Temporal summation of 500-Hz tones and octave-band noise bursts in infants and adults

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A visually reinforced operant procedure was employed to obtain 2-point threshold-duration functions in 7-month-old infants and adults in two experimental paradigms. In Experiment 1, thresholds were determined for 10- and 100-msec, 500-Hz tones and octave-band noise bursts presented in quiet and noise backgrounds. Threshold-duration functions were significantly steeper for infants than for adults under all experimental conditions, and did not differ in slope as a result of differences in either stimulus bandwidth or masking noise. In Experiment 2, thresholds for trains of brief 500-Hz tone pulses were examined in infant and adult subjects. Infant functions were adult-like for integration of multiple-pulse stimuli, suggesting that the traditional, long-term process of temporal summation is mature by 7 months of age. Differences between the present results and those previously obtained for 4-kHz stimuli appear to be consistent with the view that different mechanisms are involved in the detection of low- and high-frequency signals.

Temporal summation refers to the well-documented finding that thresholds for detection of a signal decrease as the signal increases in duration. For auditory stimuli, thresholds decrease at a rate of 8-10 dB per decade increase in duration up to a maximum duration of approximately 200-300 msec. It is generally agreed that the slope of the function describing this relationship varies with signal frequency (Gerken, Bhat, & Hutchison-Clutter, 1990; Watson & Gengel, 1969), and perhaps also with bandwidth (Garner, 1947b). However, these effects are small and, in normal adult listeners, decreases in threshold closely approximate perfect integration of signal energy over a wide range of stimulus conditions (Gerken et al., 1990).

Recent investigations of temporal summation in young infants suggest that this generalization may not hold early in development. Thorpe and Schneider (1987) determined thresholds for 4-kHz octave-band noise bursts in a group of 6-month-old infants and found that the slope of their temporal summation function was exceptionally steep, exceeding 20 dB per decade of change in duration over the range of linear integration. Berg (1991) reported similar steep functions for 4-kHz octave-band noise bursts in 6- to 7-month-old infants, but found that their threshold-duration functions were adult-like for 4-kHz tones. When stimuli were presented in a background of continuous masking noise, infants' steep functions for octave-band noise bursts were significantly reduced in slope, while those of adults remained un-

changed. More recently, Berg (1993) examined thresholds for 1/3-octave filtered clicks and 300-msec noise bursts, and found that differences between click and noise thresholds were significantly larger in infants than in adults at low and high ends of the frequency spectrum but not for stimuli in the midfrequency range. Considered together, results of these studies suggest that while factors such as stimulus bandwidth, stimulus frequency, and masking noise have only minimal effects on the temporal summation functions of adult subjects, they may be important determinants of temporal summation in young infants.

A second issue raised by studies of temporal summation early in development concerns the mechanisms underlying these age differences. Traditionally, temporal integration has been viewed as a relatively long-term process that reflects accumulation of signal energy over intervals on the order of hundreds of milliseconds. This model has been highly successful in accounting for the threshold-duration functions of adult subjects, but is difficult to apply to data obtained from young infants, whose exceptionally steep functions imply accumulation of more energy than was present in the signal. To explain these findings, investigators have proposed that additional processes, such as attentional difficulties (Gray, 1990) or a specific insensitivity to stimulus onsets (Berg, 1993), may selectively elevate thresholds for brief stimuli in young subjects. A similar distinction between short- and long-term processes has also been proposed in the adult literature to explain apparent differences in the time constant of integration required to account for performance in different types of auditory tasks (Green, 1985). Such discrepancies have led to a number of alternative formulations, including the postulation of separate short- and long-term integration processes (e.g., de Boer, 1985) or, more recently, short-term integration followed by a longer term process based upon the combination of in-

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dependent multiple "looks" or samples of the stimulus (Viemeister & Wakefield, 1991).

In the standard temporal summation paradigm, changes in threshold due to short-term processes specific to brief signals are not readily distinguishable from those occurring as a result of long-term temporal summation. However, it is possible to examine effects of long-term integration alone by using an alternative paradigm in which thresholds are measured as a function of the number of brief pulses in a stimulus train (Carlyon, Buus, & Florentine, 1990; Gerken et al., 1990). In the present investigation, temporal summation of low-frequency stimuli was examined in 7-month-old infants and adults using two different paradigms. Experiment 1 employed the standard temporal summation paradigm to obtain 2-point threshold-duration functions for 500-Hz tones and octave-band noise bursts presented in either quiet or noise backgrounds. Its purpose was to determine if signal bandwidth and masking noise, two variables demonstrated to significantly alter the slope of infants' temporal summation functions at high frequencies, would also be effective at 500 Hz. Experiment 2 examined temporal summation of multiple brief 500-Hz tone pulses. The goal of this study was to determine if traditional, long-term integration of low-frequency stimuli differs in 7-month-old infants and adults when possible confounding effects of short-term processes are eliminated.

EXPERIMENT 1

Method

Subjects. The subjects were 32 normal, healthy infants, tested when 28 to 33 weeks of age (mean age = 30.6 weeks). They were randomly assigned to one of four experimental groups ($n = 8$ per group) resulting from the factorial combination of stimulus bandwidth and background conditions. Each infant received stimuli of two durations, presented in counterbalanced order. Within a session, testing was continued until acceptable threshold estimates had been obtained for both durations, or until the infant became agitated or disinterested as determined by preset criteria. Parents of infants successfully tested on only a single condition during their initial visit to the laboratory were asked to return for a second session. Fifteen of the 16 infants assigned to tone groups completed the procedure within a single session. Infants receiving octave-band noise bursts required a mean of 1.6 sessions. Forty-seven additional infants were tested but not included in the final sample: 1 was replaced due to equipment problems, 12 failed to meet training criteria, and 34 lost interest in the visual reinforcers before testing could be completed.

Sixteen young adult subjects were tested under the same conditions for comparison. They were assigned to either tone or octave-band noise groups and received stimuli presented in both quiet and noise backgrounds during a single 30-min session. All were enrolled in introductory psychology courses and received class credit for their participation.

Stimuli. Test stimuli were 500-Hz tones and octave-band noise bursts, gated with a rise/decay time of 3 msec and durations of 10 and 100 msec, as measured at half-power points. Onset and offset ramps were linear. The stimuli were presented in trains consisting of up to seven repetitions per trial. Onset-to-onset interval of individual stimuli was 600 msec, resulting in a train approximately 4 sec in duration. All stimuli were delivered to the subject's left ear

via a pair of lightweight headphones (Sony MDR-70II). For subjects in masked threshold groups, test stimuli were presented over a background of continuous noise, generated by an independent source and lowpass filtered at 2 kHz. Level of the noise masker within a 1-octave band centered at 500 Hz was 44 dB, corresponding to a spectrum level of 18.5 dB/Hz.

Procedure. Each infant subject was tested while seated on his/her parent's lap in the center of an IAC sound-attenuating chamber. A loudspeaker and three smoked-Plexiglas boxes, each containing a battery-operated toy, were located 90° to the infant's left in a corner of the room adjacent to a one-way window. One experimenter, seated directly in front of the infant, manipulated colorful toys to engage his/her attention at midline, and initiated trials when state and head position were judged appropriate. A second experimenter outside the chamber viewed the infant through one-way glass and made judgments on head turns. Both wore headphones and received a 4-sec signal marking the observation interval on each trial, but did not hear stimuli presented to the infant.

The experimental paradigm was a single-interval, go/no-go procedure in which signal and nonsignal trials were presented with equal probability. They occurred in random order, with the restriction that no more than three trials of either type be presented consecutively. Trials were initiated at variable intervals and only when the infant was judged to be in a state best described as "mildly interested" in the objects displayed at midline. If the infant turned to the left during an observation interval, the experimenter outside the chamber pressed a button to record the response and terminate the interval. Head turns on signal trials were considered correct detections, and were immediately reinforced by a 3-sec activation of the toy within one of the Plexiglas boxes. If the infant became obviously distracted during an observation interval, the trial was rejected.

Sessions began with a training phase in which infants first received 75-dB, 100-msec stimuli delivered over the loudspeaker until a criterion of four consecutive correct headturns had been met. For subjects designated to receive the short-duration condition first, this sequence was repeated with 10-msec stimuli. Once the headphones had been secured in position, the infants were required to meet an additional criterion of three consecutive correct head turns in response to their assigned test stimulus. Three consecutive correct head turns at training level were also required following within-session changes in stimulus duration.

On completion of training, an adaptive one-up, two-down tracking procedure was initiated. Tracking began with the signal set either 30 dB above adult threshold, for infants tested in quiet, or 25 dB above adult threshold, for infants tested in masking noise. Signal level was decreased following two consecutive correct head turns and increased after a single failure to turn. Outcomes on nonsignal trials did not contribute to alterations of signal level. Step size was initially fixed at 8 dB; on subsequent up-down reversals, it was decreased until a minimum step size of 2 dB had been reached. After the first reversal, suprathreshold probe trials with the signal set at conditioning level were presented every eighth trial to assess the infant's interest in the visual reinforcer. Tracking continued until the fifth reversal, and threshold estimates were computed as the mean stimulus level over the last two reversals. If false alarms occurred on more than one-third of the nonsignal trials, or if the infant failed to respond on more than two probe trials, the threshold estimate was considered unacceptable and the procedure was repeated. Average length of sessions was approximately 25 min.

Procedures used with adult subjects were intended to duplicate the critical aspects of the infant test situation as closely as possible. Adults were provided with a response box and instructed to press a button whenever they heard the stimulus train. Observation intervals were not marked, and intertrial intervals varied randomly from 1 to 15 sec in duration to ensure that time of signal presenta-

tion was uncertain. Lights within the Plexiglas boxes were briefly flashed as feedback for correct detections. All other procedures were identical to those described for infants.

Results and Discussion

Absolute thresholds for 500-Hz tones and octave-band noise bursts are illustrated for both infant and adult subjects in Figure 1; comparable masked thresholds are shown in Figure 2. At least two major findings are apparent from these figures. First, the threshold-duration functions of young infants were steeper than those of adults under all experimental conditions. Adult thresholds for 10- and 100-msec stimuli differed by approximately 8 to 12 dB across the four conditions, in good agreement with values previously reported for similar stimuli in the adult literature (e.g., Chung, 1981; Gerken et al., 1990; Plomp & Bouman, 1959). By contrast, differences in infants' thresholds for the two stimulus durations ranged from 18 to 21 dB. Analysis of variance indicated that these differences in slope were highly significant for both absolute [age $\times$ duration: $F(1,28) = 29.23$, $p < .001$] and masked threshold groups [age $\times$ duration: $F(1,28) = 41.92$, $p < .001$]. Second, the slopes of infants' temporal summation functions showed no significant variation as a result of differences in either stimulus bandwidth or masking noise. Adult functions, like those of infants, did not differ in slope in quiet and noise backgrounds. However, adult functions were significantly steeper for tones than for octave-band noise stimuli [bandwidth $\times$ duration: $F(1,14) = 10.39$, $p < .01$].

Absolute thresholds for 500-Hz octave-band noise bursts were significantly higher than those for 500-Hz tones in both infant and adult subjects [bandwidth: $F(1,14) = 26.60$, $p < .001$, for infants; $F(1,14) = 8.11$, $p < .05$, for adults], but the increase in threshold with increasing bandwidth was significantly larger for infants [age $\times$ bandwidth: $F(1,28) = 7.24$, $p < .05$]. For 100-msec

Figure 1. Mean infant and adult thresholds for 500-Hz tones and octave-band noise bursts (OBN), 10 and 100 msec in duration, presented in quiet. Error bars represent ± 1 standard deviation from the mean.

Figure 2. Mean infant and adult thresholds for 500-Hz tones and octave-band noise bursts (OBN), 10 and 100 msec in duration, presented in 18.5-dB/Hz masking noise. Error bars represent ± 1 standard deviation from the mean.

stimuli, infants' absolute thresholds were approximately 22 and 28 dB above those of adults for tones and octave-band noise bursts, respectively. These estimates are considerably higher than infant thresholds for 4-kHz tones and noise bursts obtained under similar conditions (Berg, 1991), but are consistent with results from other laboratories indicating that auditory sensitivity is less mature at low than at high frequencies during infancy and early childhood (Olsho, Koch, Carter, Halpin, & Spetner, 1988; Trehub, Schneider, & Endman, 1980). Since high thresholds are typically associated with unusually shallow, rather than steep, threshold-duration functions (e.g., Florentine, Fastl, & Buus, 1988), it is unlikely that this difference in threshold level can account for the difference in slope of temporal summation functions for infant and adult subjects.

Effects of masking noise also differed for the two age groups. Adult thresholds increased by approximately 25 dB in the presence of the noise masker, while infant thresholds for tones increased by 15 dB, and thresholds for octave-band noise bursts increased by less than 10 dB. Since infant subjects were tested in only a single background condition and adults were tested in both quiet and masking noise, error terms for assessing background effects were calculated separately for the two age groups and then pooled (Winer, 1971, pp. 371-378). Age differences in amount of masking were highly significant overall [age $\times$ background: $F(1,42) = 54.24$, $p < .001$] but did not differ for tone and noise stimuli. Examination of adult-infant differences indicated that, for 100-msec stimuli, infant masked thresholds were approximately 10 dB above those of adults for both tones and octave-band noise bursts. This 10-dB difference is similar to the 12- to 13-dB infant-adult difference in masked thresholds reported by Schneider and his associates (Schneider & Trehub, 1992; Schneider, Trehub,

Morrongiello, & Thorpe, 1989) for stimulus frequencies ranging from .4 to 10 kHz. They noted that although age differences in masked threshold appear to be independent of stimulus frequency, differences between absolute and masked threshold are not, showing much larger increases with age at low than at high frequencies as absolute thresholds mature. Thus, it seems likely that age differences in amount of masking in the present study are primarily a reflection of infants' elevated thresholds in quiet.

False-alarm rates were significantly higher for infants than for adults in both absolute and masked threshold groups [for absolute thresholds, .18 vs. .04, $F(1,28) = 31.62$, $p < .001$; for masked thresholds, .21 vs. .10, $F(1,28) = 13.53$, $p < .001$]. There were no reliable differences in incidence of false alarms among the various conditions for infant subjects, but adult false-alarm rates were significantly higher in masking noise than in quiet [background: $F(1,14) = 5.79$, $p < .05$]. As determined from computer simulations, this difference in percentage of false alarms would be expected to alter estimated thresholds by less than .5 dB.¹

The exceptionally steep threshold-duration functions obtained for infants in the present study are consistent with threshold differences reported by Berg (1993) for low-frequency filtered clicks and noise bursts. However, the failure to observe alterations in the slope of these functions with changes in stimulus bandwidth and background noise is in marked contrast to results previously reported for 4-kHz stimuli. A comparison of temporal summation at low and high frequencies is shown in Figure 3, where the present results are plotted along with those obtained by Berg (1991) in a similar study of temporal summation for tones and octave-band noise bursts centered at 4 kHz. Values represent the amount of temporal summation for each age group and condition, computed as the difference in thresholds for short- and long-duration stimuli. For infants, but not adults, variation

across stimulus conditions was clearly greater at 4 kHz. Temporal summation was significantly larger in infants than in adults for 4-kHz octave-band noise bursts in quiet, but did not differ for the two groups when stimuli were 4-kHz tones. For stimuli presented in masking noise, this pattern was reversed; infant subjects showed increased temporal summation for tones while temporal summation for 4-kHz octave-band noise was significantly reduced.

One possible explanation for these discrepant findings lies in the absolute bandwidths of stimuli employed in the two studies. Since the width of a one-octave band is considerably smaller at low than at high frequencies, one might argue that the difference between bandwidth conditions at 500 Hz was not sufficiently large to be effective. This seems unlikely for two reasons. First, the slopes of adult functions were significantly different for the two bandwidth conditions; and second, the main effect of stimulus bandwidth was significant for both infants and adults. A similar argument can be made with regard to effects of background: although the slopes of infants' temporal summation functions for 500-Hz tones and noise bursts were unchanged by the introduction of masking noise, mean thresholds were significantly increased for both 10- and 100-msec duration conditions. These considerations suggest that the absence of slope differences in infants' temporal summation functions for 500-Hz stimuli was not because the experimental manipulations were ineffective, but because their effects were equivalent at both short and long durations.

EXPERIMENT 2

According to traditional views of temporal summation, signal energy is integrated over an interval of 200–300 msec without regard for its distribution within the interval. A number of investigators have demonstrated that this assumption does not quite hold; in normal adult subjects, temporally contiguous energy is integrated more efficiently than energy separated into discrete bursts (e.g., Garner, 1947a). However, the difference is slight, and single- and multiple-burst stimuli are generally considered to be integrated in a similar manner (Gerken et al., 1990). The major difference between integration in single- and multiple-burst paradigms lies in the contribution of short-term processes associated with stimulus onsets or very short durations. When stimuli are brief pulses presented at a fixed rate, increases in duration are achieved by increasing the number of pulses in the series. As a result, the contribution of short-term processes remains equivalent at both short and long durations, thereby permitting the examination of changes in threshold due to long-term processes alone. In the single-burst paradigm employed in Experiment 1, infants' threshold-duration functions were found to be steeper than predictions based solely on integration of stimulus energy, suggesting that immaturity of short-term processes may have significantly influenced the results. This hypothesis was evaluated in Experiment 2 by de-

Figure 3. Amount of temporal summation obtained for 500- and 4000-Hz tones and octave-band noise bursts (OBN) in infants and adults. Values represent the difference in mean thresholds for 10- and 100-msec durations for all conditions except 4000-Hz octave-band noise, where durations were 10 and 300 msec.

termining thresholds for stimuli consisting of either one or eight brief 500-Hz tone pulses. Its purpose was to examine traditional, long-term temporal summation in infants when effects of short-term processes are held constant.

A second question addressed in this study was the effect of repeated stimulus presentations during the 4-sec observation interval. Although integration of signal energy is assumed to be complete within the first 300 msec of an auditory stimulus, thresholds may continue to decrease with further increases in duration due to the combination of multiple independent observations (Green, Birdsall, & Tanner, 1957). In an effort to reduce attentional demands on infant subjects, we employed a procedure that permits as many as seven presentations of the stimulus on a given trial. According to the predictions of signal detection theory, these additional signal presentations may reduce estimated threshold by as much as 4 dB (Green et al., 1957). While the temporal uncertainty associated with unmarked observation intervals would be expected to minimize effects of multiple observations, the possibility remains that differences in threshold attributed to integration of signal energy in this paradigm might be due in part to differences in processing multiple repetitions of the stimulus tokens. This possibility was evaluated by measuring the latency of responses in both infants and adults.

Method

Subjects. Eight normal, healthy infants, 29–33 weeks of age, served as subjects (mean age = 30.9 weeks). Thirteen additional infants were tested but excluded from the final sample: 2 were replaced due to equipment problems, 1 refused to wear the headphones, and 10 lost interest in the visual reinforcers before testing could be completed. A group of 8 young adults with normal hearing were recruited from introductory psychology courses and received class credit for their participation.

Stimuli and Procedure. Test stimuli consisted of a single 10-msec, 500-Hz tone pulse, and a train of eight such pulses presented with an onset-to-onset interval of 20 msec. The duration of individual tone pulses was measured from half-power points. Each pulse was gated on and off with a 3-msec cosine-squared ramp, yielding a silent gap of 6 msec between successive stimuli. Total duration of the pulse train was 154 msec. As in Experiment 1, stimulus tokens were presented up to seven times per trial with an onset-to-onset interval of 600 msec. Each subject received both single- and multiple-pulse stimuli, presented in counterbalanced order. For all trials on which responses occurred, a measure of response latency was computed as the time between trial onset and the buttonpress made either by the subject, in the case of adults, or by the experimenter, in the case of infants. All other procedures were identical to those described previously.

Results and Discussion

Threshold estimates for one and eight tone pulses are shown in Figure 4. For both infant and adult subjects, mean thresholds for single 10-msec stimuli were nearly identical to those obtained in the previous study. In addition, the difference in thresholds for the two stimulus conditions was also nearly identical in the two age groups. As the number of tone pulses increased from one

Figure 4. Mean infant and adult thresholds for one and eight 500-Hz, 10-msec tone pulses. Error bars represent ± 1 standard deviation from the mean.

to eight, thresholds decreased by 9.7 and 8.4 dB in infants and adults, respectively. This decrease was highly significant for both infants [$F(1,7) = 36.84, p < .001$] and adults [$F(1,7) = 33.16, p < .001$], with no evidence of an age $\times$ duration interaction ($F < 1$).

To determine the extent to which threshold estimates may have been influenced by multiple repetitions of the stimulus during the observation interval, mean response latencies were computed for each subject and experimental condition. Only response times for correct detections that occurred after the third reversal were included in this measure so that values would be indicative of responses to near-threshold signals. Mean latency was slightly longer for infant subjects (2.5 sec for infants vs. 2.1 sec for adults). A difference of this magnitude would be expected since infants' response latencies also included the reaction time of the experimenter. Analysis of variance indicated that latencies for one- and eight-pulse stimuli were not significantly different for either age group. These data suggest that the processing of multiple events over long intervals does not contribute significantly to estimated thresholds in either infants or the untrained adults tested in this paradigm. Regardless of age, subjects appear to make their decisions within the first two to three presentations of the stimulus.

False-alarm rates also did not differ for the two stimulus conditions, but, as in the previous experiment, incidence of false alarms was significantly higher in infants than in adults [.19 vs. .03, $F(1,14) = 48.70, p < .001$].

The 8.4-dB difference in adult thresholds for one and eight tone pulses represents a temporal summation function slightly less steep than that obtained for single-burst tones in Experiment 1, in good agreement with slope differences reported by Gerken et al. (1990) for single- and multiple-burst paradigms. The difference between paradigms was more striking for infant subjects: Although infant threshold-duration functions were exceptionally steep for the single-burst low-frequency tones and noise presented in Experiment 1, they were adult-like when

stimuli were trains of brief tone pulses. This pattern of age differences is consistent with the view that infants' exceptionally steep threshold-duration functions are primarily due to immaturity of processes occurring within the first few milliseconds after stimulus onset. When the contribution of these short-term processes is equivalent across durations, traditional long-term temporal summation appears to be mature by 7 months of age.

GENERAL DISCUSSION

One goal of the present study was to determine if alterations in the slope of infants' threshold-duration functions previously reported for 4-kHz stimuli would also be evident at 500 Hz. This was clearly not the case. In Experiment 1, infants' 2-point threshold-duration functions were significantly steeper than those of adults under all experimental conditions and showed little variation with changes in either stimulus bandwidth or background noise. In Experiment 2, infants' functions were adult-like for integration of brief tone pulses, confirming that developmental differences in slope reflect immaturities in the detection of brief stimuli rather than immaturity of temporal summation in the traditional sense.

There appears to be no simple, straightforward explanation that will account for the pattern of results at both low and high frequencies. Although non-sensory factors, such as attentional difficulties, have frequently been cited as a possible explanation for reduced sensitivity at short durations early in development (e.g., Gray, 1990; Saunders & Salvi, 1993), the variation of thresholds across stimulus conditions suggests that sensory processes probably play a more significant role. A mechanism that may explain the alterations in infants' threshold-duration functions at 4 kHz is suggested by the recent work of van den Brink and Houtgast (1990a, 1990b) on spectral integration of short- and long-duration stimuli. When the duration of a signal is longer than approximately 100 msec, integration across frequencies is consistent with predictions of the classical energy-detector model (Green, 1960), which specifies that the total energy required for detection should increase by 1.5 dB for each doubling of signal bandwidth. However, data reported by van den Brink and Houtgast indicate that when durations are short, this process is more efficient, approaching complete integration of stimulus energy. As a result, thresholds for short-duration stimuli increase more slowly, and threshold-duration functions become more shallow with increasing stimulus bandwidth, as was found for adult subjects in the present study. To account for the observed slope changes in infants' threshold-duration functions, it is necessary to propose that the threshold for this duration-specific process is considerably higher in infants than in adults. Evidence consistent with this hypothesis has recently been obtained by Berg and Boswell (1994), who examined spectral integration of high-frequency multiple-component tones at both absolute and masked threshold. When signals were 10 msec in duration, their 7-month-old infants dem-

onstrated efficient spectral integration for stimuli presented in masking noise, but appeared unable to combine signal energy across frequency when the same stimuli were presented in quiet. This pattern was not seen for 100-msec tones, where thresholds were consistent with predicted values in both quiet and noise backgrounds. These findings support the view that infants' threshold-duration functions for 4-kHz octave-band noise bursts are exceptionally steep in quiet due to the absence of efficient spectral integration of brief stimuli at low signal intensities. With the introduction of masking noise, stimulus levels exceed the threshold for efficient spectral integration and threshold-duration functions become adult-like in slope.

Since experimental manipulations of stimulus bandwidth did not alter the slope of infants' threshold-duration functions for 500-Hz stimuli in the present study, it is clear that spectral integration mechanisms cannot account for the pattern of results at low frequencies. A possible alternative is suggested by results of studies investigating the role of place and periodicity mechanisms in the coding of signal frequency. Although the notion that encoding mechanisms are qualitatively different at high and low frequencies is not a new one, the extent to which these different codes are actually used by the nervous system has been difficult to determine. Recent studies of frequency discrimination provide convincing evidence that, at least in human subjects, "rate-place" coding predominates at high frequencies, while temporal codes derived from the phase-locked firing patterns of auditory neurons are predominant at low frequencies (e.g., Dye & Hafter, 1980; Sinnott & Brown, 1993a, 1993b; Sinnott, Petersen, & Hopp, 1985). The evidence is less clear that temporal mechanisms play a significant role in detection, as well as in discrimination, of low-frequency stimuli, although reports that synchronization thresholds of auditory neurons are consistently lower than rate thresholds suggest that this is likely (Javel, McGee, Horst, & Farley, 1988).

For the present results, the relevance of the distinction between rate-place and temporal coding is twofold. First, there is evidence that temporal coding mechanisms may require longer to reach maturity than do rate-place mechanisms. Studies of auditory development in the kitten indicate that phase-locking matures much more slowly than other functional properties of auditory neurons (Kettner, Feng, & Brugge, 1985), and behavioral studies of frequency discrimination in human infants are also consistent with this interpretation. Olsho and her associates (Olsho, 1984; Olsho, Koch, & Halpin, 1987) reported that their 6- and 12-month-old subjects were able to perform at near-adult levels for signal frequencies of 4 kHz and higher but that, for both age groups, discrimination performance was significantly poorer at lower frequencies. These findings support the view that, in human infants, rate-place coding is adult-like within 6 months after birth, while temporal coding mechanisms have not yet reached maturity by 1 year of age. Second, temporal mechanisms may be more sensitive to signal

duration than are rate-place mechanisms. Sinnott and Brown (1993b) recently reported a cross-species comparison of frequency discrimination in humans and monkeys in which they obtained frequency difference limens for stimuli ranging from 12 to 400 msec in duration. Their results indicated that decrements in performance with decreasing duration were significantly larger at 500 Hz than at 4 kHz in human subjects. By contrast, monkeys, who are believed to use primarily rate-place mechanisms (Sinnott & Brown, 1993a; Sinnott et al., 1985), showed no differential effects of signal duration at the two frequencies. The authors suggested that rate-place coding mechanisms might rely more on information available at stimulus onset, while temporal, phase-locked information is accumulated throughout the duration of the signal.

Given that the coding of low-frequency signals remains relatively immature in young infants, it would not be surprising if decrements in performance at short durations were larger in 7-month-olds than in adults. The likely result would be exceptionally steep low-frequency threshold-duration functions such as those found in the present study. Immature phase locking would also be expected to result in increased levels of internal noise independent of signal duration, and might therefore contribute to adult-infant differences in threshold for long-duration stimuli as well. The effect on spectral, as opposed to temporal, integration is difficult to predict, but infants' exceptionally high thresholds for octave-band noise bursts suggest that internal noise may increase rapidly with increases in stimulus bandwidth at low frequencies.

Although infants' threshold-duration functions for 500-Hz stimuli, unlike those previously obtained at 4 kHz, showed no evidence of the duration-specific efficient integration process described by van den Brink and Houtgast (1990a, 1990b), adult functions for 500-Hz tones and noise bursts did differ significantly in slope, providing additional support for the view that efficient spectral integration is present at low frequencies in mature subjects. Since both neural phase-locking (Javel et al., 1988) and discrimination of low-frequency tones (e.g., Dye & Hafter, 1980; Sinnott & Brown, 1993a) are known to improve with increases in signal level, infant threshold-duration functions for low-frequency stimuli might prove to be more adult-like in higher levels of masking noise.

REFERENCES

- BERG, K. (1991). Auditory temporal summation in infants and adults: Effects of stimulus bandwidth and masking noise. *Perception & Psychophysics*, **50**, 314-320.
- BERG, K. (1993). A comparison of thresholds for 1/3-octave filtered clicks and noise bursts in infants and adults. *Perception & Psychophysics*, **54**, 365-369.
- BERG, K., & BOSWELL, A. (1994). *Spectral integration of multiple-component tones in infants*. Manuscript submitted for publication.
- CARLYON, R., BUUS, S., & FLORENTINE, M. (1990). Temporal integration of trains of tone pulses by normal and by cochlearly impaired listeners. *Journal of the Acoustical Society of America*, **87**, 260-268.
- CHUNG, D. (1981). Masking, temporal integration, and sensorineural hearing loss. *Journal of Speech & Hearing Research*, **24**, 514-520.
- DE BOER, E. (1985). Auditory time constants: A paradox? In A. Michelsen (Ed.), *Time resolution in auditory systems* (pp. 141-158). Berlin: Springer-Verlag.
- DYE, R. H., & HAFTER, E. R. (1980). Just-noticeable differences of frequency for masked tones. *Journal of the Acoustical Society of America*, **67**, 1746-1753.
- FLORENTINE, M., FASTL, H., & BUUS, S. (1988). Temporal integration in normal hearing, cochlear impairment, and impairment simulated by masking. *Journal of the Acoustical Society of America*, **84**, 195-202.
- GARNER, W. (1947a). Auditory thresholds of short tones as a function of repetition rates. *Journal of the Acoustical Society of America*, **19**, 600-608.
- GARNER, W. (1947b). The effect of frequency spectrum on temporal integration of energy in the ear. *Journal of the Acoustical Society of America*, **19**, 808-815.
- GERKEN, G., BHAT, V., & HUTCHISON-CLUTTER, M. (1990). Auditory temporal integration and the power function model. *Journal of the Acoustical Society of America*, **88**, 767-778.
- GRAY, L. (1990). Development of temporal integration in newborn chickens. *Hearing Research*, **45**, 169-178.
- GREEN, D. M. (1960). Auditory detection of a noise signal. *Journal of the Acoustical Society of America*, **32**, 121-131.
- GREEN, D. M. (1985). Temporal factors in psychoacoustics. In A. Michelsen (Ed.), *Time resolution in auditory systems* (pp. 122-140). Berlin: Springer-Verlag.
- GREEN, D. M., BIRDSALL, T. G., & TANNER, W. P. (1957). Signal detection as a function of signal intensity and duration. *Journal of the Acoustical Society of America*, **29**, 523-531.
- JAVEL, E., MCGEE, J., HORST, J., & FARLEY, G. (1988). Temporal mechanisms in auditory stimulus coding. In G. Edelman, W. Gall, & W. Cowan (Eds.), *Auditory function: Neurobiological bases of hearing* (pp. 515-558). New York: Wiley.
- KETTNER, R., FENG, J.-Z., & BRUGGE, J. (1985). Postnatal development of the phase-locked response to low frequency tones of auditory nerve fibers in the cat. *Journal of Neuroscience*, **5**, 275-283.
- OLSHO, L. W. (1984). Infant frequency discrimination. *Infant Behavior & Development*, **7**, 27-35.
- OLSHO, L. W., KOCH, E., CARTER, E., HALPIN, C., & SPETNER, N. (1988). Pure-tone sensitivity of human infants. *Journal of the Acoustical Society of America*, **84**, 1316-1324.
- OLSHO, L. W., KOCH, E., & HALPIN, C. (1987). Level and age effects in infant frequency discrimination. *Journal of the Acoustical Society of America*, **82**, 454-464.
- PLOMP, R., & BOUMAN, M. (1959). Relation between hearing threshold and duration for tone pulses. *Journal of the Acoustical Society of America*, **31**, 749-758.
- SAUNDERS, S., & SALVI, R. (1993). Psychoacoustics of normal adult chickens: Thresholds and temporal integration. *Journal of the Acoustical Society of America*, **94**, 83-90.
- SCHNEIDER, B., & TREHUB, S. (1992). Sources of developmental change in auditory sensitivity. In L. A. Werner & E. W. Rubel (Eds.), *Developmental psychoacoustics* (pp. 3-46). Washington, DC: American Psychological Association.
- SCHNEIDER, B., TREHUB, S., MORRONGIELLO, B., & THORPE, L. (1989). Developmental changes in masked thresholds. *Journal of the Acoustical Society of America*, **86**, 1733-1742.
- SINNOTT, J., & BROWN, C. (1993a). Effects of varying signal and noise levels on pure-tone frequency discrimination in humans and monkeys. *Journal of the Acoustical Society of America*, **93**, 1535-1540.
- SINNOTT, J., & BROWN, C. (1993b). Effects of varying signal duration on pure-tone frequency discrimination in humans and monkeys. *Journal of the Acoustical Society of America*, **93**, 1541-1546.
- SINNOTT, J., PETERSEN, M., & HOPP, S. (1985). Frequency and intensity discrimination in humans and monkeys. *Journal of the Acoustical Society of America*, **78**, 1977-1985.

- THORPE, L., & SCHNEIDER, B. (1987, April). *Temporal integration in infant audition*. Paper presented at the meeting of the Society for Research in Child Development, Baltimore, MD.
- TREHUB, S., SCHNEIDER, B., & ENDMAN, M. (1980). Developmental changes in infants' sensitivity to octave-band noises. *Journal of Experimental Child Psychology*, **29**, 282-293.
- VAN DEN BRINK, W., & HOUTGAST, T. (1990a). Efficient across-frequency integration in short-signal detection. *Journal of the Acoustical Society of America*, **87**, 284-291.
- VAN DEN BRINK, W., & HOUTGAST, T. (1990b). Spectro-temporal integration in signal detection. *Journal of the Acoustical Society of America*, **88**, 1703-1711.
- VIEMEISTER, N., & WAKEFIELD, G. (1991). Temporal integration and multiple looks. *Journal of the Acoustical Society of America*, **90**, 858-865.
- WATSON, C., & GENDEL, R. (1969). Signal duration and signal frequency in relation to auditory sensitivity. *Journal of the Acoustical Society of America*, **46**, 989-997.
- WINER, B. J. (1971). *Statistical principles in experimental design*. New York: McGraw-Hill.

NOTE

1. Computer simulations were carried out to determine how variations in false-alarm rate would be expected to alter threshold estimates

obtained with this procedure. The probability of a head turn on a given trial was computed as

$$p(\text{HT}) = p(C) + [1 - p(C)][p(\text{FA})],$$

where $p(\text{FA})$ is the probability of a head turn on a nonsignal trial, and $p(C)$ is the logistic function

$$p(C) = 1/[1 + \exp(-L/S)],$$

where the parameters L and S refer to signal level and spread of the psychometric function, respectively. Five hundred simulated threshold runs were averaged for each parameter value. Results of these simulations indicated that false alarms had little effect at low rates, but computed thresholds decreased rapidly as probability of false alarms approached and exceeded .5. As false-alarm rate increased from 0 to the maximum acceptable rate of .33, estimated threshold decreased by approximately 2.5 dB. For the mean false-alarm rate of approximately .20 obtained for infant subjects in the present study, the decrease in computed threshold was less than 1.5 dB. Varying the spread of the psychometric function from 1.5 to 3.0, intended to cover the range from typical adult functions to the more shallow functions reported for young infants (Olsho et al., 1988), produced only minimal effects.

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