Infants' sensitivity to broadband noise

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Infants have higher pure-tone thresholds than adults. One explanation is that infants do not adopt the frequency-selective listening strategy that adults use when detecting tones. In contrast to other models of infants' immature sensitivity, the listening strategy account predicts that infants will be more sensitive to broadband sounds, relative to adults. Infants 7–9 months old were tested in two experiments to examine their sensitivity to broadband noise. Unmasked and masked thresholds for a 1000-Hz tone and for broadband noise were estimated adaptively for infants and adults using an observer-based behavioral procedure. The difference between infants and adults in unmasked threshold were 14 and 7 dB for tones and noise, respectively. The difference between infants and adults in masked threshold were 10 and 5 dB for tones and noise, respectively. Psychometric functions for detection of broadband noise were also obtained from some infants and adults. Infants' psychometric functions were similar to those obtained in tone detection with shallower slopes and lower upper asymptotes than adults'. This suggests that the relative improvement in infants' threshold for broadband noise is not due to greater attentiveness to the noise. A model of infants' sound detection invoking inattentiveness, listening strategy, and an unspecified source of internal noise may account for the characteristics of the infant psychometric function. © *2001 Acoustical Society of America.* [DOI: 10.1121/1.1365112]

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I. INTRODUCTION

Infants' detection thresholds for tones, in quiet or in noise, are higher than those of adults (reviewed by Werner and Gray, 1998). Infants' pure-tone thresholds at 1000 Hz are about 15 dB higher than adults' in quiet and about 8 dB higher than adults' in noise. The age difference for thresholds in quiet is partially accounted for by immaturity of the middle ear (Keefe *et al.*, 1993). The remaining 8-dB age difference in sensitivity has been explained in various ways.

Inattentiveness has been offered as an explanation for many age differences in performance on psychophysical tasks, including the infant–adult detection threshold difference. Inattentiveness is commonly modeled as guessing on some proportion of trials. The guessing rate that would be required to account for infants' detection thresholds, however, is much greater than infants' responses to clearly audible tones would suggest. For example, Bargones, Werner, and Marean (1995) found that infants detected apparently audible tones about 85% of the time, consistent with a guessing rate of 30%. Analyses by several investigators have suggested that a guessing rate of about 50% would be necessary to account for the observed age difference in threshold (Allen and Wightman, 1994; Bargones *et al.*, 1995; Schneider and Trehub, 1992; Viemeister and Schlauch, 1992; Werner, 1992; Wightman and Allen, 1992). Thus, inattentiveness alone does not appear to be a sufficient explanation for the observed immaturity of infants' pure-tone detection thresholds, although it is likely to make some contribution.

Schneider, Trehub, and colleagues have argued that the most reasonable explanation for infants' immature detection thresholds is immaturity of the nonlinear ''transfer function mapping sound pressure onto neural activity,'' resulting in slower growth of neural activity with increasing sound level in the infant system than in the adult system (Schneider and Trehub, 1992; Schneider *et al.*, 1989, p. 41). Thus, a higher signal-to-noise ratio would be required to produce a given level of neural activity in the infant auditory nervous system than in the adult auditory system. Under the assumption that detection by infants and adults requires the same increase in neural activity, infants' detection thresholds would be higher. It might be expected that immaturity of the relationship between sound intensity and primary neural activity would be reflected in the characteristics of auditory evoked potentials, and there is some evidence that evoked potentials mature along a time course similar to that of masked thresholds (Durieux-Smith *et al.*, 1985; Eggermont, 1985; Fabiani *et al.*, 1979; Hall, 1992). However, there is no direct evidence linking immaturities of evoked potentials to those of sensitivity after 3 months of age.

Bargones *et al.* (1995) pointed out that the characteristics of the infant psychometric function for pure-tone detection and the observed age differences in threshold could be accounted for by immaturity of listening strategies. There is a wealth of evidence indicating that adults' listening strategy in pure-tone detection is to monitor the output of the auditory filter centered at the frequency of the expected signal (e.g., Green and Swets, 1988; Hafter and Schlauch, 1992; Scharf, 1987). Infants, however, may not monitor the output of the optimal auditory filter as adults do. In fact, using the probe-signal method, Bargones and Werner (1994) demonstrated that infants listen less selectively in the frequency domain than adults do. If infants monitor the output of an auditory filter centered at a frequency well removed from that of the expected tone, their psychometric function would be predicted to be shallower than that of adults, as observed by Bargones *et al.* (Hübner, 1993). In addition, the expected age difference in threshold would be on the order of 7 dB (Dai, Scharf, and Buus, 1991), close to the observed age difference in masked threshold at 1000 Hz. We refer to this listening strategy as the ''wandering listening band.''

The observed age differences in pure-tone sensitivity as well as the findings of Bargones and Werner (1994) could also be explained by infants' monitoring a broad range of frequencies in pure-tone detection, rather than a narrow frequency range that is not centered on the frequency of the expected tone. Hübner (1993) has shown that such a ''broadband'' listening strategy will produce a steeper psychometric function than monitoring the output of a single auditory filter centered on the frequency of the expected tone. Because the psychometric functions of infants and children are typically shallower than those of adults, the broadband listening strategy has not been discussed in any detail as a potential explanation for age-related differences in sensitivity (e.g., Allen and Wightman, 1994; Bargones *et al.*, 1995). If infants are broadband listeners, then additional factors must be invoked to account for the slope and upper asymptote of their psychometric function. We return to this point at the end of the paper.

These alternative explanations for infants' detection of frequency-specific stimuli make different predictions concerning infants' detection of broadband stimuli. The growth-of-neural-response explanation predicts that infants' detection of broadband noise, for example, would be similar to their detection of pure tones with about the same threshold relative to adults. The listening strategy account predicts that infants will be relatively better at detecting broadband noise, because broadband noise contains energy at all frequencies, making selective listening more or less irrelevant.[1] If infants listen in a more mature, broadband way when detecting broadband sounds, a threshold improvement on the order of 7 dB would be predicted relative to pure-tone thresholds (Dai *et al.*, 1991). A change in inattentiveness could lead to relatively better infant thresholds for broadband noise, but only if infants are more attentive to noise than to tones. If infants are perfectly attentive to noise, threshold for broadband noise would improve at most by 2 or 3 dB relative to pure-tone thresholds (see analyses by Viemeister and Schlauch, 1992; Schneider and Trehub, 1992; Werner, 1992; and Wightman and Allen, 1992).

Several investigators have noted that infants appear to be more responsive to broadband than to narrow-band sounds (e.g., Eisenberg, 1976; Gerber and Mencher, 1979; Turkewitz, Birch, and Cooper, 1972). Different investigators have published thresholds for sounds of different bandwidths, but no consistent interactions between age and bandwidth are evident in cross-study threshold comparisons. Berg and her colleagues examined the effects of bandwidth on infants' detection threshold (Berg, 1991; Berg and Boswell, 1995). Berg obtained unmasked thresholds for 1/3-octave filtered clicks and 300-ms noise bursts centered at 4000 Hz, and for unfiltered clicks and 300-ms broadband noise bursts to examine the effects of bandwidth on temporal summation in infants' detection in quiet. The difference between infants' and adults' thresholds was smaller for the broadband noise burst than for the 1/3-octave filtered noise burst, but the opposite appeared to be true for the clicks. Berg's thresholds for ''long-duration'' 4000-Hz tones and 4000-Hz, octave-band noise detected in quiet and in noise are consistent with infants' being more sensitive to the broader bandwidth sound, but the tone and noise band were also of different durations. Berg and Boswell conducted a similar study, but with 500-Hz tones and octave-band noises. In this case, no interaction between bandwidth and age effects on sensitivity was observed. In sum, there is no compelling evidence that infants' sensitivity is dependent on bandwidth, but the issue has not been directly addressed.

The purpose of the present study was to compare infants' and adults' detection of a 1000-Hz tone and a broadband noise under unmasked and masked conditions. We chose 1000 Hz, because we have previously studied infants' detection at that frequency extensively (e.g., Bargones and Werner, 1994; Bargones *et al.*, 1995; Werner and Bargones, 1991; Werner and Marean, 1991). In experiment 1, thresholds for unmasked and masked tones and noise were estimated adaptively for the two age groups. Experiment 2 was a preliminary examination of the infant psychometric function for detection of unmasked noise.

II. EXPERIMENT 1: THRESHOLDS FOR MASKED AND UNMASKED TONES AND BROADBAND NOISE

A. Method

1. Subjects

Seventy-three 7–9-month-old infants and 40 18–30-year-old adults provided thresholds. The average age of the infants was 33.0 weeks (s.d.=4.8 weeks), and the average age of the adults was 22.1 years (s.d.=2.8 years) at the first test session. All subjects were free of risk factors for hearing loss, assessed by parental- or self-report, had had no more than two episodes of otitis media, had not been under treatment for otitis media within the prior week, and were healthy on the day of testing. All subjects passed screening tympanometry at each test session, with a peak admittance of at least 0.2 mmhos at a pressure between -200 and 50 daPa. No subject had participated in other psychoacoustical experiments or had more than 2 years of musical training. The data of 64 additional infants who participated in the study were excluded from analysis; 21 infants did not reach training criterion, 8 did not provide enough data to estimate a threshold, 35 completed testing but were excluded because of high false-alarm rate, low probe trial response rate, or high variability of reversals in the adaptive run. The data of 3 adults were excluded, 1 due to equipment failure, 1 due to failure to meet training criteria, and 1 due to highly variable reversals.

2. Stimuli and procedure

The stimuli were a 1000-Hz tone and a broadband noise. The tone was digitally produced, attenuated, filtered, and amplified. The noise was produced by a noise generator, attenuated, low-pass filtered (48 dB/oct) at 6000 Hz, and amplified. Signal duration was 500 ms, with 16 ms rise–fall. When used, the same noise was presented continuously as a masker at a level of 20 dB N_0. All stimuli were presented via an Etymotic ER1 insert earphone in a foam tip, trimmed to fit the ear canal as necessary. Stimuli were calibrated in a Zwislocki coupler. Each subject was tested in one of four detection tasks: unmasked tone detection, unmasked noise detection, masked tone detection, or masked noise detection. In the masked noise detection task, the signal was produced by increasing the level of the background noise for 500 ms. The stimuli and experiment were controlled by computer.

Infants were tested using an observer-based procedure (Werner, 1995). This is a go/no-go procedure in which an observer decides on each trial whether a signal was presented to the infant based solely on the infants' behavior. The infant was tested while sitting on the parent's lap in the test booth. An assistant in the test booth kept the infant entertained and attentive by manipulating silent toys on a table in front of the infant. The parent and the assistant wore headsets and listened to masking sounds to make certain that they could not hear any of the sounds presented to the infant. The observer was seated outside the booth and watched through a window or on a video monitor. When the infant was quiet and alert, the observer began a trial. Signal and no-signal trials were presented with equal probability. Four tone or noise bursts occurred, at 1-s intervals, on signal trials. On no-signal trials, either no sound was presented or the background noise continued unchanged for 4 s. The observer's response had to be recorded during the trial. The observer had no prior knowledge of trial type, but received feedback after each trial. The infant was reinforced for responding on signal trials by the activation of a mechanical toy.

Each session began with a training phase, in which the signal was presented at levels expected to be clearly audible to the infants. The infant/observer team was required to achieve 80% correct on both signal and no-signal trials to meet training criterion. The number of trials to criterion averaged 20.3 (s.d. = 11.2) and did not vary systematically with condition. Thresholds were then determined adaptively using a one-up, two-down algorithm. Tone level started at 45 dB SPL in quiet and at 65 dB SPL in noise. Noise burst spectrum level started at 5 dB SPL in quiet and at 35 dB SPL in noise. Initial step size was 10 dB; step size varied during a run according to PEST rules (Taylor and Creelman, 1967). Only signal trials affected the direction of the adaptive track. Testing continued until at least eight reversals were obtained; the average of the last six reversals was taken as threshold. Thresholds were only accepted if the false-alarm rate during the run was less than 0.4. Infant false-alarm rate averaged 0.25. In every six trials, a ''probe'' trial was included at a randomly determined position. Probe trials were signal trials with the signal level set at the training level. The outcome of probe trials did not affect the adaptive track, but the thresholds were only accepted if the response rate on probe trials was greater than 0.6. Infant probe response rate averaged 0.94. Infant thresholds were based on an average of 40.9 trials (s.d. = 8.4) with no differences across conditions.

Adults were tested in as similar a way to the infants as possible. Adults listened alone in the test booth and were instructed to respond when they heard a sound that would make the mechanical toy come on. They were told that their goal was to make the toy come on as much as possible. Training and testing procedures and criteria were the same as those used for the infants. Adults reached training criteria in a minimum number of trials (M = 10.0, s.d. = 2.6), had a mean false-alarm rate of 0.01 (s.d. = 0.05), a universal probe response rate of 1.0, and thresholds based on an average of 44.1 trials (s.d. = 7.7).

The number of sessions required to obtain a threshold was 2–4 for infants (mode = 2) and 1 for adults. Infants who reached training criterion but did not produce a threshold in a session, completed only a ''reminder'' phase, 2–3 trials at the original training level, prior to testing in subsequent sessions. All visits were completed within a 2-week period.

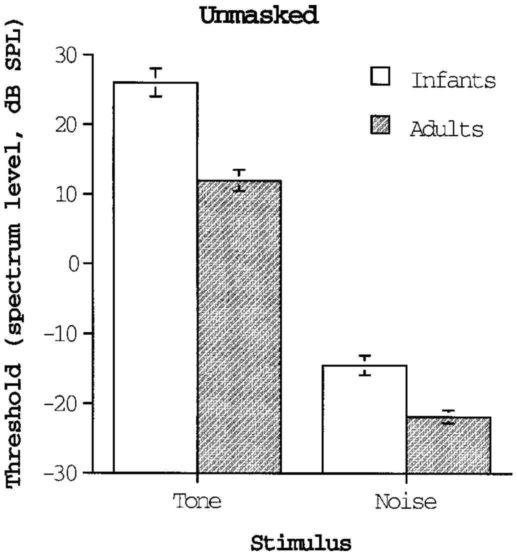

FIG. 1. Average (±1 standard error) unmasked thresholds for a 1000-Hz tone and a broadband noise, for infants and adults, from experiment 1.

B. Results

All thresholds were calculated as the spectrum level of the signal in dB SPL. The mean detection thresholds for unmasked tones and noise are plotted in Fig. 1. Infant thresholds for both tones and noise were higher than those of adults, but it appears that infants are relatively better at detecting noise than they are at detecting tones in a quiet background. Because there were apparent differences in variability across experimental conditions, nonparametric tests of statistical significance are reported, although parametric analysis produced the same results. The Mann-Whitney U test, corrected for ties, indicated that the difference in threshold between infants and adults was highly significant both for tones ($p < 0.001$) and for noise ($p < 0.001$). More important for the present question, however, is whether the size of the infant–adult difference depends on the stimulus. The adjusted ranks test (Sawilowsky, 1990) was used to test the age×stimulus interaction. The interaction was significant ($p < 0.05$). Thus, the infant–adult threshold difference for tones, about 14 dB, is significantly greater than the infant–adult threshold difference for noise, about 7 dB, when detection is tested in quiet.

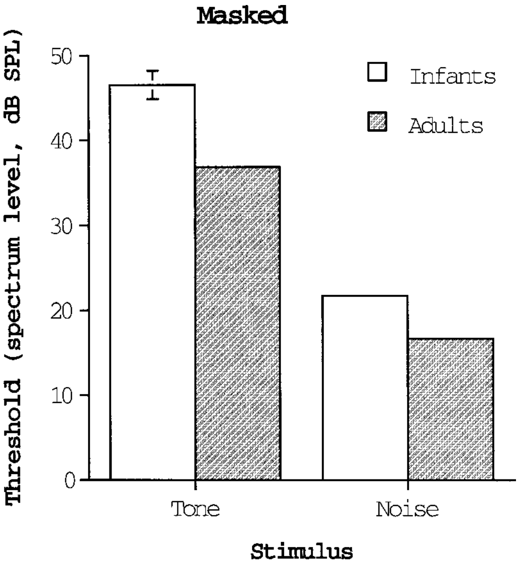

FIG. 2. Average (±1 standard error) masked thresholds for a 1000-Hz tone and a broadband noise, for infants and adults, from experiment 1. The masker was a broadband noise. Some of the error bars are very small; the standard deviation in those conditions was 2–3 dB.

The mean detection thresholds for masked tones and noise are plotted in Fig. 2. Again, infants' thresholds appear to be higher than those of adults in both stimulus conditions, and again, it appears that infants are relatively better at detecting noise than they are at detecting tones. The statistical analyses confirmed that the difference between infants' and adults' thresholds was highly significant in both stimulus conditions ($p < 0.001$ for tones and for noise), but the adjusted ranks analysis also indicated a significant age×stimulus interaction ($p < 0.01$). Thus, in a noise background, infants' thresholds for detecting noise are relatively more mature than their thresholds for detecting tones. The infant–adult threshold difference for tones was about 10 dB, while that for noise was about 5 dB.

C. Discussion

The 1000-Hz thresholds reported here are comparable to those previously reported for both infants and adults. The thresholds for an unmasked 1000-Hz tone in quiet are within 5 dB of those reported by Bargones *et al.* (1995) for adults and for infants of the same age, tested using the same transducer, and by Nozza and Wilson (1984) for 6-month-old infants and for adults, tested using a TDH-49 earphone calibrated in a 6-cc coupler. Perhaps more importantly, the age differences in threshold at 1000 Hz reported in these studies were 16 dB (Bargones *et al.*, 1995) and 14 dB (Nozza and Wilson, 1984), while that observed in the present study was 15 dB. Similarly, signal-to-noise ratio (S_0/N_0) at masked threshold was within 5 dB of that reported for 1000-Hz tones in the Bargones *et al.* and Nozza and Wilson studies, as well as to those reported by several investigators for tones of other frequencies (Berg, 1991; Berg and Boswell, 1995; Nozza and Wilson, 1984). The age difference in masked threshold reported by Bargones *et al.* and by Nozza and Wilson, 8 dB, is close to the 9.5-dB difference found here. Berg reports an age difference of 12 dB at 4000 Hz and Berg and Boswell report an age difference of 10 dB at 4000 Hz.

The thresholds for detecting a masked noise in this study are more or less consistent with previous reports. For adults, the threshold here was about -4 dB S_0/N_0. Green and Sewall (1962) report values for trained observers tested in a two alternative, forced-choice (2AFC) paradigm of -10 to -8 dB. Berg and Boswell's (1998) thresholds for octave-band noise increments for adults tested in an infant test procedure are equivalent to -5 or -6 dB S_0/N_0. For infants, estimates of S_0/N_0 at threshold for broadband sounds range from -2 to 4 dB (Kopyar, 1997; Bull, Eilers, and Oller, 1984; Schneider, Bull, and Trehub, 1988). The current estimate of -0.43 dB falls within this range. Thresholds for a broadband noise in quiet have not been previously estimated for infants,^{2} and in fact have not often been reported for adults. Yost and Klein (1979), however, reported a threshold of 5 dB SPL for broadband noise, low-pass filtered at 10 000 Hz and Raab, Osman, and Rich (1963) reported a threshold of 4 dB SPL for broadband noise, low-pass filtered at 7000 Hz for adult subjects. The threshold for detection of noise bursts in quiet here, low-pass filtered at 6000 Hz, was about 16 dB SPL overall level, quite a bit higher than the published reports. Whether this difference results from training, the difference in transducers, the difference in test method, or some other variable is not clear.

Experiment 1 demonstrates that infant's thresholds are closer to those of adults when they are detecting a broadband noise than when they are detecting a pure tone, for both masked and unmasked signals. Models that account for threshold immaturity in terms of primary sensory immaturity, such as reduced growth of neural response with increasing intensity, do not predict greater sensitivity to broadband sound in infants. The present finding is consistent with the idea that infants do not listen in a frequency selective way, or at least that they are not listening at the optimal frequency, when they are detecting a pure tone. A model of threshold immaturity based on inattention also predicts better infant sensitivity to broadband sounds, if one assumes that infants are inattentive less often to broadband than to narrow-band sounds.

The characteristics of the psychometric function for broadband detection could help to distinguish between listening strategy and inattention explanations of the improvement in infants' threshold for broadband noise relative to pure tones. The slope of adults' psychometric function for detection has generally been reported to be independent of bandwidth (Buss *et al.*, 1986; Green and Sewall, 1962; but see de Boer, 1966; Scholl, 1961). If infants are more attentive to broadband noise than to tones, but they listen as adults do, the prediction is that the psychometric function will be steeper than that for detecting tones and have an upper asymptote closer to 1. The inattention model also predicts that correcting or ''rescaling'' the infant psychometric function, using a guessing rate based on the upper asymptote, would make the slope and threshold for tone and noise equivalent, relative to those of adults. An upper asymptote of the infant psychometric function less than or equal to that for tones would argue that infants are not more attentive to noise than to tones.

Either a wandering listening band or a broadband listening strategy hypothesis would predict an adultlike psychometric function slope and asymptote for detection of broadband noise. In the case of pure-tone detection, if infants listen at a frequency removed from the signal frequency, excitation increases as a function of both the intensity of the tone and the frequency monitored by the infant, presumably a random variable. If infants listen to a broad range of frequencies in pure-tone detection, excitation increases as a function of both the intensity of the tone and the bandwidth monitored by the infant. In the case of broadband noise detection, excitation increases as a function of intensity in the same way at all frequencies. If infants do not match their listening bandwidth to the noise bandwidth, their threshold could still be somewhat elevated relative to adults', but the psychometric function slope in this case should be adultlike.

III. EXPERIMENT 2: PSYCHOMETRIC FUNCTIONS FOR DETECTION OF UNMASKED BROADBAND NOISE

A. Method

1. Subjects

Ten infants and 11 adults, meeting the same inclusion criteria as in experiment 1, provided psychometric function data. At the first test session, the average age of the infants was 32.6 weeks (s.d.=1.7 weeks), and the average age of the adults was 22.8 years (s.d.=3.5 years). Four additional infants participated in the study but did not provide enough data to fit a psychometric function. Eight additional infants and four additional adults produced psychometric functions with slope not significantly greater than zero; these functions were excluded from analysis.[3] Ten infants were tested at just one suprathreshold level to estimate the upper asymptote of the psychometric function. The average age of these infants was 34.6 weeks (s.d.=2.6). Three additional infants did not complete testing in this condition.

2. Stimuli and procedure

The stimulus was the same noise used in experiment 1, low-pass filtered at 6000 Hz, and presented in bursts of 500-ms duration.

The same training procedures were used as in experiment 1. The average number of training trials required to reach criterion was 26.9 (s.d.=8.7) for infants and 13.1 (s.d.=4.2) for adults. Once the subject had reached training criteria, a block of 35 test trials was completed in which 15 trials were no-signal trials, 15 trials were signal trials with signal level fixed, and 5 were probe trials with the signal level at the initial training level. Once the infant had completed the training procedure, only a few reminder trials were presented prior to testing in subsequent visits. Infants who provided psychometric function data were tested at signal spectrum levels of −15 and −10 dB SPL, counterbalanced for order across subjects, in the first two visits to the lab. Depending on performance in these two conditions, the infant was tested at −20 or −5 dB SPL spectrum level, and then at levels 5 dB higher or lower, in order to place as many data points as possible along the slope of the psychometric function. If performance was worse at −10 dB SPL than at −15 dB SPL, −10 dB SPL was retested. At least five sessions were attempted for each infant. A similar procedure was used for adults, except that the initial spectrum levels were −30 and −25 dB SPL. A test block was accepted only if the response rate on probe trials was greater than 0.6. The average response rate on probe trials was 0.8 for infants (s.d.=0.24) and all adults responded on all probe trials. In the final sample, four infants and four adults provided four data points, seven infants and five adults provided three data points, and two infants and two adults provided two data points.

The infants who provided upper asymptote data were tested only at 5-dB SPL spectrum level, with no probe trials. The choice of level was based on the psychometric functions. Although not all psychometric functions had a well-defined upper asymptote, the highest level at which a psychometric function was estimated to reach asymptotic performance was −1.5 dB and most were around −7 dB. A single block of test trials was obtained in one or two visits. The average number of trials required to reach training criterion was 33.4 (s.d.=12.6) for these infants.

Hit rates of 1 were converted to $1-(1/2N)$ or 0.97 and false-alarm rates of 0 were converted to $(1/2N)$ or 0.03 (Macmillan and Creelman, 1991). Performance was described as $p(C)_{\max}$. Psychometric functions were fit to each subject's data using the procedure of Bargones *et al.* (1995). Three linear segments were fit to each subject's data using piecewise regression: a lower asymptote with slope=0 and *y* intercept=0.5; an upper asymptote with slope=0 and *y* intercept equal to the average of all data points within the 95% confidence interval of the best $p(C)_{\max}$ achieved in a block; and a segment defined between the levels at which asymptotic performance was reached with slope and intercept the free parameters. The slope of the psychometric function was taken as the slope of the middle segment.

B. Results

1. Psychometric function slope

Examples of data and psychometric functions fits for two infants and two adults are shown in Fig. 3. In general the fits to the data were good: r^2 ranged from 0.67 to 0.99 for the functions based on 3 or more data points, averaging about 0.9 for both infants and adults.

Average psychometric function slope for detection of broadband noise for infants and adults are shown in Fig. 4. Infants' psychometric function slope was significantly shallower than that of adults ($p<0.05$). The observed psychometric function slope for infants detecting noise in this study was $0.03p(C)_{\max}$/dB, while that reported for infants detecting tones by Bargones *et al.* (1995) was $0.04p(C)_{\max}$/dB. The psychometric function slope for adults detecting noise was $0.06p(C)_{\max}$/dB, compared to $0.05p(C)_{\max}$/dB reported by Bargones *et al.* for adults detecting a tone. Statistical comparison of the results of the present study to those of Bargones *et al.* indicated that the difference between the

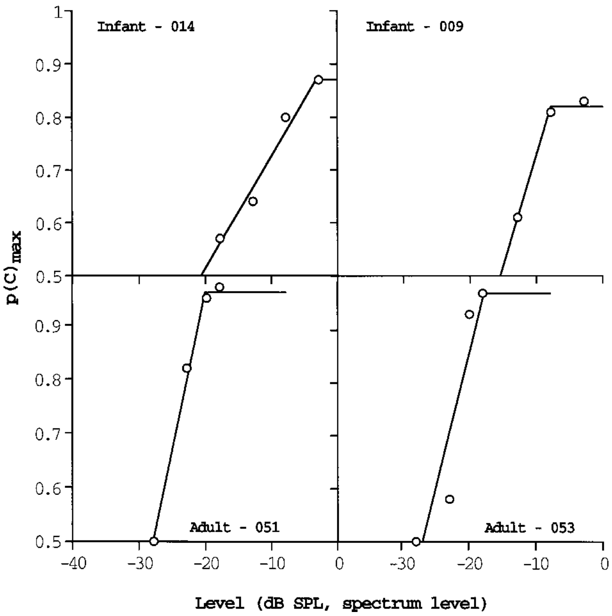

FIG. 3. Examples of psychometric function data (circles) and best-fitting psychometric functions (lines) from experiment 2. The task was detection of broadband noise bursts.

slopes for noise detection and tone detection was not significant for infants ($p > 0.05$) or adults ($p > 0.10$). The slopes obtained here are within the range typically reported for adults (e.g., Buus *et al.*, 1986).

2. Upper asymptote

The average $p(C)_{\max}$ attained by the infants who were tested at a spectrum level of 5 dB SPL was 0.83 (s.d. $= 0.06$). This value is very close to that reported by Bargones *et al.* (1995) for infants detecting a tone under various conditions, about 0.85. The infants who provided psychometric function slopes had an average maximum performance of $p(C)_{\max} = 0.81$ (s.d.$= 0.09$); this value was not significantly different from the upper asymptote estimated for the other group of infants ($p > 0.05$). Thus, on average, the infants in the psychometric function study achieved asymptotic performance within the range of levels tested. This level of performance, however, was significantly poorer than that attained by adults, $p(C)_{\max} = 0.96$ (s.d.$= 0.01$) ($p < 0.001$).

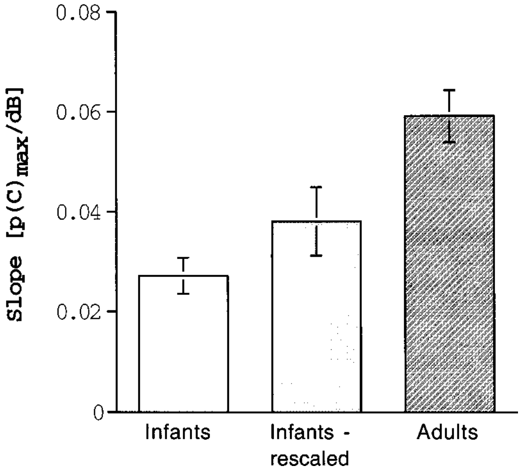

FIG. 4. Average (±1 standard error) slope of the psychometric functions for detection of broadband noise for infants and adults from experiment 2. ''Infants—rescaled'' refers to the average slope of the infants' function after correction for inattentiveness.

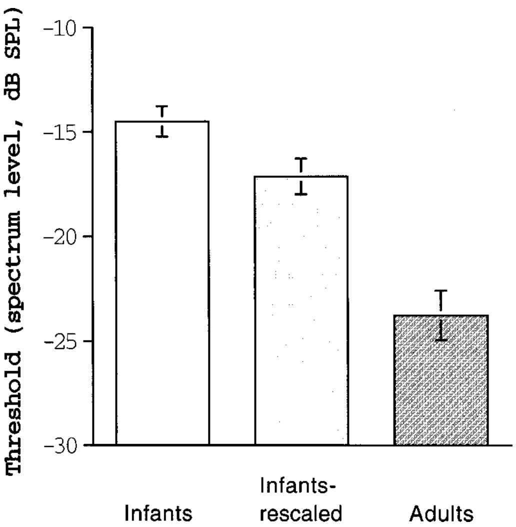

FIG. 5. Average (±1 standard error) unmasked thresholds for a broadband noise, for infants and adults, from experiment 2. ''Infants—rescaled'' refers to the average threshold calculated after the infants' psychometric function had been corrected for inattentiveness.

As the slope and upper asymptote of infants' psychometric function for noise and tone detection are not different, rescaling the psychometric function to correct for inattention would not affect the slope or threshold for noise relative to those for a tone. However, the comparison between the rescaled infant and adult psychometric functions for noise detection may have some relevance for understanding the factors underlying the age differences in slope, upper asymptote, and threshold. Consequently, for each infant it was assumed that the highest $p(C)_{\max}$ attained represented the upper asymptote (UA) of the psychometric function. Rescaled $p(C)_{\max}$ was defined as $[p(C)_{\max} - 0.5]/[\mathrm{UA} - 0.5] + 0.5$. A new psychometric function was then fit to the rescaled data points using the original procedure. Because the adults clearly approached an upper asymptote of 1, their psychometric functions were not rescaled. The average slope of the rescaled infant psychometric function is plotted in Fig. 4 along with the original infant and adult slopes. Although the rescaled infant slopes were steeper than the original infant slopes ($p < 0.05$), they were still shallower than adult slopes ($p < 0.05$).

3. Threshold

Thresholds were also calculated for each subject who provided psychometric function data. Threshold was defined as the level at which $p(C)_{\max} = 0.75$. Average thresholds for infants and adults are plotted in Fig. 5. The threshold values estimated from the psychometric functions were very similar to those obtained using the adaptive method in experiment 1 (compare to Fig. 1). Infants' thresholds were, not surprisingly, significantly poorer than those of adults ($p < 0.001$), and the infant–adult difference remained, at 9 dB, smaller than that observed for a 1000-Hz tone in experiment 1 and by Bargones *et al.* (1995).

Thresholds were also calculated for the infants' rescaled psychometric functions. The average of those thresholds is also plotted in Fig. 5. The ''rescaled thresholds'' were about 3 dB lower than the original thresholds estimated for the same infants; this improvement was statistically significant ($p < 0.05$). The rescaled thresholds were still significantly poorer than adults' thresholds ($p < 0.01$).

C. Discussion

Neither the slope nor the upper asymptote of infants' psychometric function for the detection of broadband noise is different from that for the detection of tones (experiment 2), but infants' thresholds for detecting broadband noise are more adultlike than are their thresholds for detecting tones (experiments 1 and 2). This pattern of results is strong evidence against the inattentiveness explanation for infants' relatively better detection of broadband noise over tones. However, it is not readily explained solely by a listening strategy explanation of infants' pure-tone detection.

If infants' threshold for broadband noise is relatively better than their threshold for pure tones because they are more attentive to broadband noise, then the slope and upper asymptote of the psychometric function for noise detection should be greater than those observed for pure-tone detection. In addition, thresholds calculated from rescaled psychometric functions for tone and for noise detection, using a guessing rate based on the respective upper asymptotes, should be equivalent, relative to adults' threshold. In fact, neither the slope nor the upper asymptote of the infants' psychometric function for noise detection is different from that for tone detection. Thus, there is no evidence that infants are more attentive to noise, and infants' threshold for noise detection, whether corrected for inattention or not, is relatively better than their threshold for tone detection.

The observed results, however, cannot be explained entirely by a model of infants' relative insensitivity to tones based on their listening strategy. The broadband listening model predicts that infants' psychometric function for pure-tone detection will be steeper than that of adults with an upper asymptote of 1. That prediction is inconsistent with published observations (e.g., Bargones *et al.*, 1995). The model based on a wandering listening band predicts that the slope of the infants' psychometric function for pure-tone detection will be shallow and its upper asymptote will only slowly approach 1. That prediction is consistent with published observations (e.g., Bargones *et al.*, 1995). However, both models predict that the slope and upper asymptote of the psychometric function for broadband noise detection should be adultlike even if infants do not match their listening bandwidth to the bandwidth of the signal. Neither model is consistent with the current observation that infants' psychometric function for broadband noise detection is no more adultlike than that for pure-tone detection.

In the interest of parsimony, we began by trying to understand infants' auditory sensitivity in terms of a single immaturity. A realistic model of infants' sound detection apparently must recognize multiple immaturities. The difference between infants' and adults' sound detection could be modeled in terms of conductive efficiency, frequency resolution, inattentiveness, and an internal noise of unspecified origin, as follows:

(1) The difference between masked and unmasked thresholds provides an estimate of the contribution of conductive efficiency to the infant–adult difference in unmasked threshold. Based on the current data, we would estimate the conductive component of infants' absolute threshold immaturity at 3–4 dB. That estimate is consistent with the findings of Keefe *et al.* (1993) with respect to the development of ear-canal conductance levels with an insert earphone.

(2) Because frequency resolution is mature by 6 months of age (Hall and Grose, 1991; Olsho, 1985; Spetner and Olsho, 1990), it should be irrelevant to the age difference in masked threshold.

(3) If the reduced upper asymptote of the infant psychometric function for detection is largely due to inattentiveness, then about 2 dB of the age difference in thresholds and most of the age difference in psychometric function slope for both tones and noise could be accounted for by inattentiveness.

(4) The infants' masked thresholds, relative to adults', were elevated by 5 dB for a broadband noise and 10 dB for a 1000-Hz tone. The corresponding differences for unmasked thresholds were 7 and 14 dB, respectively. Given the observations of Bargones and Werner (1994) that infants do not demonstrate frequency selective listening, this 5–7-dB increase in threshold for the tone could still be consistent with a broadband listening strategy in pure-tone detection. If infants simultaneously monitor the outputs of multiple auditory filters when detecting a pure tone, their pure-tone threshold would still be worse than their broadband noise threshold, but their psychometric function for pure-tone detection would be steeper than that for broadband noise detection (Hübner, 1993). Although not statistically significant, the difference between psychometric function slopes observed here for broadband noise and those reported by Bargones *et al.* (1995) for a 1000-Hz tone is in the direction predicted by such a broadband listening model. Further, Bargones *et al.* reported that infants' rescaled psychometric function slopes in pure-tone detection were consistently steeper than those of adults. Thus, most of the age difference in psychometric function slope could be accounted for by broadband listening combined with inattentiveness. The broadband listening model could be tested directly, for example, by estimating the weights infants assign to different spectral regions when detecting a tone in noise as in Stellmack *et al.* (1997) and Willihnganz *et al.* (1997).

(5) Once inattentiveness is taken into account, a 3-dB age difference in threshold for masked broadband noise detection remains to be explained by age differences in the level of internal noise. The possible sources of the increased level of internal noise include a failure to match

> listening bandwidth to stimulus bandwidth, variability in auditory intensity coding, higher levels of spontaneous activity in the auditory system, higher levels of physiological noise, or noise in the measurement of threshold by an adult observer. Besides increasing threshold, any of these factors could account for the difference between infants and adults in psychometric function slope that remains after rescaling the infant function.

The exact value of the relative level of internal noise, of course, depends on our estimates of all the other components. An independent estimate of the level of internal noise in infant detection can be obtained from an analysis by Schneider and Trehub (1992), who calculated the ratio of mechanical advantage to internal noise as a function of age and frequency, based on thresholds for octave-band noise in sound field. If infants' relative mechanical advantage is taken as the relative diffuse-field absorption cross-sectional area level reported by Keefe *et al.* (1994), the infants' relative level of internal noise estimated from Schneider and Trehub's data would be 5–6 dB higher than adults' between 1000 and 4000 Hz. Schneider and Trehub's model does not include an influence of inattentiveness. Their estimate of relative internal noise level is about the same as the combined effects of inattentiveness and internal noise in our model.

IV. SUMMARY AND CONCLUSIONS

Infants' thresholds for broadband noise detection are closer to those of adults than are their thresholds for tone detection. This observation is not consistent with the hypothesis that infant–adult differences in threshold are due to immature nonlinear growth of neural response with intensity in the infant auditory system. A preliminary examination of infants' psychometric function for detecting broadband noise does not support the idea that infants are less inattentive to broadband noise than to tones. Rather, like adults tested in the current procedure, infants produce similar psychometric functions for broadband noise and tone detection. Inattention combined with a broadband listening strategy and an additional source of internal noise may account for the observed pattern of results.

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[1] If infants were able to listen within a flat spectrum broadband noise at frequencies to which they are more sensitive, their detection thresholds for noise might also be better than for tones. Schneider *et al.* (1989), however, report that masked detection threshold matures at the same rate at all frequencies, and the data of Keefe *et al.* (1993) suggest that infant–adult differences in ear-canal impedance at 7 to 9 months of age are as small at 1000 Hz as at any other frequency. Thus, attempting to listen to more audible frequencies is unlikely to produce an improvement in either masked or unmasked threshold for a broadband noise over a 1000-Hz tone for infants of that age.

[2] Nozza (1995) reported that the minimum level of a broadband noise that would mask a tone was 8 dB higher for infants than for adults. That value is consistent with the 7-dB age difference in unmasked noise threshold reported here,

[3] No attempt was made to retest adults who produced nonmonotonic psychometric functions. Some of these relatively untrained listeners produced inconsistent results.

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