, N_0S_π, narrowband noise maskers) for one behavioral session. Each point represents a tone-plus-noise trial. The number that labels each trial is the noise sample number (0–9). Each circle represents a CR; each x symbol represents a UR. The confidence interval for this track was 1.6 dB.

A statistical power analysis of the data collected for a previous study (Early *et al.*, 2001) indicated that eight sessions for each condition would yield sufficient numbers of trials for each noise sample (approximately 40 trials/noise) to allow statistical testing of responses across reproducible noise samples. Therefore, at least eight test sessions were completed for each stimulus condition for the three rabbits in this study.

Each session consisted of a single track, an example of which is shown in Fig. 2. For each track, the tone level was initially set to 70 dB SPL and was adjusted from one tone-plus-noise trial to the next following a one-down-one-up rule, resulting in tracks that converged to a level at which CRs were present on 50% of the tone-plus-noise trials (Levitt, 1971). The step size was fixed at 2 dB. Each point in the representative track illustrated in Fig. 2 shows a tone-plus-noise trial; each CR (conditioned response, which precedes the shock) is indicated by a circle, and each UR (unconditioned response) is indicated by an x. The noise sample number used as the masker for each tone-plus-noise trial is indicated on the track.

Each trial was either a tone-plus-noise trial or a noise-alone trial. The noise masker in each trial was randomly chosen from the ten pregenerated reproducible noise samples. There were 33–47 noise-alone trials between each pair of tone-plus-noise trials, randomized such that tone-plus-noise trials occurred on average once per minute, with the interval between tone-plus-noise trials ranging from 49.5 to 70.5 s.[1] Animals were given a 1-min break after every 10 tone-plus-noise trials and a 3-min break after every 30 tone-plus-noise trials. Eighty to 90 tone-plus-noise trials were completed in a 2-h session.

Eyelid position was recorded during all tone-plus-noise trials and noise-alone trials. Occasionally, fidgeting or chewing by the animal resulted in fluctuations of the eye voltage signal that met the automated criterion for an eyeblink. This behavior was more common for one animal (R6) than for the other two. For this animal, the recorded eyeblinks on noise-alone trials were reviewed manually; trials that had obvious cyclic changes associated with chewing, or small, brief movements associated with fidgeting, were removed. The records removed were qualitatively different from typical eyeblinks, and represented approximately 1.5% of all noise-alone trials for this animal in the sessions that were included in the analysis. However, two sessions for this rabbit (R6) had an exceptionally large number (a factor of 5 higher than average) of noise-alone trials that were apparently affected by fidgeting and/or chewing behaviors; these sessions were excluded from further analysis, and those conditions were repeated on other days.

B. Data analysis

A confidence interval (Howell, 1992; Leek *et al.*, 2000) was computed to quantify the stability of a given track. The 95% confidence interval was calculated using the tone levels visited during the track, excluding the trials at the beginning of the track preceding the fourth reversal. If the confidence interval of a track was greater than 2.2 dB, it was excluded from analysis. Using this criterion, 1 out of 65 sessions was excluded from R4's data; 2 out of 66 sessions from R7's data; and 22 out of 88 sessions from R6's data. In the case of R6, most of the excluded sessions (20 of the 22) were for the narrowband N_0S_π condition (see later in this work).

The tone level at which CRs were present on 50% of the tone-plus-noise trials was determined by averaging the reversals (excluding the first four reversals of each track) across individual tracks. Tone-plus-noise trials at a tone level one step above and two steps at or below this level were included in the reproducible noise analysis (Early *et al.*, 2001). In order to test the statistical significance of performance differences across samples, a χ^2-test (Siegel and Colburn, 1989) was used in this study.

Because responses across the set of reproducible noises are affected by the starting phase of the tone (e.g., Gilkey *et al.*, 1985), responses were separated according to reproducible noise masker and starting phase of the tone into two sets of ten for the statistical analysis of the N_0S_0 results, thus creating a set of 20 stimuli for these analyses (ten for the $N_0S_0(0°)$ condition and ten for the $N_0S_0(180°)$ condition). One set of ten reproducible noises (with approximately the same number of overall trials as the combined N_0S_0 results) was used in the statistical analysis of the N_0S_π results. For comparison of responses across the N_0S_0 and N_0S_π conditions, the responses to each reproducible noise for the two starting phases of the tone for N_0S_0 were averaged together and then compared to the responses for the N_0S_π condition (Gilkey *et al.*, 1985).

C. Results and discussion

Three rabbits were tested over 3 to 4 months each. The session-by-session performance for each rabbit is shown in Fig. 3. Each point represents the mean signal level with respect to the noise level (E_s/N_0 in dB) for the reversals in the track (excluding the first four reversals). These E_s/N_0 values thus represent the mean across all ten reproducible noise waveforms of the signal-to-noise ratio that elicited responses on 50% of the tone-plus-noise trials. Only sessions with tracks that had a confidence interval size less than or equal to 2.2 dB are shown. This figure shows that the performance of all animals was relatively consistent across sessions, except for R6's performance for the narrowband N_0S_π condition.[2] Compared with R4 and R6, there is a slight downward trend over time in the mean reversals of R7. This improvement over time may be due to R7's more limited experience in binaural detection experiments before testing began.

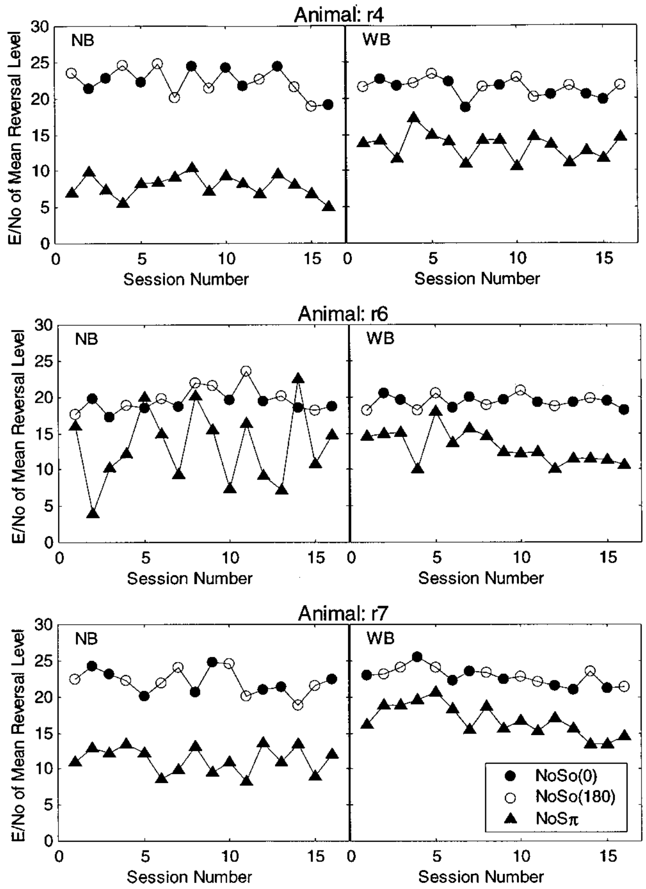

FIG. 3. The session-by-session mean reversal levels for three rabbits: R4, R6, and R7. In each plot, the left panels show results for narrowband maskers (NB); the right panels show results for wideband maskers (WB). Only sessions with a confidence interval less than or equal to 2.2 dB are shown.

Table I provides a summary of the experimental data for the three rabbits tested. E_s/N_0 in dB was calculated as:

$$\frac{E_s}{N_0} = \text{Tone level (dB SPL)} - \text{Noise spectrum level (dB SPL)} + 10\log_{10}\frac{\text{duration (s)}}{1\text{ s}}.$$

The duration used for this calculation was 400 ms, which is the entire duration of the CS before the onset of the US. The noise spectrum level was always 40 dB SPL.

The E/N_0 (in dB) for which the animals had CRs on 50% of the tone-plus-noise trials was within 1 dB across bandwidths for the N_0S_0 condition for all three rabbits (Table I). This result supports the assumption that the critical band for the rabbit is less than or equal to 200 Hz. Preliminary tests showed that the E_s/N_0 required for a 50% CR rate was reduced for a 100-Hz bandwidth masker (Carney *et al.*, 2000), thus the 200-Hz bandwidth was chosen for this ex-

TABLE I. Results from Experiment 1. χ^2 values are given for the results across reproducible noise maskers for tone-plus-noise and noise-alone trials.

Interaural configuration	Noise bandwidth[a]	Rabbit	Tone-plus-noise trials			Noise-alone trials	
			E_s/N_0[b]	χ^2[c]	N[d]	χ^2[c]	N[d]
N_0S_0	NB	R4	22.4	48.4[e]	78	63.5[e]	4978
		R6	19.5	32.2[f]	89	26.3	5181
		R7	22.1	37.1[e]	74	142.9[e]	4950
	WB	R4	21.4	74.3[e]	83	241.0[e]	4925
		R6	19.3	35.3[f]	93	48.1[e]	5228
		R7	22.8	87.0[e]	91	562.7[e]	4900
N_0S_π	NB	R4	7.9	28.4[e]	67	70.1[e]	5002
		R6	13.1	20.8[f]	43	16.7	4946
		R7	11.4	30.5[e]	69	73.2[e]	4955
	WB	R4	13.4	52.7[e]	68	379.7[e]	4911
		R6	13.0	27.3[e]	65	18.4[f]	5148
		R7	16.8	47.4[e]	69	478.0[e]	4927

[a] NB=200 Hz bandwidth; WB=100–3000 Hz.

[b] E_s/N_0 in dB of the stimulus at the mean reversal level of the tracks (50% CRs).

[c] χ^2 for the N_0S_0 conditions was calculated using 20 stimuli [ten for the $N_0S_0(0°)$ condition and ten for the $N_0S_0(180°)$ condition; 19 degrees of freedom]. There are nine degrees of freedom for the ten-stimulus N_0S_π condition.

[d] N is the average number of trials per reproducible noise sample. The N for the N_0S_0 conditions combines trials from the $N_0S_0(0°)$ condition and the $N_0S_0(180°)$ condition.

[e] $p<0.01$.

[f] $p<0.05$.

periment to ensure that the narrowband masker was at least as wide as the critical band. For the N_0S_π condition, E_s/N_0 in dB at the 50% CR level was lower for narrowband than for wideband maskers, as expected. As a result, the MLD (the difference in performance between N_0S_0 and N_0S_π) of all rabbits was larger for narrowband maskers than for wideband maskers. This trend was consistent with previous studies of human listeners (e.g., Bourbon and Jeffress, 1965; Metz *et al.*, 1968; Staffel *et al.*, 1990; Bernstein *et al.*, 1998; van de Par and Kohlrausch, 1999; Evilsizer *et al.*, 2002).

D. Responses across reproducible noises

According to a χ^2 test, the variability in responses across the set of reproducible noises was significantly ($p<0.05$) greater than would be expected due to chance for all rabbits and conditions for the tone-plus-noise trials (Table I). Figure 4 shows responses across the set of reproducible noises; percentages of trials with conditioned responses to tone-plus-noise trials (upper panels of each set) and percentages of noise-alone trials for which there were responses are shown. The variations in performance across noises, as well as across the bandwidths, interaural configurations, and rabbits, can be qualitatively seen by comparing the panels in Fig. 4; quantitative comparisons will be presented later in this work. $N_0S_0(0°)$ and $N_0S_0(180°)$ responses for each reproducible noise masker were averaged and plotted together for comparison to the N_0S_π responses (Fig. 4). For all rabbits, the overall percentage of conditioned responses on tone-plus-noise trials is approximately 50% (as expected for the one-up–one-down track), and the overall percentage of responses on noise-alone trials is very low, about 1%–5%. Spontaneous eye-blinks occur infrequently in the rabbit (1–3 per hour, Gormezano, 1966). The percentage of responses to noise-alone trials is higher for wideband maskers than it is for narrowband maskers, a result that is consistent across all rabbits.

E. Correlation across bandwidths

The correlations between the narrowband and wideband responses for individual rabbits are shown in Table II. As described earlier, the wideband maskers had the same spectra in the 200-Hz frequency band centered at 500 Hz as the narrowband maskers. If the responses in the presence of the different reproducible noise maskers were determined only by the masker spectrum near the tone frequency, i.e., if the spectrum outside this narrow band had no effect on detection, the narrowband results should have been highly correlated to the wideband results. Yet in most conditions, results for the two bandwidths were not significantly correlated. There was a significant correlation for one comparison (the N_0S_π tone-plus-noise trials) in a single rabbit (R7). The same rabbit was the only animal tested that showed correlated responses across the two bandwidths for the noise-alone trials, for both N_0S_0 and N_0S_π conditions.

For the N_0S_0 condition, the correlation of tone-plus-noise responses across the bandwidths was not significant but was always positive (Table II). This pattern was similar to that of the human study, which showed a significant effect of the frequency components outside of the narrow frequency band centered on the tone (Evilsizer *et al.*, 2002).

For the N_0S_π condition, the correlation of the tone-plus-noise trials across bandwidths was near zero for two of the three rabbits and was high for one rabbit (R7). This pattern was similar to that of the human subjects, for which the

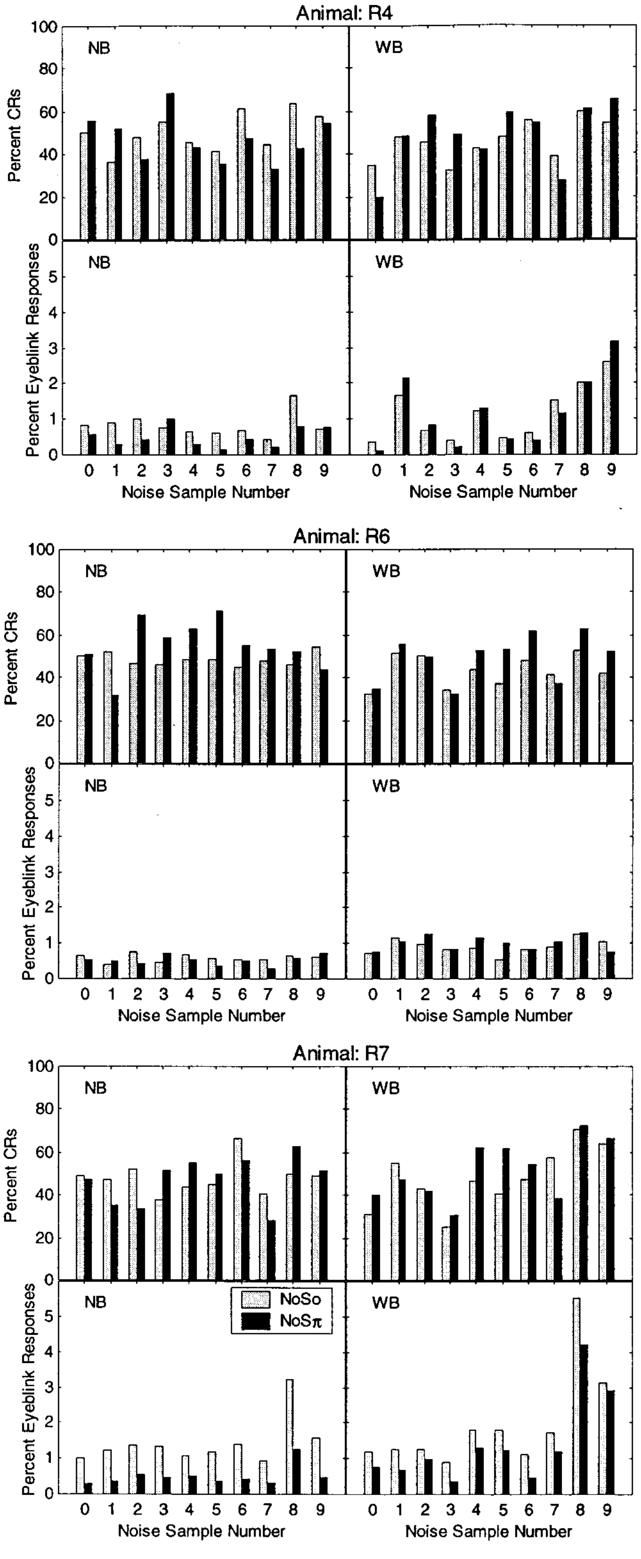

FIG. 4. Performance across reproducible noise maskers for the N_0S_0 and N_0S_π conditions for R4, R6, and R7. The left panels show results for narrowband maskers (NB), and the right panels show results for wideband maskers (WB). The responses to tone-plus-noise trials (upper panel) and to noise-alone trials (lower panel) are shown for each bandwidth. $N_0S_0(0°)$ and $N_0S_0(180°)$ were averaged for comparison to N_0S_π.

TABLE II. Pearson's product-moment correlations between responses for wideband and narrowband maskers.

Interaural configuration[a]	Rabbit	Tone-plus-noise trials *r*	Noise-alone trials *r*
N_0S_0	R4	0.25	0.24
	R6	0.39	−0.29
	R7	0.33	0.80[b]
N_0S_π	R4	−0.03	0.12
	R6	−0.07	−0.37
	R7	0.64[c]	0.82[b]

[a] Responses for the N_0S_0 condition represent the combined data from the $N_0S_0(0°)$ condition and the $N_0S_0(180°)$ condition, resulting in 18 degrees of freedom. There were eight degrees of freedom for the ten-stimulus N_0S_π condition.

[b] $p < 0.01$.

[c] $p < 0.05$.

correlations of hits across bandwidths were near zero for three listeners, and positive but insignificant for one listener (Evilsizer *et al.*, 2002). The lack of strong correlation in tone-plus-noise and noise-alone results across bandwidths for these noise maskers, which have identical spectra in the frequency region near the tone frequency, suggests that the frequency components outside the 200-Hz frequency band affect the responses for the wideband condition.

F. Correlation across interaural configurations

The correlation between responses for the N_0S_0 and the N_0S_π conditions is shown in Table III. The responses for each of the reproducible noise maskers in the N_0S_0 condition were averaged across the two starting phases for comparison to the responses to the N_0S_π responses (Gilkey *et al.*, 1985). In general, the N_0S_0 and the N_0S_π responses were not significantly correlated for narrowband maskers, but were significantly correlated for wideband maskers for all three rabbits. This result suggests that similar physical properties of the noise may be affecting detection for both the N_0S_0 and the N_0S_π conditions in the wideband case, but that different stimulus characteristics may control the CR in the narrowband case.

Because the noise-alone trials were exactly the same for both the N_0S_0 and N_0S_π conditions, it might be expected that the performance on noise-alone trials would be correlated between the N_0S_0 and N_0S_π conditions. However, Table III shows that these responses were highly correlated for one

TABLE III. Pearson's product moment correlations between responses for the N_0S_0 and N_0S_π conditions. Note: To compare interaural configurations, the results for each reproducible noise for the $N_0S_0(0°)$ condition and the $N_0S_0(180°)$ condition were averaged together and then compared to the results for the N_0S_π condition, resulting in eight degrees of freedom for all correlations.

Noise bandwidth[a]	Rabbit	Tone-plus-noise trials *r*	Noise-alone trials *r*
NB	R4	0.31	0.48
	R6	−0.56	−0.04
	R7	0.27	0.97[b]
WB	R4	0.71[c]	0.97[b]
	R6	0.77[b]	0.44
	R7	0.67	0.98[b]

[a] NB=200 Hz bandwidth; WB=100–3000 Hz.

[b] $p < 0.01$.

[c] $p < 0.05$.

TABLE IV. Pearson's product moment correlations between rabbits.

Noise bandwidth[a]	Interaural configuration	Subject pair	Tone-plus-noise trails r	Noise-alone trials r
NB	N_0S_0	R4-R6	0.08	0.33
		R4-R7	0.14	0.83[b]
		R6-R7	0.25	0.10
	N_0S_π	R4-R6	−0.42	0.87[b]
		R4-R7	0.30	0.47
		R6-R7	0.11	0.30
WB	N_0S_0	R4-R6	0.75[b]	0.51[c]
		R4-R7	0.67[b]	0.62[b]
		R6-R7	0.59[b]	0.16
	N_0S_π	R4-R6	0.67[c]	0.19
		R4-R7	0.57	0.67[c]
		R6-R7	0.81[b]	0.36

[a] NB=200 Hz bandwidth; WB=100–3000 Hz. df=18 (N_0S_0) and 8 (N_0S_π); see note (a) in Table II.

[b] $p < 0.01$.

[c] $p < 0.05$.

rabbit (R7) for both narrowband and wideband maskers, and for one rabbit (R4) for wideband maskers only. This result implies that the strategy used on the tone-plus-noise trials may influence the responses to noise-alone trials.

These results showed the same trends as the companion human study, for which all comparisons across interaural configurations were significant for the wideband case, whereas no consistent trend was seen for the narrowband case (Evilsizer *et al.*, 2002). The responses to noise-alone trials tended to be more strongly correlated across interaural configurations for the wideband maskers than for narrowband maskers for both rabbit and human subjects.

The comparison of responses across interaural configurations in both the current and the companion study are also consistent with previously reported results. Gilkey *et al.* (1985) reported correlated results across interaural configurations when using wideband maskers, and Isabelle and Colburn (1991) reported uncorrelated results across interaural configurations when using narrowband maskers. The current and companion studies, which provide results for the same listeners and using stimuli that had identical spectra in the frequency region near the tone, support the hypothesis that the discrepancy between the two previous studies was due to the different bandwidths of the maskers (Isabelle and Colburn, 1991). The dependence on bandwidth of the relationship between the N_0S_0 and N_0S_π conditions also supports the conclusion that masker components well away from the tone frequency influence the detection results across reproducible noises.

G. Intersubject correlation

Table IV provides the correlation of responses across rabbits. For wideband tone-plus-noise trials, all three rabbit pairs were significantly correlated for the N_0S_0 condition, and two of three rabbit pairs were correlated for the N_0S_π condition. None of the pairs were correlated for the narrowband tone-plus-noise results for either interaural configuration. The noise-alone results showed weaker correlations across rabbits; two of six pairs were significantly correlated for the narrowband maskers, and three of six pairs were just significantly correlated for the wideband maskers.

These trends were similar to those in the companion study, which showed significant correlations across all subject pairs for the wideband maskers in both interaural configurations and relatively weak (though significant for the N_0S_0 condition) correlations for the narrowband maskers. Although the use of fewer reproducible noise maskers in the current study is probably responsible for the weaker statistical significance in many of the comparisons, all trends across conditions are comparable across the two studies.

H. Consistency of performance over time

Isabelle (1995) reported that the results for one set of reproducible noise maskers were stable for one human subject over several years. A similar result from one rabbit (R4) is shown here for two sets of data collected more than one year apart. One data set, from the study of Early *et al.* (2001) ("previous" data), was collected for at least ten sessions at one interaural configuration. The other data set ("current" data) was extracted from the larger data set of the current study that included two interaural configurations. A summary of the previous and current data sets is given in Table V. There was a strong correlation between the two data sets for tone-plus-noise trials for both the N_0S_0 and the N_0S_π conditions. Correlations between noise-alone responses for the

TABLE V. Comparison of previous and current data set. Note: These data were collected from R4 with wideband maskers. Because the previous data set included more sessions than the current set, it is characterized by higher χ^2 values.

Interaural configuration	Data set	E_s/N_0 for 50% CRs	Tone-plus-noise trials			Noise-alone trials		
			χ^2	N	r	χ^2	N	r
$N_0S_0(0°)$	Previous	22.5	85.9[a]	87	0.94[a]	187[a]	6167	0.83[a]
	Current	21.8	41.1[a]	39		95[a]	2454	
N_0S_π	Previous	13.0	62.3[a]	101	0.87[a]	212[a]	6851	0.58
	Current	13.3	52.7[a]	68		380[a]	4911	

[a] $p < 0.01$, df=8.

TABLE VI. Comparison of tracking and fixed-level data from experiment 2.

			Tone-plus-noise			Noise-alone		
Rabbit	Data set	E_s/N_0	χ^2	N^a	r	χ^2	N^a	r
R4	Tracking	21.8	41.1^b	39	0.88^c	95^b	2454	0.85^c
	Fixed level	21.0	37.0^b	64		157^b	2470	
R7	Tracking	23.0	51.3^b	44	0.76^c	174^b	2456	0.81^c
	Fixed level	19.5	108^b	96		338^b	3702	

[a] N is the average number of trials per reproducible noise sample.
[b] $p<0.01$.
[c] $p<0.05$, df=8.

two data sets were significant for the N_0S_0 condition, and nearly significant for the N_0S_π condition.

IV. EXPERIMENT 2

A. Comparison of tracking and fixed-level procedures

As mentioned earlier, most reproducible noise tests in human listeners (Gilkey *et al.*, 1985; Isabelle and Colburn, 1991; Evilsizer *et al.*, 2002) have been conducted using a fixed-level procedure, but the rabbits were tested using a tracking procedure. In order to examine differences in performance caused by these different procedures, two rabbits were tested using a fixed-level procedure for a limited set of sessions.

B. Methods

One of the difficulties in performing these tests at a fixed level is due to the influence of changes in the overall performance on the results. The steep psychometric functions associated with this task (see Early *et al.*, 2001) can result in considerable differences in overall performance at a fixed level from day to day; a change in the percentage of CRs (especially if it drops below 50%) can influence the animal's performance over time (unpublished observations). The tracking paradigm, which automatically holds performance near 50% rate of CRs, generally results in consistent performance from session to session. In particular, if the animal misses a few trials in a row, the tracking paradigm automatically emphasizes the conditioning stimulus; increasing the level of the tone tends to reinforce the behavior, whereas leaving the tone at a fixed level can extinguish behavior if the percentage of CRs drops below 50%.

Because they had the most consistent performance across sessions, the fixed-level data were collected from R4 and R7 after experiment 1 was completed. The responses for the N_0S_0 condition with wideband maskers were more consistent than they were for other conditions (as quantified by the confidence interval statistic); therefore, this condition was tested using the fixed-level procedure and compared with the data from the tracking procedure.

C. Results and discussion

Table VI summarizes the experimental data from the tracking procedure and from the fixed-level procedure for the two rabbits. Because several months of tracking data were available for these animals, and their performance was relatively consistent over that time, it was possible to carefully choose the fixed levels to use for these tests. The responses for the two different experimental procedures were highly correlated for both animals for both tone-plus-noise and noise-alone results. Limited tests on human subjects in the companion study also showed strongly correlated results for the fixed-level task and tracking (Evilsizer *et al.*, 2002). Thus, the responses for N_0S_0 across sets of reproducible noise maskers for both bandwidths appear to be robust across these two test paradigms.

V. GENERAL DISCUSSION

In this study, three rabbits were tested with a tone-in-noise detection task using Pavlovian conditioning. Narrowband and wideband reproducible noise maskers with identical spectra in the 200-Hz frequency band centered on the tone frequency were used, and responses across reproducible noises were analyzed. The trends in the results reviewed here are generally consistent with those from the companion study in human listeners (Evilsizer *et al.*, 2002). The interpretation of the results from both of these studies and the data collected provide the basis for future modeling studies of diotic and dichotic detection with reproducible noise maskers.

The responses across reproducible noise samples show that, for each rabbit subject, there were significant differences across reproducible noise samples. The χ^2 values from rabbits (Table I) were lower than those for human listeners in the companion article, in part, perhaps, as a result of the use of fewer reproducible noise maskers in this experiment (Evilsizer *et al.*, 2002) (this is true even when comparable numbers of trials are used in the analysis). The smaller performance differences across reproducible noises for rabbit may be due to the Pavlovian conditioning paradigm used for these tests or to differences in sensitivity across the two species. The rabbits were also tested at higher E_s/N_0 levels than the humans; testing at higher signal-to-noise ratios is consistent with reduced differences in responses across reproducible noise maskers because the relative contribution of the noise waveform to the overall stimulus is reduced. Whether the difference in the performance levels was due to differences in auditory sensitivity, to differences in the sensitivity of the test procedure, or to other factors is a topic for further study.

Most of the comparisons between results for wideband and narrowband maskers (Table II) showed no significant correlation. Because the wideband and narrowband maskers had the same spectra around the tone frequency, the lack of correlation between wideband and narrowband performance suggests that frequency components outside the narrow band influence performance. Therefore, to explain these reproducible noise results with a model would require either a filter with a relatively wide passband or the combination of multiple filters covering a frequency range wider than the critical band. However, to explain these data, the model must also have similar thresholds for these two bandwidths for the N_0S_0 condition. This aspect of the results places a modeling constraint on either the nature of the information used at the output of a single filter, or on the ways in which information is combined across multiple filters.

Comparisons between the N_0S_0 performance and the N_0S_π performance (Table III) show that the responses on tone-plus-noise trials were not correlated for narrowband maskers, but were significantly correlated for wideband maskers. This result is consistent with the results from human listeners [i.e., the narrowband study of Isabelle and Colburn (1991), the wideband study of Gilkey *et al.* (1985), and the companion study of Evilsizer *et al.* (2002), which included both narrowband and wideband maskers]. Although the noise-alone trials were exactly the same for both the N_0S_0 and the N_0S_π conditions, the correlation across conditions was stronger for wideband than for narrowband maskers for both the rabbit and the human studies. This result suggests that the detection strategies used for tone-plus-noise trials may influence the performance for noise-alone trials.

The intersubject comparison (Table IV) shows that the results across animals were not correlated for narrowband maskers, but were significantly correlated for wideband maskers. This result indicates that one model may be sufficient to explain the wideband performance of all subjects, but that different models (or different model parameters) will be required for individual animals to explain the narrowband performance (Isabelle, 1995).

As with human subjects in the companion study, the responses of rabbit subjects varied significantly across noise samples for both narrowband maskers and wideband maskers, and performance was robust over time. An important aspect of this preparation is its potential for future electrophysiological experiments to investigate neural responses related to binaural detection. Physiological recordings from single neurons in the awake (and potentially behaving) rabbit preparation should contribute to an understanding of how different noise samples influence the firing of a single neuron. Future studies will concentrate on physiological recordings from these animals using the ten reproducible noises from these behavioral experiments. Combined with physiologically based modeling studies of both human and rabbit psychophysical results, these behavioral and physiological results should provide new insight to the classical problem of detection of a tone in noise.

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[1] In the current study, the proportions of conditioned responses for tone-plus-noise trials and of eyeblink responses for noise-alone trials are reported, rather than proportions of "hits" and "false alarms." In the paradigm used, which was chosen to optimize conditioning, the *a priori* probability of a noise-alone trial was approximately 40 times greater than that of a tone-plus-noise trial. In addition, the animal was not forced to respond. The one-up-one-down tracking procedure described above kept the animal at a "hit rate" of approximately 0.5, and the "false-alarm rate" in this paradigm was approximately 0.02. In order to use the standard signal-detection terminology of hits, false alarms, and the metric d', the absence of responses on noise-alone trials must be regarded as correct rejections, and their absence on tone-plus-noise trials as misses. If the absence of responses on noise-alone trials were considered correct rejections, the animal would be operating in a proportion-correct range of about 0.97. Furthermore, the involuntary nature of the Pavlovian response runs counter to the notion of criterion placement in signal detection theory. Because of the differences between this paradigm and the traditional yes–no detection task used in humans, the use of the d' metric and associated terminology has been avoided here.

[2] Because some of R6's N_0S_π results were at a level comparable to her N_0S_0 results, her daily calibrations were checked before and after 15 sessions to ensure that no changes in earmold position had occurred during the session (perhaps as a result of movement by the animal) that would prevent proper delivery of the N_0S_π stimuli. No changes in calibration were observed that might have explained the large variation in the behavioral data for this condition for this animal.

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