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Auditory frequency sensitivity of human newborns: Some data with improved acoustic and behavioral controls

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Two studies were performed where five sinusoids, 125 Hz, 250 Hz, 500 Hz, 2 kHz, and 4 kHz, were presented to babies up to 9 days old along with several no-signal trials. Although variability in responding was the key result, a flat curve was representative of the intensities required for motor responding 50% of the time across the frequencies studied. In the second experiment, fixed intensities were chosen for each signal frequency, so d′ values could be estimated. The d's differed over frequency. Evidence is cited that responding in the auditory response cradle which was used here varies with acoustic parameters. Some reasons are suggested as to why the newborns exhibit such variability.

There are two interpretations of the auditory sensitivity data on human newborns. Eisenberg (1969) argues that newborns have a flat elevated audiogram showing an overall hearing loss of about 40 dB hearing level (HL) ISO, i.e., there are equal losses over different frequencies. She argues that the loss can be explained by the presence of vernix caseosa in the external meatus or by mesenchymal tissue in the middle ear. The other viewpoint is that the neonate audiogram shows a hearing loss of about 30 or 40 dB HL relative to the adult but that this loss is greater for higher frequency tones, i.e., those above 1 kHz. This view is represented in the data of Hutt, Hutt, Lenard, Bernuth, and Muntjewerff (1968) and Weir (1976). These authors argue that the shape of the sensitivity curve may be an indication of tuning of the neonatal auditory system to its eventual ecological niche so that fundamental frequencies of adult speech or of the baby's own cry are prepotent stimuli. The second view is supported further by brainstem-evoked-response studies by Hecox (1975). He discovered that the neonate's evoked responses indicate a slight hearing loss (about 20 dB) when compared to those of an adult, and this loss is greater for the higher frequencies. Differences in absolute levels using different techniques can be readily explained by calibration of stimuli and responses, but methodological explanations would not apply so readily to variations *over* frequency in sensitivity curves.

The reason such different points of view emerge from the same data is that studying neonatal auditory sensitivity requires the solution of many experimental problems. Despite these problems, the study is worthwhile, since knowledge of the normal newborn threshold curve may yield some understanding of the development of the speech system and the nervous system in general. Perhaps more important is having reliable norms of newborn hearing to permit more efficient screening for deafness.

One problem is that neonates are nonverbal; therefore investigators have special problems in defining a response. EEG, heart rate, respiration rate, sucking, and overt motor responses (EMG) have been used by various experimenters [see Eisenberg (1976, pp. 241-266) for a listing]. However, no matter which response was selected, the results may not be the same as those where verbal report is used in adult threshold studies. It is incumbent on the researcher to show that the neonatal response selected is affected by acoustic parameters and that responding to the sound is more frequent than spontaneous levels. Both of these objectives were achieved by Weir (1976) when d′, a signal detection theory measure, was used to measure pure tone sensitivity for neonates. In signal detection theory, objective (sensitivity) and subjective (criteria) elements of perception can be evaluated separately (e.g., Green & Swets, 1966). The aim of the present research was to extend the earlier findings by obtaining additional normative data on newborns with improved acoustic control, where d′s as well as threshold levels were evaluated, much as Watson, Franks, and Hood (1972) did for adults. These authors related the signal detection theory measure, d′, to traditional threshold measurements by obtaining isosensitivity curves for standard audiometric signal frequencies. If there are similarities between the curves relating responding of a nonverbal organism to the curves derived from adult verbal

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reports, then this may be taken as evidence of similar information processing (Bitterman, 1960; Blough & Blough, 1977), although there are limitations in such a comparison.

A second problem encountered in assessing auditory sensitivity of newborns is that the state of arousal changes frequently. Using four categories—(1) regular sleep, (2) irregular sleep, (3) quiet wakefulness, and (4) crying—Bennett (personal communication) found that, on the average, the state altered eight times in every 15 min without external stimulation. Because such lability is characteristic, Hutt, Bernuth, Lenard, Hutt, and Prechtl (1968) argued forcibly that most demonstrations of habituation may be simply alterations of state of arousal which occur in the absence of stimuli. State of arousal therefore must be considered when deciding if perception has occurred. Weir (1976) showed that no-signal response levels (false-alarm rates) vary with state, but d′ did not so vary. Thus, testing auditory sensitivity of sleeping babies with motor responses is probably not different from tests on waking babies, so long as d′ can be calculated. Since the calculation of d′ involves the difference between responses to stimulus and no-stimulus trials within a given state, signal detection methods are able to partially solve the problem mentioned by Prechtl (1965), that motor movements may be qualitatively different in each state of arousal because the subject is his own control. Alternations in state would be expected to affect both stimulus and no-stimulus trials randomly.

Acoustic control is yet another source of difficulty in studying neonatal sensitivity. It is difficult to measure the intensity of a stimulus presented by a loudspeaker to an infant in a crib due to the reflections of sound off the sides of the crib and off the baby's head (Bench, 1973; Hutt, 1973). The optimal placement of ear-phones can also be a problem since the infant cannot indicate when a good position has been obtained.

Bennet's (1975b, 1977) auditory response cradle solves some of the acoustic and behavioral problems. He developed earpieces which are inserted in the external meatus of the neonate, circumventing loudspeaker and earphone problems. The signal originates from an audiometer and is delivered via tubing directly to the wave guides. Also connected to the wave guide by tubing is a probe microphone so that intrameatal pressure can be monitored constantly. In addition, the auditory response cradle has a state of arousal control, since signals are delivered only to a subject who is "quiet" for 5 sec immediately before the trial. That is, any motor response automatically postpones an experimental trial until a 5-sec "quiet" period is achieved, thereby assuring that the baby is in State 1, State 2 or State 3 during each trial. Use of a controlled state of arousal yielded better sound to no-sound response ratios in early studies with the cradle (Bennett, 1977). The motor responses monitored were: (1) head turn, (2) body activity, and (3) backward head movement. In each case, criteria for each response in terms of its latency and intensity were determined from the records of more than 200 neonates in other studies (Bennett, 1977, Note 1). The auditory response cradle is currently being used for screening purposes so that the time available to study any given neonate was limited to about 30 min, which makes studying individual perceptual capacities difficult. Despite the time limitation, it was hoped that by using many babies in the cradle, with its built-in acoustic and behavioral controls, a valid, though brief, assessment of the hearing could be achieved.

In Experiment 1, a sequential technique (after Levitt, 1971) was used to estimate the point at which the subject would respond (perform any one of the three motor responses) 50% of the time. Five frequencies were chosen for study, 125 Hz, 250 Hz, 500 Hz, 2 kHz, and 4 kHz, in order to span as great a range as the equipment allowed. Each frequency was presented initially at a predetermined level. Its intensity was increased by 10 dB if no response occurred or decreased by 5 dB if a response was noted.

In Experiment 2, fixed intensity levels for each of the five frequencies were used. To select intensities, approximately 5 dB were added to each mean "threshold" level found in the first study. More responding to these signals would be expected since they were louder on average than in Experiment 1. In each experiment, there were no-signal trials so that an assessment of the spontaneous rate of responding for the baby's state of arousal in the auditory response cradle could be obtained. In the second experiment, d′ values could be determined for subjects, since estimates of the probabilities of responding could be made for each frequency. This second study was essentially a yes/no signal detection experiment.

EXPERIMENT 1

Method

Design. Sinusoids of five frequencies (125 Hz, 250 Hz, 500 Hz, 2 kHz, and 4 kHz) were presented to subjects following a sequential technique to estimate the point where there was a response 50% of the time. Each frequency was presented at a nominal 75 dB (the audiometer setting), initially. If the subject responded, i.e., made a head turn, body movement, or backwards head movement, then the tone was reduced by 5 dB on the audiometer. If no response occurred, then the intensity was increased by a step of 10 dB, with a limiting nominal value of 95 dB for all frequencies (the audiometer had a cutout at 80 dB for 125 Hz and at 85 dB for 250 Hz). No-signal trials were interspersed throughout the session, so there were 15 no-signal and 25 signal presentations to each subject.

Table 1
Details of Criteria for Each Response

Body Activity Response

Latency: .67 sec or longer (derived as mean-standard deviation on sample of 50 subjects over 16 trials).

Sensitivity on mattress is set by eye. Mattress voltage varies from 0 to 5 V, digital response triggers at 2.1 V.

Head Turn Response

Latency: As for body activity

Sensitivity: A response occurs when there is a 300-mV/sec alteration in the rate of change of the head turn; 30 mV is the minimal acceptable response.

Backward Head Movement

Latency: As for body activity.

Sensitivity: A response occurs when there is a 200-mV/sec alteration in the rate of change of head pressure; 200 mV is the minimal acceptable response.

Respiration Response

Latency: No criterion.

Irregularity is defined as: (standard deviation of t_{pre})/(mean t_{pre}), where t is the interbreath period during a 5-sec interval; pre refers to 5 sec before stimulu onset; stimulus refers to 5 sec during trial.

A qualification for a respiration response is the $\text{Irreg}_{pre} \leqslant .375$.

There are four criteria for achieving the response:

(1) Mean change:

$$|\bar{t}_{pre} - \bar{t}_{stim}| > .4 \text{ sec}$$

Or

(2) Maximum interbreath time:

$$(\max t_{stim} - \bar{t}_{pre}) \leqslant -.2 \text{ sec or } (\max t_{stim} - \bar{t}_{pre}) \geqslant .6 \text{ sec}$$

Or

(3) Minimum interbreath time:

$$(\min t_{stim} - \bar{t}_{pre}) \leqslant -.8 \text{ sec or } (\min t_{stim} - \bar{t}_{pre}) \geqslant .2 \text{ sec}$$

Or

(4) Irregularity change:

$$|\text{Irreg}_{pre} - \text{Irreg}_{stim}| \geqslant .24.$$

Subjects. Eighteen babies born at Hillingdon Hospital served as subjects. They were 87 h old on average (range 17 to 204 h), and had a mean gestation of 40 weeks. The mean maternal age was 26 years. On average, the birth weight was 3272 g and the 1-min APGAR score was 9.[1] Most of the births were normal, with labor spontaneous, although about 85% of the mothers had been given pethidine or pethidine + sparine during labor.

Apparatus and Stimuli. The stimuli were 5-sec-duration sine waves produced by a Madsen TBN 60 audiometer and conveyed through 2-mm tubing to the specially designed earpieces for newborns. Intensities were controlled from the audiometer and more 2-mm tubing connected the wave guide to a Bruel and Kjaer probe microphone (Type 4170) and thence to a Bruel and Kjaer measuring amplifier (Type 2607) so that the SPL (re .0002 dynes/cm^2) in the external auditory meatus could be monitored. No clicks occurred at signal presentation, and rise and fall time was 20 msec.

The ambient intrameatal noise was about 45 dB SPL, depending on the size of the neonatal ear and the fit of the ear insert. However, the variability between individuals was not large: the standard error measured was .5 dB SPL in the 175 ears studied in Bennett's thesis (1977). The spectrum of the intrameatal noise, measured by a Fenlow power spectral density analyzer, peaked at 2 Hz, corresponding to the neonatal cardiac rate. There were additional peaks at 4, 6, and 8 Hz, so virtually all the energy in the external auditory canal was less than 20 Hz. A 22-Hz high pass filter was switched into the microphone amplifier to reduce the cardiac resonance peak. The noise level in the experimental room was examined. Double glazing and heavy doors were installed to attenuate the ambient noise and a sound-insulated box surrounded the pen recorder during test sessions.

Responses. In the auditory response cradle, three motor responses and respiration are monitored. Each response was recorded on an Allco eight-channel pen recorder (Type EN88, Series 1404). The requirements for each response are listed in Table 1. These figures are based on responding of more than 100 pilot subjects (Bennett, 1977). For some of the subjects in this study, the respiration was used not only as a measure of state of arousal, but also as an additional response according to the criteria given in Table 1. Equipment malfunction prevented using respiration as a response for all subjects. When it was used, any motor response *or* respiration change was counted as a response.

The occurrence of any of the three motor responses was assessed automatically and lights indicated which response occurred on each trial. An automatic 5-sec "quiet" period was required before each trial during which no motor response occurred (see Figure 1). This assured that most subjects were in regular or irregular sleep. Subjects who responded frequently between trials so that they received no trial for a few minutes were returned to the ward and used in the experiment later. Respiration responses were determined by manual processing of pen recordings.

Procedure. The neonates served as subjects midway between feeds, i.e., 1 h after the last feed, and 1 h before the next feed. They were fully dressed and swaddled by a nurse, then placed supine in the auditory response cradle. A transducer for the respiration was inserted into a velcro fastening belt with a pocket. The nurse positioned both ear inserts, although only the left ear was used in these studies. She monitored the placement of the ear inserts and vital signs of the neonate throughout the session.

There were five blocks of eight trials. In each block, one frequency was used and presented five times at varying intensities according to the sequential rules discussed under design. Three no-signal trials were randomly mixed into each block so that an assessment of the false alarm rate could be obtained. Each subject had a different random order for the presentation of the five trial blocks.

Results and Discussion

None of the babies responded to all five tones. Figure 2 shows that on average only about 50% of the subjects responded to each tone. The median number of tones responded to was 2.5 and there were no discernible groups of tones responded to most frequently. For instance, of the five babies responding to only two tones, all five had different pairs. This hit-and-miss data is reminiscent of hearing tests with 10-day-old mice, where a 50% response rate over subjects was found (Ehret, 1977). It may be that the tones were too

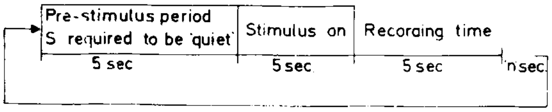

Figure 1. Scheme of events during each trial.

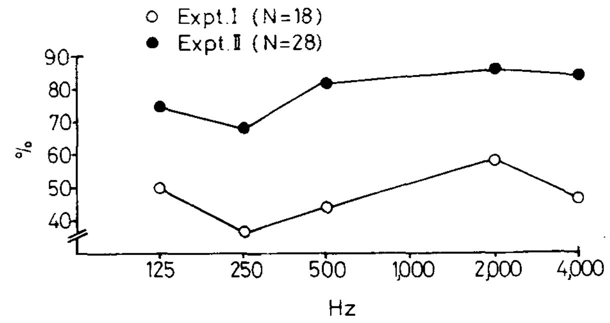

Figure 2. Percentage of babies responding to each frequency.

soft, on average, to elicit reliable responses, and they were to be of increased intensity in Experiment 2. Alternatively, it may be that the immaturity of the neonatal auditory system is such that variability is the main result at this age. Ehret demonstrated that with mice this variability in number of mice responding decreased considerably with days of age, and it would be interesting to follow up the human babies as they grow.

Estimates of the mean intensity required for babies to respond 50% of the time are shown in Figure 3. These estimates are based on subjects who responded at least once to the given frequency. The intensity values are estimates of the decibels SPL above the average intrameatal noise level (45 dB SPL). Across all frequencies, the mean value is 30 dB above meatal noise, which is similar to values found in other studies. Note that although 125 Hz and 2 kHz have slightly elevated intensities relative to the rest, the general impression is of a flat intensity curve. This flat intensity curve over frequency measured by motor responses differs from the normal adult's verbal report threshold function, which is decreasing for the frequencies used here. These differences could be due to the different responses being evaluated and could reflect qualitatively different hearing patterns. Because of the patchy performance of subjects, testing the significance of the differences between intensities required for motor responses 50% of the time would be dubious. It was hoped that more stable data would be available in the second study.

Bennett (Note 1) used each subject's *own* intrameatal noise level and signal sound pressure rather than estimates based on a sample of subjects as used here. He calculated the intensity required for 50% *of the babies* to respond at 74 dB SPL for 250 Hz and 85 dB SPL for 1 kHz. These values seem comparable with the 70 dB (25 dB average above intrameatal noise from Figure 3 + 45 dB intrameatal noise) for 250 Hz and the interpolated 77 dB (32 + 45) for 1 kHz found here, where the 50% response level was determined within subjects, not between.

The false-alarm rate was .23 over all trials (SE = .04). This spontaneous response rate is typical in the cradle and is less than the .50 rate to signals obtained for the data reported in Figure 3. In a sense, this constitutes weak evidence that the presence of a signal makes a response occurrence about twice as likely as the absence of a signal for the state of arousal of babies in the cradle. However, the main result of this study is that, at these intensity levels, variability in the pattern of motor responding to signals is the rule for newborns.

EXPERIMENT 2

Method

Design. Since the responding to different frequencies was not universal in Experiment 1, it was decided to present the five signals to all subjects at a predetermined higher intensity so that a better estimate of the probability of response to each signal could be obtained. The intensity chosen for each frequency was the "threshold" obtained in Experiment 1 plus the next 5-dB step adjustment on the audiometer. The presentation of slightly louder stimuli in Experiment 2 would be expected to produce more responding if the motor responses monitored were reflecting auditory sensitivity. With this data, it may be possible to compare the neonatal data with that of adults in Watson et al., since estimates of d′ were obtained for the adults at standard audiometric frequencies. Five blocks of trials were used, with five signals and three no-signal trials in each. Different subjects had different orders for trial blocks.

Subjects. Twenty-eight neonates were used as subjects. Their medical histories were similar to those in Experiment 1, although the range of ages was slightly less, 19 to 165 h.

Apparatus. The stimuli and responses were the same as in Experiment 1, except that tones were presented at the following intensity levels to all subjects: 125 Hz, 35 dB (re .0002 dynes/cm^2) above intrameatal pressure; 250 Hz, 35 dB; 500 Hz, 36 dB; 2 kHz, 42 dB; and 4 kHz, 33 dB. These values were based on pen recording measurements on a sample of nine subjects, and since the standard error (<1.0 dB) is small, they are representative of all subjects.

Results and Discussion

As Figure 2 shows, the predicted increase in responding to sounds was obtained. On average, 75% of the babies responded to each frequency. There were nine subjects who responded at least once to each frequency; however, the median number of tones responded to was 3.4. There is a significant increase in the number of signals responded to in Experiment 2 relative to Experiment 1 (median test, $\chi^2(1) = 7.6, p < .01$).

This increase in responding to signals in Experiment 2 can be seen against the almost unchanged mean false-alarm rates in the two experiments (.21,

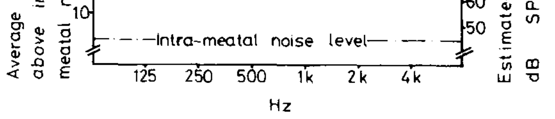

Figure 3. Intensity in decibels SPL above intrameatal noise required for subjects to respond 50% of the time.

Table 2
Mean d′ Values for the Five Tones for Various Selected Groups of Subjects and the SPLs for Each Tone

		d′						
				For Subjects Who Responded to the Tone**			For 8 Subjects Responding to All Five Tones and with no $p(H) = 1$	
Frequency of Tone	dB SPL*	For All 28 Subjects	For 26 Subjects with No-Signal Trial Rates	d′	SE	N	d′	SE
125	35	.24	.21	.33	.14	21	.17	.13
250	35	.28	.26	.30	.12	19	.37	.13
500	36	.50	.44	.58	.15	22	.51	.18
2000	42	.60	.48	.68	.14	22	.91	.23
4000	33	.18	.12	.21	.13	20	.29	.16

**dB SPL above ambient intermeatal noise.* ***Omits tones when subject did not respond.*

SE = .03, in Experiment 2). Thus, even though spontaneous responses occurred with the same frequency, more intense signals produced more responding across subjects, lending credence to the notion that responding in the cradle varies with signal intensity.

The d′ values were calculated for each subject. There are difficulties in calculating Gaussian equivalents used to obtain d′ when there is a cell with no responding (or 100% responding), so various selections of subjects are indicated in Table 2, to take account of this problem. The means for the first two groups of subjects were calculated by setting zero (or 1.0) response levels at $1/2N$ [or $(1 - 1/2N)$], where N is the number of trials for that stimulus. The assumption made when applying this rule is as follows: If there had been twice as many trials, there would have been at least one response (or one instance when no response occurred). The last two selections of subjects give better estimates of d′ levels, since it was unnecessary to invoke the somewhat arbitrary rule stated above. Even these estimates are not good, since the permitted experimental time limited the number of trials and many more trials would have provided better estimation. It is hoped that more data per subject can be obtained in future experiments, and that trends *over* subjects will be consistent there.

A noticeable feature of the mean d′s in Table 2 and Figure 4 is that 2 kHz is elevated relative to the other frequencies. An analysis of variance performed on d′s for the 18 subjects who reponded to at least four of the five signals showed a significant frequency effect [$F(4,68) = 2.69$, $p < .05$]. Both the quadratic [$F(1,17) = 4.56$, $p < .05$] and the cubic [$F(1,17) = 7.81$, $p < .01$] trends over frequency were significant. Ten d′s were estimated, based on the mean of the other subjects for this analysis. A similar result emerged from an analysis of variance performed on the eight subjects who had no estimated d′s (no occasions when probability of a response was 0 or 1) [$F(4,28) = 3.45$, $p < .05$, for frequency; quadratic trend, $F(1,7) = 9.6$, $p < .01$]. The presence of nonlinear trends indicates that the frequency differences are complex, though reliable. The simplest description would be that there is peak sensitivity at 2 kHz. This could have arisen from the selection of intensity levels alone, rather than genuine processing differences in neonates. In both analyses, the mean d′ differed from zero [$F(1,17) = 24.2$, $p < .01$; $F(1,7) = 22.97$, $p < .02$], showing that there are higher motor response levels to sound than to no-sound trials.

Using the respiration results which were available as additional ways to achieve a response for these two groups of subjects, similar analyses on d′s can be performed. The frequency effects failed to reach significance [$F(4,48) = 2.22$, $p < .10$, for 13 subjects; $F(4,28) = 1.48$, $p < .25$, for 8 subjects], probably due to increased variability. Inspection of Figure 4 shows that the overall quadratic trend was still present visually. The spontaneous response rate increased when respiration changes qualified as additional ways to achieve a response: no-signal response was .37 (SE = .05) for the eight-subject group. So, although respiration allowed for more ways to achieve a response, no new trends were found and more variance occurred. This would seem to validate the

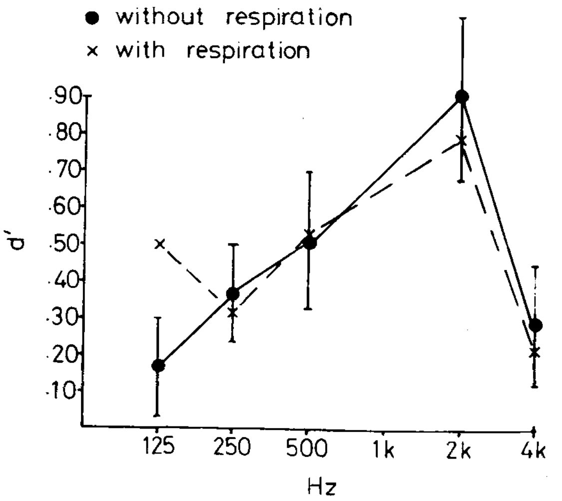

Figure 4. d′ values for the eight subjects responding to every signal with and without respiration counted as a way to achieve a response.

use of motor responses only in the cradle where significant trends over auditory signal parameters occurred.

Another way in which respiration can be used is as a measure of state of arousal. The higher the state of arousal, the shorter interbreath times (IBT) (States 3 and 4) and the greater irregularity (States 2, 3, and 4). If mean IBT or irregularity correlates with responding, then state of arousal as measured by respiration would be an important determinant of response emission regardless of the presence of a signal. Point-biserial correlations between irregularity and the occurrence of a response (exceeding any one of the seven criteria listed in Table 1) and between mean IBT and the occurrence of a response were calculated for the eight subjects responding to every signal. These correlations were not significantly different from zero: $r = .12$ for irregularity and .07 for mean IBT, on average (N varied between 11 and 39 trials). The lack of significant correlations probably results from subjects' being in a sleep state (1 or 2), i.e., "quiet," as required by the operation of the cradle. Thus the small correlations essentially confirm that arousal level was well controlled in the cradle.

If one equivocates between the motor response defined here and adult verbal reports, preliminary comparison can be made between neonates reported on here and the adults in the Watson et al. (1972) study. An estimate of decibels SPL for the five signals used here can be made by adding 45 dB, the mean intrameatal noise, to the five signal levels used in Experiment 2. The intensities so obtained were compared to the intensities for the same d′ found by Watson et al. (1972). There are greater intensity differences between adults and neonates for higher frequencies in this speculative comparison: 125 Hz, 30 dB; 250 Hz, 52 dB; 500 Hz, 61 dB; 2 kHz, 70 dB; 4 kHz, 61 dB. This comparison should be considered as no more than a first approximation, in that d′ estimates in the neonate study were obtained from 28 nonverbal subjects based on motor responses on a few trials, while those from the adults were from 12 subjects based on verbal responses on many forced-choice trials. However, the trend is in keeping with a relatively greater high-frequency loss of neonates compared to adults found in other studies of motor responses (Weir, 1976) and in brainstem-evoked-response work (Hecox, 1975). One use of such a speculative comparison is to anchor the obtained frequency effects reported above, since the obtained frequency differences could have arisen from an unfortunate selection of intensities for the neonates in Experiment 2.

GENERAL DISCUSSION

The results of Experiments 1 and 2 confirm the views that neonatal auditory sensitivity measured by motor responses is roughly equal over all frequencies tested. This was shown both with a sequential method for estimating the 50% response level (Experiment 1) and with signal detectability d′ estimates in Experiment 2. These findings parallel those found with brainstem-evoked-response audiometry (Hecox, 1975).

Why the motor response measurement showed such flat frequency curves could arise from several sources. The development of the auditory system is advanced at birth, so the outer, middle, and inner ear could be functional then.

The external auditory meatus is about adult length (2.4 cm) but increases in diameter up to about 7 years of age, also becoming more bony (McLellan & Webb, 1957; Northern & Downs, 1974). It has been suggested (Zwislocki, 1965) that the adult peak sensitivity at 2,500 Hz may be due in part to the resonance frequency of the external canal. In neonates, since the canal is of roughly equal length, no difference in resonance peaks would be expected. The data in Experiments 1 and 2 show no meaningful peaks at any frequency, although only a few frequencies were tested. A more thorough investigation of the frequency continuum would shed light on the matter.

The middle ear appears to be functional during the first week if one considers impedance bridge data (Bennett, 1975a; Keith, 1975; Weatherby & Bennett, Note 2). The view that the middle ear is either fluid filled or gummed up with mesenchymal tissue is not consistent with the impedance data showing normal tympanograms during the first week of life. Tympanometry does not directly examine the integrity of the ossicular chain's mechanical action, although the neonate compliance curves are not like those of otosclerotic patients or of patients with ossicular discontinuities. Separate measurement of resistance and reactance indicate that there are developmental differences, however, as a function of the probe tone frequency used on the impedance bridge (Weatherby & Bennett, Note 2). Weatherby and Bennett have shown that there is almost no contribution from the reactance for low frequencies (e.g., 220 Hz) in the neonate. They suggest that the impedance data of the neonate can be accounted for by a highly compliant tympanic membrane in the newborn relative to the adult.

The inner ear appears to be anatomically capable of responding, in that it has the same size and maturation as that of an adult from 30 weeks' gestation (Northern & Downs, 1974). The maturation of the higher nervous system by, say, arborization or myelination is difficult to assess since the auditory pathways are so complex (cf. Rorke & Riggs, 1969). Higher nervous system immaturity could be a cause of differences between adults and newborns. Hecox (1975) argues similarly when considering evoked response data: The differences in the neonate curves may arise from some middle ear or higher order neural immaturity.

It is interesting that the flat curve of hearing sensitivity over frequency is similar to that obtained for submerged (adult) divers tested with ear phones (Hollien & Fishbein, 1975). Hollien and Fishbein showed empirically that the normal middle-ear route of sound transmission is not used by divers. They accomplished this by damping bone conduction transmission with a special foam hood but permitting full tympanic membrane action by drilling holes in the hood for the external meatus. Thresholds with this holey hood were similar to those for a hood without holes, but both curves were considerably elevated over thresholds in water without a hood. Hollien and Fishbein argued that their subjects, who were audiometrically normal out of water, received sounds under water primarily from bone-conduction channels. The flat bone-conduction curves of divers differ from those found in clinical populations (Studebaker, 1967), probably because of differences in transducers used in testing. Hollien and Fishbein used earphones, while normal bone-conduction assessment is performed with special transducers placed on the forehead or mastoid. Since transducer placement and calibration is important in determining the shape of the threshold curves (Dirks & Kamm, 1975), it is not surprising that the curves for Hollien and Fishbein's divers differed from clinical bone-conduction norms.

Relating this to the neonatal data reported here suggests that the middle-ear pathway for sound transmission may not be used efficiently by neonates. The sensitivity curve of newborns was like the bone-conduction curve of the divers, and the *method* of testing was similar for the neonates (ear inserts) and divers (earphones). More conventional bone-conduction testing of neonates with an appropriate transducer on the forehead would indicate how similar newborn and adult bone-conduction curves are. Such data would be complemented by testing adults with profound cochlear deafness using earphones and also with conventional bone-conduction transducers. Flat bone-conduction threshold curves for the deaf subjects would be predicted for the earphone condition, while decreasing curves would occur for the bone-conduction vibratory condition.

This line of reasoning leads one to focus on the middle ear for some critical neonate-adult differences. The tympanic membrane is known to lie at an obtuse angle, making the cross-section of the external meatus more oval shaped than the adults's (Jaffe, Hurtado, & Hurtado, 1970). Since the tympanic membrane is attached to the malleus, the critical relationships between the ossicles are probably distorted, so mechanical efficiency may be reduced. Additional flaccidity of the tympanic membrane may also contribute to this inefficiency.

These speculations are interesting but do not provide the necessary tests of the integrity of the ossicular chain transmission in the first few days of life. Another problem with the data presented here is that it has been necessary to present averaged rather than individual results due to the restrictions on use of subjects.

To summarize the empirical results, there is evidence that responding in the auditory response cradle is sensitive to acoustic parameters. More intense signals in Experiment 2 resulted in higher response rates and more subjects responding to signal trials but not to nonsignal trials. There was also differential frequency sensitivity in Experiment 2 with the fixed intensities used. State of arousal as assessed by respiration did not correlate significantly with the probability of a response. It is argued that this was because state of arousal did not vary greatly in the cradle. So, with its improved acoustic and behavioral controls, the auditory response cradle has permitted collection of better data than in other studies (e.g., Eisenberg, 1976; Hutt et al., 1968). The comparability of the motor responses used here to verbal report in adults is uncertain, especially with such high intersubject variability. However, there is some evidence that there is more discrepancy between adults and newborns in the sensitivity for the higher frequencies tested.

REFERENCE NOTES

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NOTE

1. Apgar is a rating between 0 (worst) and 10 (best) given soon after birth and describing the general physical state of the newborn.

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