

# The behavioral response of mice to gaps in noise depends on its spectral components and its bandwidth

James R. Ison,<sup>a)</sup> Paul D. Allen, Peter J. Rivoli, and Jason T. Moore  
*Department of Brain and Cognitive Sciences, Meliora Hall, University of Rochester,  
Rochester, New York 14627*

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The purpose of these experiments was to determine whether detecting brief decrements in noise level (“gaps”) varies with the spectral content and bandwidth of noise in mice as it does in humans. The behavioral effect of gaps was quantified by their inhibiting a subsequent acoustic startle reflex. Gap durations from 1 to 29 ms were presented in five adjacent 1-octave noise bands and one 5-octave band, their range being 2 kHz to 64 kHz. Gaps ended 60 ms before the startle stimulus (experiment 1) or at startle onset (experiment 2). Asymptotic inhibition was greater for higher-frequency 1-octave bands and highest for the 5-octave band in both experiments, but time constants were related to frequency only in experiment 1. For the lowest band (2–4 kHz) neither noise decrements (experiment 1 and 2) nor increments (experiment 3) had any behavioral consequence, but this band was effective when presented as a pulse in quiet (experiment 4). The lowest frequencies in the most effective 1-octave band were one octave above the spectral region where mice have their best absolute thresholds. These effects are similar to those obtained in humans, and reveal a special contribution of wide band, high-frequency stimulation to temporal acuity. © 2005 Acoustical Society of America. [DOI: 10.1121/1.1904387]

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## I. INTRODUCTION

Auditory temporal acuity in human listeners and in laboratory animals is most often assessed by measuring the detection threshold for brief quiet periods or decrements in noise level (temporal gaps) placed within a broadband noise. Average detection thresholds of about 2 to 4 ms are typically obtained in psychophysical studies in humans (e.g., Plomp, 1964), and similar gap thresholds are found in behavioral studies of gap detection in mice (Barsz *et al.*, 2002) and in other laboratory animals (chinchillas, Giraudi *et al.*, 1980; ferrets, Kelly *et al.*, 1996; gerbils, Wagner *et al.*, 2003; and rats, Ison, 1982). This uniformity in gap thresholds across mammalian species contrasts with their substantial differences in both the spectral frequencies that provide their best absolute thresholds and in the bandwidth of their effective range of hearing. The difference between species in their ability to detect particular tonal stimuli is most apparent in the comparison of humans and mice, young adult humans having their lowest absolute thresholds in the region of about 1 to 2 kHz (Brant and Fozard, 1990; Corso, 1958) and an nominal audiometric range of about 20 Hz to 20 kHz (Greenwood, 1961), while for young adult mice the best absolute thresholds are found at about 14 to 16 kHz and their nominal hearing range is about 1 kHz to 100 kHz (Fay, 1988, pp. 367–370).

The similarity of these measures of temporal acuity despite the very different spectral sensitivities of mice and human listeners is noteworthy given the reported dependence of temporal acuity in human listeners on the high-frequency

spectral composition of the noise carrier and on its bandwidth (Buus and Florentine, 1985; de Filippo and Snell, 1986; Eddins *et al.*, 1992; Fitzgibbons, 1983; Fitzgibbons and Wightman, 1982; Formby and Muir, 1988; Glasberg *et al.*, 1987; Green and Forrest, 1989; Shailer and Moore, 1983, 1985; Snell *et al.*, 1994). Buus and Florentine (1985) provided the most extensive parametric description of the effect of these two variables on gap thresholds. They reported that gap sensitivity in human listeners reached a near asymptotic value for 1-octave wide bandpass noise centered at 4 kHz, that is, at the upper limit of the spectral region of high absolute sensitivity. This high level of temporal acuity was then maintained and at high levels possibly further enhanced when the center frequency increased to 8 kHz and 14 kHz, that is, into spectral regions where absolute sensitivity is relatively poor. Moreover, temporal acuity dropped precipitously as the center frequency fell to 2 kHz and below, even for a 1 kHz stimulus that is still within the spectral region of highest absolute sensitivity. They reported also that the lowest gap thresholds were obtained with a wideband noise that covered the range of all of their separate 1-octave band carriers. This latter finding was taken as suggestive evidence that the highest level of temporal acuity apparent in human listeners results from integrating less precise temporal information across separate auditory channels.

The frequencies at which gap thresholds near their asymptotic levels for bandpass noise in these studies are relatively high in the human audiogram, but these same absolute frequencies are very low in the mouse, about two octaves below the spectral region that provide their best absolute thresholds. Our goal in the present research was to determine how gap detection in the mouse is affected by the relative width and spectral characteristics of the noise band in which

<sup>a)</sup>Corresponding author: Telephone: +1 (585) 275-8461; fax: +1 (585) 442-9216; electronic mail: jison@bcs.rochester.edu

the gap is embedded, in comparison to the data previously obtained in human listeners.

## II. METHOD

### A. Subjects

The subjects were 60 young adult CBA/CAJ mice, born and raised in the vivarium at the University of Rochester but derived from breeding stock initially acquired from the Jackson Laboratory (Bar Harbor, ME). The mice were 5 to 7 months old in experiment 1 (6 male and 9 female); 3 to 5 months old in experiment 2 (4 male, 8 female); 3 to 4 months old in experiment 3 (6 female and 6 male); and 2 to 4 months old in experiment 4 (9 male and 7 female). The mice were maintained in group cages in a constant temperature and constant humidity environment, with a 12/12 light/dark cycle (lights on at 6 a.m.). Testing was conducted usually between the hours of 9 a.m. and 6 p.m. All procedures were approved by the University of Rochester Committee on Animal Resources, and were in accord with the regulations of the Public Health Service and the Federal Animal Welfare Act.

### B. Apparatus

The details of the apparatus have been previously described (Ison *et al.*, 2002). The mouse was placed for testing in a wire mesh oval-shaped cage (approximately 8 cm long and 5 cm in both height and width), that was mounted on a suspended acrylic platform to which an accelerometer was attached. This assembly was placed in an anechoic chamber. The accelerometer was sensitive to the vertical force exerted by the startle reflex, and its output was integrated over a 100 ms period, beginning with the startle stimulus. These values were recorded in arbitrary voltage units that are linearly related to the downward force provided by the startle reaction. In experiment 1 the noise sources for the filtered noise carriers, for the unfiltered background masking noise, and for the unfiltered startle stimulus were independent noise generators (linear output from 100 Hz to 100 kHz) fabricated in the departmental electronic shop. In this experiment the noise bands were produced by gating the output of one noise source through a variable analog filter with 12 dB/octave attenuation, with the edges of the band being 3 dB down from the center level. In the last three experiments the source for the startle stimulus and for the bandpass noise carriers was a digital signal generator (RP2.1, Tucker-Davis Technologies, Gainesville, FL), presented unfiltered for the startle stimulus but filtered into bands for the various carriers of the gap by the RP2.1. These bands were constructed to be identical to those provided in experiment 1. The source of the masking noise was the same in all experiments. The filtered bandpass stimuli and the masking noise were presented through a high-frequency Panasonic leaf tweeter with an output that was flat from about 2 kHz to 30 kHz and declined thereafter at a rate of about 9 dB per octave. The startle stimulus was presented through a second high-frequency tweeter.

### C. Procedure

In all experiments the mouse was placed into the anechoic chamber for a 5 min period and then tested with two kinds of trials: (a) baseline control trials in which the startle stimulus was presented alone, and (b) trials in which the startle stimulus immediately followed a perturbation in the acoustic background. The startle stimulus was always a 20 ms noise burst with 0.2 ms rise/fall times, presented at 110 dB SPL. To human listeners this stimulus approximates the intensity of a finger snap into the palm at a distance of 5 cm from the ear. The intertrial intervals on average were 20 s apart and were randomly chosen from a rectangular distribution that had a range from 15 to 25 s. The startle alone condition was always given twice in each block of trials while the other conditions were given just once, all presented in random order within a block. Each test day in each experiment consisted of 11 blocks of trials, the number of trials within each block depending on the numbers of conditions in each experiment.

The 1-octave noise bands were presented at the same attenuator setting that provided a level of 70 dB SPL for the 5-octave noiseband. These bandpass stimuli were always mixed with an independent wideband noise that was set at 50 dB SPL, and thus the relative level of any noise band that carried the gap information was always 20 dB above the level of the same band in the background noise. The rise/fall times of the noise at both ends of the gaps in experiments 1 and 2 and the increments in experiment 3 were near instantaneous (0.2 ms) but had a 5 ms duration in experiment 4 as in this experiment the noise bands were presented in quiet.

The same set of passbands were used in all of the experiments, namely, 2–4 kHz, 4–8 kHz, 8–16 kHz, 16–32 kHz, 32–64 kHz, and 2–64 kHz. While they were presented at a constant relative level of 20 dB SPL, these bands necessarily differed in absolute level because of their different bandwidths and because of the frequency response of the speaker. The levels of the 1-octave bands between 2 and 4 kHz, 4 and 8 kHz, 8 and 16 kHz, 16 and 32 kHz, and 32 and 64 kHz were in order, 57.2, 58.9, 61.9, 63.3, and 60.9 dB SPL. The level of the 5-octave band was 67.2 dB SPL. The geometric centers of these bands were about 2.9 kHz, 5.7 kHz, 11.4 kHz, 22.9 kHz, 45.7 kHz, and 11.4 kHz. In our colony of young adult CBA mice the mean (SD, N) ABR thresholds (dB SPL) for pure tone stimuli presented near the center of these passbands are for 3 kHz, 54.7 dB (10.1, 284); 6 kHz, 28.5 dB (8.2, 284); 12 kHz, 13.2 dB (7.3, 284); 24 kHz, 25.3 dB (11.0, 284); and 48 kHz, 33 dB (11.0, 283); and for WBN, 11.1 dB (5.2, 153).

### D. Experimental designs

#### 1. *The inhibitory effects of gaps in noise bands differing in their frequency spectrum and bandwidth*

This experiment was the central focus of this work, in its examination of the varied inhibitory effects of brief gaps of different durations embedded in different noise bands, with the gaps ending always 60 ms prior to the onset of the acoustic startle. Gaps placed in broadband noise provide an inhibitory gap function that rises steeply to near asymptotic levels

as the gap duration increases from 0 to about 4 ms in mice (Ison *et al.* 2002). When this method was used to test human listeners the “threshold value for inhibition,” defined conventionally as the duration at which inhibition was 50% of its asymptotic value, approximated the gap threshold obtained using the standard psychophysical method of constant stimuli in the same set of subjects (Ison and Pinckney, 1983).

In experiment 1 eight gap durations were presented on each of six test days (0, 2, 4, 7, 11, 16, 22, and 29 ms gaps inserted into the noise bands). One no-stimulus trial on which background activity was measured was also included in each block. A different filter setting for the noise stimuli in which the gap was embedded was used on each day, their order counterbalanced across subjects. Because gap detection improves slightly with experience in mice (Ison, 2001), prior to the beginning of this experiment the mice were given three practice days with a 10 ms gap presented at different lead times prior to the startle stimulus. In the first practice test day the noise carrier for the gap was a 70 dB wideband noise and there was no background masking noise, but for the second and third days the noise that contained the gap was either a high-frequency (16–32 kHz) or a low-frequency (4–8 kHz) band of noise mixed with the constant wideband masking noise, these counterbalanced across mice.

### **2. The inhibitory effects of the offset of noise bands differing in their frequency spectrum and bandwidth**

This experiment was intended to determine whether the effects of the spectral composition and bandwidth on reflex inhibition observed to occur with “complete” gaps in experiment 1 would be found also when only the first half of a gap, that is, the noise decrement, was used as the inhibitory event. The design of experiment 2 was very similar to that of experiment 1, save that the gap was the interval between the offset of the bandpass noise and the onset of the startle stimulus, and nine gap durations were presented on each of the six test days (0, 1, 2, 4, 7, 11, 16, 22, and 29 ms). In experiment 2 a gap was placed between the offset of the noise band and the onset of the startle stimulus and its duration was simply the time interval between the two stimulus events. The time constant and the asymptotic level of the inhibitory effect of noise offset are similar to that of a complete gap of the same duration (Ison *et al.*, 1998).

### **3. The inhibitory effects of brief increments in the level of noise bands differing in their frequency spectrum and bandwidth**

Experiment 3 was the complement of experiment 2, to determine whether the effects of spectral composition and bandwidth on asymptotic  $Rd'$  produced by complete gaps observed in experiment 1 would be observed as well if only the “second half” of the gap, that is, a noise increment, was used as the inhibitory event. In experiment 3 the increments in the background noise were 20 ms in duration and they were presented 60 ms prior to the startle stimulus. This is the same lead time as the onset of noise at the end of the gap in experiment 1. Each pulse had a duration of 20 ms. The series of trials in which the seven stimulus conditions were given

(including the five 1-octave noise bands, the 5-octave noise band, and a baseline condition) was repeated on each of three identical test days.

### **4. The inhibitory effect of brief noise bands differing in their frequency spectrum and bandwidth, when presented in quiet**

The purpose of experiment 4 was to determine if each of the noise bands used in the prior experiments was audible, as would be demonstrated by their having an inhibitory effect when they were presented as pulses in a quiet background. The design of this experiment was exactly that of experiment 3, save that the stimuli were shaped by 5 ms rise and fall times and they were presented in quiet. The noise bands presented in quiet elicited startle reactions on some trials, and these trials were eliminated from subsequent analyses in order to eliminate any possible confounding between the prestimulus reaction and the reaction to the explicit startle stimuli. The criterion used to identify startle reactions to the preliminary stimuli in each mouse was that the response were more than three standard deviations above the mean background activity level for baseline control trials on which prestimuli were not presented.

## **E. Data analysis**

The analysis of the data for reflex inhibition began with the arithmetic difference in response voltage between the mean of the two control trials and the mean for each prestimulus condition for each individual trial. (The first block of trials was not used in these analyses, in order to eliminate the sometimes unusually large responses that may appear in the first trials of a test session.) The differences were calculated within each block of trials for each subject, and were then used to calculate a standardized “effect size” measure (“ $d$ ,” Cohen, 1992) for each condition for each mouse for each test day. This measure was obtained by dividing the mean difference in ASR strength between the control condition and the prestimulus condition by the pooled standard deviation of the differences across all prestimulus conditions. This provides a  $d'$ -like response measure of the salience of each gap condition for each mouse, which we call  $Rd'$ :

$$Rd' = \frac{ASR_{\text{Baseline Condition}} - ASR_{\text{Prestim Condition}}}{\sigma_{\text{Pooled}}}$$

The  $Rd'$  measures were subjected to repeated measures analyses of variance (ANOVA) with gap duration and noise bands as within- $S$  variables (using SPSS, version 12.0). The degrees of freedom for the ANOVA were adjusted for non-homogeneity of between-cell correlations by the Huynh–Feldt procedure (Huynh and Feldt, 1976). The graphical presentation, regression analyses, and effect size calculations used GraphPad Prism software (version 4.2).

## **III. RESULTS**

### **A. Experiment 1**

Figure 1 depicts the mean (SEM)  $Rd'$  values across gap duration for the six frequency bands in which the gap was

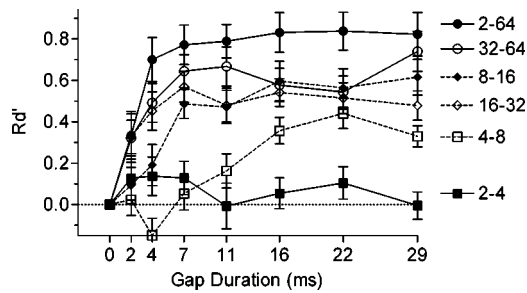


FIG. 1. Mean (SEM) levels of  $Rd'$ , showing the inhibitory effect of presenting a gap in noise just prior to the acoustic startle response in mice as a function of gap duration and the bandpass frequency of the carrier of the gaps. The gap ended 60 ms before the onset of the startle stimulus. A continuous wideband noise that was 20 dB SPL below the level of the 2–64 kHz bandpass carrier was always present (Experiment 1).

inserted. The behavioral function obtained with the 5-octave bandpass noise is typical of the effect of a gap in a wideband noise for the young CBA mouse in its rapid increase to attain a near asymptotic level of reflex inhibition at about 4 ms. The 1-octave bands with upper cutoffs of 32 kHz and 64 kHz were the equal of the wideband noise in their providing an identical early onset of strong inhibition for the 2 ms gap. In contrast this 2 ms gap provided, at best, a minimal level of inhibition when it was presented in any of the three lowest 1-octave bands with their upper cutoffs at 4 kHz, 8 kHz, and 16 kHz. Even the longest gaps in the 2–4 kHz band had no behavioral effect ( $p > 0.2$ ), while the smallest gap that had a significant effect ( $p < 0.05$ ) in each of the other conditions varied according to the bandpass frequencies: 16 ms for 4–8 kHz, 7 ms for 8–16 kHz, and 2 ms for both 16–32 kHz and 32–64 kHz. The ANOVA across all 1-octave bands provided significant main effects for frequency,  $F(4/56) = 14.11$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.50$ ; and gap duration,  $F(6/84) = 12.54$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.47$ ; and a significant interaction,  $F(24/336) = 4.02$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.22$ . The  $Rd'$  means for each of these frequency bands were fit with a one-phase exponential function and the resulting rate constants,  $K$  (SE), for each frequency band are provided in Table I. This analysis indicates that the rate of approach to an asymptote was slower for the two 1-octave bands with their upper frequencies at 8 kHz and at 16 kHz. The asymptotic mean  $Rd'$  values for the 22 and 29 ms gaps were not different between the three highest 1-octave bands ( $p > 0.20$ ), but in the adjacent bands of 8–16 kHz vs 4–8 kHz, and 4–8 kHz vs 2–4 kHz, the higher-frequency band within each pair provided a higher asymptotic performance ( $p < 0.02$ ). No 1-octave band provided as high a level of asymptotic performance as the 5-octave band of noise (the differences between the 5-octave band and each of the 1-octave bands for gaps of 22 and 29 ms were all significant,  $p < 0.01$ ). The upper limit of  $Rd'$  is

TABLE I. Time constants [ $K$ , (SE)] for the growth of  $Rd'$  in Experiments 1 and 2.

	4–8 kHz	8–16 kHz	16–32 kHz	32–64 kHz	2–64 kHz
Exp. 1:	0.02(.04)	0.14(.04)	0.53(.19)	0.38(.12)	0.34(.08)
Exp. 2:	0.51(.14)	0.57(.12)	0.51(.10)	0.39(.07)	0.57(.11)

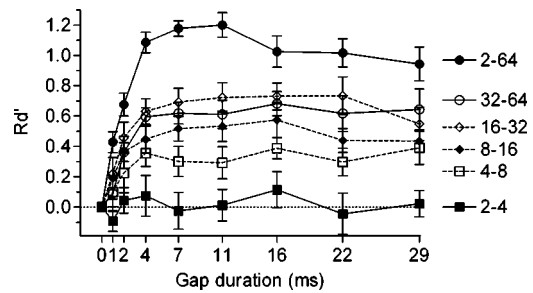


FIG. 2. Mean (SEM) levels of  $Rd'$ , showing the inhibitory effect of presenting a gap in noise just prior to the acoustic startle response in mice as a function of gap duration and the bandpass frequency of the carrier of the gaps. The gap ended with the onset of the startle stimulus. A continuous wideband noise that was 20 dB SPL below the level of the 2–64 kHz bandpass carrier was always present (Experiment 2).

set by the average background activity, which in this experiment was 1.43 (SEM=0.08). None of the asymptotic  $Rd'$  values approached this ceiling.

## B. Experiment 2

Figure 2 depicts the mean (SEM)  $Rd'$  values provided by the offset of the bandpass noise stimuli as the interval between this offset and the onset of the startle stimulus increased from 0 ms to 29 ms. As in Fig. 1, the asymptotic performance increased with the upper frequencies and the bandwidth of the noise and there was no suggestion that the offset of the lowest center frequency octave band with its upper bound set at 4 kHz had any effect on the response. The critical characteristic of these noise-offset data that contrasts with those obtained with a complete gap is that only the asymptotic levels of  $Rd'$  were differentially affected by the different frequency bands, as in this experiment all of these behavioral functions were at their asymptotic levels for a gap duration of about 4 ms. The overall ANOVA of the 1-octave band data provided significant main effects for frequency band,  $F(4/44) = 10.03$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.48$ , and for gap duration,  $F(7/77) = 11.89$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.52$ , but the interaction of these two variables had a near zero effect,  $F(28/308) = 0.99$ ,  $p > 0.40$ ,  $\eta_p^2 = 0.08$ .

The first duration at which  $Rd'$  was significant ( $p < 0.01$ ) was 1 ms for the 5-octave band; 2 ms for the three highest 1-octave bands, namely, 32–64 kHz, 16–32 kHz, and 8–16 kHz; and 4 ms for the 4–8 kHz band. The  $Rd'$  means for each of these frequency bands were fit with a one-phase exponential function and the resulting rate constants  $K$  (SE) for each frequency band are provided in Table I. There were no systematic differences apparent in these rate constants across frequency bands within this experiment, but it should be noted that the two 1-octave bands of 4–8 kHz and 8–16 kHz had considerably shorter time constants here compared to experiment 1, while the time constants for the two higher 1-octave bands of 16–32 kHz and 32–64 kHz were similar in the two experiments. An ANOVA comparing the overall asymptotic  $Rd'$  values (the mean values at 22 ms and 29 ms) in the 1-octave bands (ignoring the 2–4 kHz band in this analysis) provided a significant main effect for frequency band,  $F(3/33) = 4.79$ ,  $p < 0.01$ ,  $\eta_p^2 = 0.30$ , with a significant linear trend ( $p < 0.01$ ). Subsequent analyses

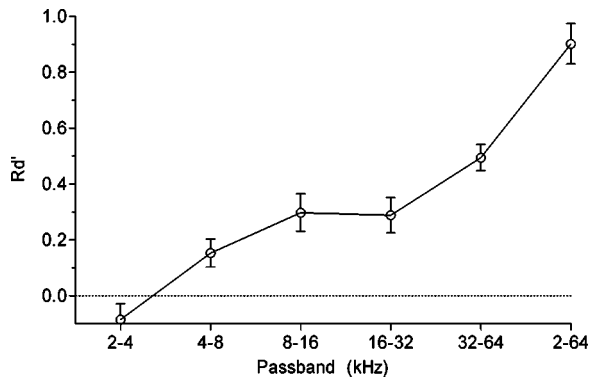


FIG. 3. Mean (SEM) levels of  $Rd'$ , showing the strength of the inhibitory effect of presenting a noise increment just prior to the acoustic startle response in mice as a function of the band-pass frequency of the pulse. The increment began 60 ms before the onset of the startle stimulus. A continuous wideband noise that was 20 dB SPL below the level of the 2–64 kHz bandpass carrier was always present (Experiment 3).

showed that the 4–8 kHz band was significantly different from both the 16–32 kHz and the 32–64 kHz bands ( $p < 0.02$ ), and marginally different from the 8–16 kHz band ( $p = 0.06$ ). The three 1-octave bands of 8–16 kHz, 16–32 kHz and 32–64 kHz did not differ from each other ( $p > 0.10$ ). The asymptotic levels for each of these 1-octave bands approximated those of experiment 1. The asymptotic level of  $Rd'$  produced by the offset of the 5-octave band was significantly greater than for in any 1-octave band ( $p < 0.01$ ). The average  $Rd'$  for background activity was 1.59 ( $SE = 0.10$ ).

### C. Experiment 3

Figure 3 depicts the mean (SEM)  $Rd'$  for each of the bandpass pulses, each presented at +20 dB over the same band within the wideband masking noise. The effect of increasing the upper frequency of each band was to produce an approximately linear increase in  $Rd'$  that approximated the asymptotic levels obtained in the prior experiments. The ANOVA of these data provided a significant main effect for frequency band,  $F(5/100) = 64.73$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.76$ , which had a significant linear component,  $F(1/20) = 214.88$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.92$ . All of the pulses except the 2–4 kHz band provided significant levels of  $Rd'$  ( $p < 0.01$ ), and the  $Rd'$  means for all adjacent bands were significantly different from each other ( $p < 0.05$ ), save for the 16–32 kHz and 32–64 kHz bands. The average  $Rd'$  for the no-stimulus activity condition was 1.72 ( $SEM = 0.12$ ).

### D. Experiment 4

Figure 4 depicts the mean (SEM)  $Rd'$  describing the effect size for inhibition for each of the bandpass pulses presented in quiet, excluding trials in which startle responses to the explicit startle stimulus were preceded by a response to the initial stimulus (see methods). The ANOVA of these data yielded a significant main effect for frequency band  $F(5/55) = 48.44$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.82$ , which had significant linear and quadratic components,  $F(1/11) = 105.73$ , 21.35,  $p < 0.001$ ,  $\eta_p^2 = 0.91$ , 0.66. In contrast to the preceding experiments, here the lowest 1-octave band of 2–4 kHz signifi-

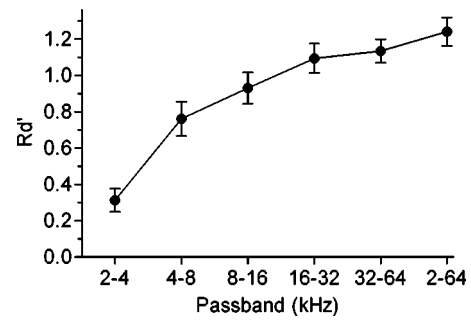


FIG. 4. Mean (SEM) levels of  $Rd'$ , showing the inhibitory effect of presenting a noise pulse just prior to the acoustic startle response in mice as a function of the bandpass frequency of the pulse. The pulse began 60 ms before the onset of the startle stimulus. These stimuli were presented in quiet (Experiment 4).

cantly inhibited the startle response (mean  $Rd' = 0.31$ , 95% confidence interval = 0.17, 0.45,  $p < 0.001$ ). The lowest adjacent bands from 2–4 kHz to 4–8 kHz, to 8–16 kHz, and to 16–32 kHz were all significantly different from each other ( $p < 0.005$ ), but the higher bands of 16–32 kHz, 32–64 kHz, and 2–64 kHz did not significantly differ ( $p > 0.01$ ). The average  $Rd'$  for the no-stimulus activity condition was 1.53 ( $SEM = 0.09$ ). This value was significantly higher than the  $Rd'$  for the 2–64 kHz band,  $t(11) = 4.14$ ,  $p < 0.002$ , indicating that inhibition was not limited by an artificial ceiling.

Gaps or noise offsets never elicit startle reactions in the mouse, but in this experiment the brief 1-octave bandpass stimuli presented in quiet did elicit a small increased level of prestartle activity while the 5-octave wideband noise provided a relatively vigorous response. The response to the 32–64 kHz 1-octave noise burst was slightly elevated compared to the no-prestimulus condition, at a mean of 452(45) compared to 302 (19),  $t(11) = 2.98$ ,  $p < 0.05$ . In contrast, the mean response to the 5-octave 2–64 kHz stimulus (presented at 67 dB SPL) was substantial at 1414 (209), about one-third of the amplitude of the control response to the explicit startle stimulus presented at 110 dB SPL, which produced a mean response of 4165 (411). The median number of trials on which criterion startle responses occurred in response to the 2–64 kHz bandpass stimulus was 10.5 (range = 0 to 25) out of a possible 30, while the median number for the 32–64 kHz stimulus was 3.0 (range 0 to 13). Few instances of a criterion response occurred for the other stimuli.

## IV. DISCUSSION

Experiment 1 showed that gap thresholds and the time constants for the growth of  $Rd'$  improved with an increase in the high-frequency components of the 1-octave wideband noise carriers extending beyond the upper end of the spectral region where the mouse is most sensitive, e.g., up to about 16 kHz; and then was at least maintained when the noise bands included the increasingly higher frequencies to which mice are increasingly less sensitive. The improvement in temporal acuity observed with higher-frequency noise bands that maintain a constant relative bandwidth is consistent with the data obtained in human listeners by Buus and Florentine (1985). In fact, the entire pattern of the beneficial effect of increasing the high-frequency content of the noise bands pre-

viously seen with human listeners was duplicated in the mouse, save for its being transposed by about two octaves. These data obtained in the mouse are also similar to those obtained in human listeners by Buus and Florentine (1985), Fitzgibbons (1983), and Snell *et al.* (1994) in their showing that increasing the relative carrier bandwidth enhances temporal acuity, as the asymptotic effect of the 5-octave band was higher than any of the 1-octave bands. These data indicate that the mouse, like the human, must also be able to combine information across frequency channels in order to achieve high levels of temporal acuity.

In experiment 2 the magnitude of  $Rd'$  increased rapidly with an increase in delay time between the noise decrement and the onset of the startle stimulus. The asymptotic level of  $Rd'$  was greater with an increase in the high-frequency components of the 1-octave bands of noise, and also with the increase in bandwidth from 1 to 5 octaves. But there was no change in the time constant of the increase in  $Rd'$  with an increase in gap duration in this experiment, and near-asymptotic levels of  $Rd'$  were reached within 4 ms for all of the carriers. If it can be assumed that noise decrement by itself captures the effect of a noise decrement at the start of a regular gap, then the data of experiment 2 suggest that the beneficial effect of the highest-frequency components of the complete gap on time constants for the growth of  $Rd'$  results from some beneficial effect of these high frequencies for encoding the noise increment at the end of the gap, rather than differences in encoding the noise decrement at the beginning of the gap. Recent data on "cross-frequency-channel" gaps in the mouse (Moore *et al.*, 2005) support this hypothesis, in their showing that the combination of an onset of a relatively high-frequency noise band at the end of a gap and the offset of a relatively low-frequency band at its beginning provides better gap detection than the reverse order.

Experiment 3 was designed to isolate the effect of the noise increments at the end of the gap, by presenting each noise band as a discrete pulse at the same 60 ms lead time before the startle that followed the end of the gap in experiment 1. The inhibitory effect of these bandpass noise increments as revealed in  $Rd'$  approximated their asymptotic effect when they were present at the end of the gap, suggesting that in this comparison gap detection and increment detection shared a common behavioral effect. This finding may be analogous in mice to those of Plomp (1964) and others, who have shown that for human listeners gap detection thresholds are fundamentally related to increment thresholds. These data suggest that the increment detection threshold for bands of noise may improve with an increase in their bandwidth in mice as well as in human listeners (Grose and Hall, 1997), and possibly in their high-frequency components as well.

Experiment 4 was undertaken to determine if all of the noise bands were audible for the mouse if presented in quiet. Although there were differences in effectiveness between the bands of noise, all provided a significant inhibitory effect. The large difference between the 2–4 kHz band and the next highest band of 4–8 kHz is possibly related to the poor sensitivity of the mouse for this very low-frequency band, but this band was at least audible. The relatively high level of startle responding to the 5-octave noise band compared to

any of the 1-octave bands suggests that the sensory processes that drive the acoustic startle reflex must summate across frequency bands.

The outcome of these experiments suggests that the fundamental bases of high temporal acuity in humans and in mice are different from those that affect absolute sensitivity, and depend on the high-frequency components of the noise band in which the gap is embedded and on its relative bandwidth. While there are other hypotheses that have been persuasively proposed to explain similar findings in some earlier experiments, we suggest that these other hypotheses may be restricted in their domain to relatively low-frequency stimuli that first are not relevant for a high-frequency species like the mouse, and second, even in human listeners do not provide the high levels of temporal acuity that are routinely found for broadband stimulation that includes high frequencies.

One alternative to the "high-frequency" hypothesis is the "high-absolute-bandwidth" hypothesis, and because these two characteristics of the noise carrier are often confounded, we must concede (with Buus and Florentine, 1985, p. 166) that these hypotheses are typically difficult to distinguish even in experiments that seem to support the importance of high-frequency stimulation. In experiments performed with human listeners gaps have been embedded in noise bands as narrow as 50 Hz (e.g., Eddins *et al.*, 1992; Shailer and Moore, 1985) or as wide as 12 000 Hz (Snell *et al.*, 1994). Center frequencies of the noise band may be as low as 200 Hz (Shailer and Moore, 1983) or as high as 7 000 Hz (Buus and Florentine, 1985). The upper frequencies in the noise band may be as low as 250 Hz (Shailer and Moore, 1983) or as high as 12 000 Hz (Snell *et al.*, 1994). It is not surprising that gap thresholds obtained under these very different conditions are very different, varying from about 2 ms at best, which can be obtained with very wide noise bands that necessarily include very high frequencies (Snell *et al.*, 1994), to thresholds in excess of 30 ms at worst, obtained with narrow band noise that includes only very low frequencies (Eddins *et al.*, 1992). In one report using narrow band noise at low frequencies, an increase in the upper frequency content of noise band with the same absolute width resulted in an improved threshold (Shailer and Moore, 1985); in another report an increase in the upper frequency content of noise bands with the same absolute bandwidth resulted in no change in gap thresholds (Eddins, *et al.*, 1992); and in a third report (Snell *et al.*, 1994) an increase in the high-frequency content of a noise band with a constant absolute bandwidth resulted in an improved gap threshold with an initial increase in the upper frequency of the noise, but as the upper frequencies further increased then gap thresholds got much worse. These profound differences obtained with supposed common manipulations suggest that the gap detection for human listeners is affected by different processes as the stimulus conditions vary across the spectral range of human hearing: not all of these effects may appropriately transfer across species.

Moore (2003) described the inherent intensity fluctuations that are present in narrow band noise, and affect gap detection if the noise bandwidth is less than the bandwidth of the appropriate auditory filter. These fluctuations, produced by sparse sampling, so confuse the listener that the percep-

tual task becomes “gap discrimination” between long target gaps and random dips in stimulus level, rather than gap detection. In human listeners these random fluctuations would be apparent for noise bands with bandwidths below about 250 Hz and upper frequencies below about 1000 Hz, but this acoustic explanation of poor gap thresholds in “absolute” frequency-defined narrow band noise would not apply to mice. If the auditory filter is narrow relative to the noise band, then the acoustic fluctuations are less noticeable, and it is the time constant of the filter that limits gap detection (Moore, 2003). The time constant of a filter is proportional to the reciprocal of its absolute bandwidth, and because the bandwidth of auditory filters increases with their center frequency (Scharf, 1961), then high-frequency filters must have short time constants. Filters with long time constants “ring” at noise offset, and thus the programmed gap would be partially filled with continued activity. This effect must increase gap detection thresholds in human listeners when the gap is inserted in relatively low-frequency noise. Theoretical considerations (de Boer, 1985) as well as direct measures of the rate of decay in auditory nerve firing at noise offset (Pfeiffer and Kim, 1972) indicate that auditory filter characteristics would limit gap detection only for auditory filters with their center frequencies below about 1000 Hz. Thus, this second explanation of poor gap thresholds in humans for relatively low-frequency stimuli also would not apply to gap detection in the mouse.

Noise bands with a low-pass cutoff set at 1 kHz yield gap thresholds of about 10 ms in human listeners (Fitzgibbons, 1983; Snell *et al.*, 1994) but gap thresholds continue to improve rapidly with an increase in the low-pass cutoff from 1 kHz up to about 4 kHz and continue to improve for higher frequencies, but more slowly (Fitzgibbons, 1983; Snell *et al.*, 1994). What is responsible for this further increase in sensitivity to gaps? The experiment of Eddins *et al.* (1992) indicated that the increase in absolute bandwidth can be a critical variable, but the persuasive outcome of their clever experiment appears to be restricted in applicability to the particular choice of bandwidths and upper frequencies, given the different results reported by Shailer and Moore (1985) and Snell *et al.* (1994), as described above. From a physiological perspective the enormous biological factor limiting the general applicability for the gap detection of a “constant absolute bandwidth” is that the position along the basilar membrane is allocated to log frequency, that is, to near constant octaves, not linear frequency (Greenwood, 1990). Adding to the apparent heavy weighting of low frequencies along the basilar membrane is the fact that the density of sensory receptors is not uniform, but is highest towards the low-frequency apex (Wright *et al.*, 1987). These characteristics of the auditory periphery must certainly be important for high absolute sensitivity, and they are probably similarly important for auditory tasks that depend on phase locking. Perhaps they are also important in affecting gap detection for low-frequency narrow band noise, but they are unlikely to play a significant role in determining the most sensitive gap detection thresholds, as these are evident only with very wide noise band signals that contain very high-frequency components.

Shailer and Moore (1983) hypothesized that the best gap detection thresholds, which they obtained for spectral frequencies above the spectral regions with the best absolute sensitivity, are the result of neural processing. The data of Zhang *et al.* (1990) support this conclusion, in their showing in chinchilla auditory nerve fibers that thresholds for gaps embedded in broadband noise improve continuously with the CF of the fiber, over a range of CF from below 2 kHz to above 8 kHz. Similarly, Eggermont (1999) found with multiunit recording in the auditory cortex of the cat that the mean thresholds for gaps in noise decreased with an increase in CF, over a range from 2 kHz up to about 20 kHz. Chinchillas and cats have a broad range of very sensitive absolute thresholds, that may extend from about 1–2 kHz to about 8–10 kHz in both species (Fay, 1988, pp. 347–352; 357–362), and so these electrophysiological data agree with the principles we propose for mice and humans, that temporal acuity improves with high-frequency stimulation and is maintained for high frequencies above those that provide the best absolute thresholds.

## V. CONCLUSIONS

The behavioral findings obtained here in the mouse confirm those obtained with human listeners in showing a similar pattern of first improvement and then the maintenance of highly sensitive gap thresholds with an increase in the high-frequency components of the noise bands and with an increase in their bandwidth. Both mouse and human data, as well as the data obtained in electrophysiological experiments, show that temporal acuity is relatively independent of the mechanisms that contribute to or develop from differences in absolute sensitivity, given at least a moderate level of audibility for the carrier. Remarkably, mice and human listeners have species-specific spectral regions of peak absolute sensitivity that differ by as much as two to four octaves depending on how they are measured, but share with other mammals gap thresholds that are at least very similar, and may be identical. Differences in best frequencies for absolute thresholds vary with species-specific resonances of the ear, and match the resonances of the vocal apparatus and the resulting dominant frequencies in the vocal output in mice and in humans. In contrast, the similar values for gap detection that are found across mammalian species encourage the hypothesis that temporal acuity evolved to match the common rate of amplitude modulation that has been found in the envelope of their vocal output, and not its spectral content (Geissler and Ehret, 2002).

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