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Auditory Frequency Analysis in Infancy

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AUDITORY FREQUENCY ANALYSIS IN INFANCY

by

Lynne Werner Olsho

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VITA

The author, Lynne Werner Olsho, is the daughter of William Donald Werner and Shirley (Hastings) Werner. She was born in Pittsburgh, Pennsylvania on June 28, 1951.

Her elementary education was obtained in the parochial schools of Wheeling, West Virginia, and secondary education at Mount de Chantal Visitation Academy of Wheeling and at Magnificat High School, Rocky River, Ohio, where she graduated in 1969.

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The author will join the faculty of Virginia Commonwealth University, Richmond, Virginia, in August, 1979 as Assistant Professor of Psychology.

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INTRODUCTION

Major advances in our understanding of sensory and perceptual processing in infancy have been made within the last 15 years. The number of studies dealing with infant hearing has skyrocketed since 1960. In fact, in 1974 alone more papers on infant audition were published than from 1910 to 1960. Naturally occurring as well as conditioned responses to noise, pure tones, square wave stimuli, clicks, music and speech have been examined. Attempts have been made to determine the absolute sensitivity, the intensity response and the frequency selectivity of the auditory system in early life (Eisenberg, 1976). Nevertheless, a consistent body of behavioral observations of the infant's auditory capacity has yet to emerge.

Our restricted knowledge in this area stems to a large extent from the infant's limited response repertoire. Since infants are preverbal organisms, most of the techniques used to assess hearing in older children and adults cannot be applied to them. Moreover, conditioning techniques such as those commonly used with other nonverbal subjects often cannot be used with human infants for ethical reasons. Even when such a technique can be used ethically, it is often difficult to establish a conditioned response in young infants.

It is this interaction of sensory and response factors which poses a particular problem for studies of infant perception. The problem is further compounded by the continual expansion of both sensory and response capacities during the early months, as well as the continuing maturation of systems which integrate sensory and response systems. As a result, inconsistencies in observations are often found depending upon the response measure employed (Kessen, Haith & Salapatek, 1970), the behavioral state of the infant at the time measurements are made (Ashton, 1971), and the specific parameters of the stimulus used (Eisenberg, 1976).

To further complicate matters, stimulus control has not been a major concern in infant auditory research. Infants are not very responsive to stimuli such as pure tones (Hutt, Hutt, Lenard, Bernuth & Muntjewerff, 1968). Consequently, more complex stimuli such as square wave sounds, noise, clicks or voices are frequently used to assess the infant's auditory capacity. Unfortunately, it is more difficult to quantify the effective loudness of this type of stimulus. It is not uncommon, moreover, to find no mention of the actual spectral composition of a stimulus in a paper. This failure to completely describe and control the characteristics of the stimulus is particularly crucial in infant studies in which sounds are usually presented through a loudspeaker rather than headphones: sound waves may interact with the environment in such a way as to produce large variations in amplitude and spectrum across different stimuli and over presentations of the same stimulus. As a result, if the infant is found to be differentially responsive to a particular sound, it is often not clear which dimension of the stimulus is producing the effect. And, therefore, only very imprecise or global statements can be made about the infant's auditory capacity.

At the present time, then, we have very little specific information regarding hearing in infancy. This research examines the infant's ability to discriminate sounds on the basis of frequency, with the goal of contributing to a systematic description of infant hearing. As a point of departure, the existing information on this topic will be summarized, beginning with an examination of the anatomy and electro physiology of the developing auditory system, then proceeding with a review of the literature dealing with the stimulus parameters which affect the infant's response and ending with a summary of studies of infant speech perception. It is thought that basic psychoacoustic research with infants is needed to provide information about the relationship of specific structures in the nervous system to sound perception and about the infant's perception of complex sounds such as speech.

Histological Studies of the Infant Auditory System

Among the various sensory sytems, the auditory system seems to develop quite early. The fetal ear begins differentiation at 5 wk gestational age (GA) (Ballinger, 1969) and the auditory nerve emerges by the fourth week. Fetal responses (movement and heart rate acceleration) to sound have been observed as early as the 26th week (Wedenberg, 1965, Murphy & Smith, 1962, Johansson, Wedenberg & Weston, 1964). At birth, however, some immaturity is still evident, increasing as the auditory pathway ascends toward the cortex.

At the peripheral level, the external auditory meatus and the tympanic membrane are found to continue growing until 12 months postpartum (Ballinger, 1969), and impedance audiometry (Keith, 1973) shows that the compliance of the tympanic membrane is high compared to that of adults. The greater compliance of the tympanic membrane will result in the selective attenuation of some frequencies, but the amount of attenuation and the frequencies affected are unknown. The middle ear ossicles attain adult size and transmission properties by birth (Kirikae, 1960), however, and Robertson, Peterson and Lamb (1968) report only a 5- to 10 -dB elevation of the acoustic reflex threshold in newborns, arguing against a major conductive impairment. So while changes in the dimensions and characteristics of the outer ear and in impedance matching properties of the middle ear must affect the ear's response, direct measurements suggest that these changes account for no more than a 10 dB loss in sensitivity.

Data on inner ear development are available only with respect to the hair cells and their innervation, and Bredberg's 1968 monograph summarizes most of that information. The gross structural features of the inner ear were found to be attained by the sixth fetal month. Bredberg reports, however, that at birth, inner hair cells are more mature than outer hair cells, and that while the number of hair cells is nearly equal to that of adults, a small segment of the most basal region of the cochlea and the apical segment of the outer hair cells continues to differentiate postnatally. The only gross features which might account for postnatal changes in sensitivity, then, are the development of the basal region of the cochlea and the outermost row of hair cells. However, since no data are available with respect to the response characteristics of other inner ear structures such as the tectorial and basilar membranes, a complete evaluation of the contribution of inner ear maturation to the development of auditory responsivity is not possible at this time.

Still less is known about the maturation of neural structures in the auditory system. While the auditory nerve emerges by the fourth week GA and appears to be well myelinated by birth, the age at which it attains adult status is not known. At a higher level in the auditory pathway, a report by Rorke and Riggs (1969) suggests, the auditory brain stem nuclei are not completely myelinated at birth. This might cause slower conduction speed, and therefore, prolonged response latencies. Further, should a gradation of myelination across fibers exist, activity across fibers may be desynchronized, contributing to a diminished overall response amplitude. Finally, Conel's (1963) exhaustive studies of human cerebral cortex indicate that while the number of fibers projecting to the auditory cortex does not increase postnatally, axonal and dendritic lengths and diameters, as well as myelination of projection fibers continues for several years postnatally. Myelination of intracortical fibers was found to continue into adolescence. It appears, then, that the auditory cortex is quite immature at birth.

In sum, maturation of the auditory system is found to proceed in a caudocephalad direction, with more immature patterns appearing at and beyond the level of the inferior colliculus in the newborn. However, at this point it is not clear how the infant's behavioral response to sound is affected by this lack of maturity.

Electrophysiological Studies of the Auditory System in Infancy

Studies of auditory evoked potentials in infancy show that such responses exhibit elevated thresholds, prolonged latencies and diminished amplitudes in comparison to adult responses. These findings are consistent with those of the anatomical data described earlier, especially with regard to the lack of myelination at higher levels in the auditory system.

Beginning at the level of the eighth nerve, whole nerve action potentials recorded with surface electrodes in response to click stimuli demonstrate a 10 -dB difference in threshold between infants and adults which disappears sometime during the first year of life (Lieberman, Sohmer & Szabo, 1973). Portmann, Aran and LaGorque (1973) find normal thresholds in infants as young as 10 months.

Infant brain stem evoked responses (BSERs) have also been examined. Hecox and Galambos (1974a) report that the BSER in infancy is distinguished from adult responses by a longer latency and lower amplitude. These characteristics remain until about 18 months. In addition, Hecox and Galambos (1974b) examined the effect of a masker on the BSER to clicks. These investigators systematically decreased the cut-off frequency of a high-pass masker noise and found that the masker cut-off had to be much lower to produce a change in the latency and amplitude of the infant response to the click as compared to adults. They conclude that infant responses are produced in a more apical region of the cochlea than are adult responses. The infant response pattern, however, approached adult status by the tenth week of life. This pattern of results is consistent with Bredberg's (1968) report of the immaturity of the most basalward portion of the cochlea, and argues for the existence of a reduced high-frequency response in early infancy.

Cortical evoked responses (CERs) in newborns have been found to exhibit thresholds of 46-76 dB ISO (International Organization for Standardization) to tone bursts of 500-2000 Hz in frequency (Taguchi, Picton, Orpin & Goodman, 1969). Threshold for adults is estimated at 12.5 dB ISO (Davis, 1965). While Suzuki and Taguchi (1968) describe developmental changes in CER threshold up to 3 or 4 years of age, the exact age at which adult CER thresholds are attained has not been established.

To summarize, infant whole nerve potentials, BSERs and CERs all differ in several respects from adult responses. These differences seem to reflect some immaturity of the inner ear as well as deficiencies in arborization and myelination of the auditory system. Infant responses tend to approach adult status by 18 months, with some components maturing in the second half of the first year. Interestingly, these electrophysiciological studies find the infant to be more sensitive to sounds than do the behavioral studies of auditory responsivity to be examined next.

Behavioral Studies of Infant Response to Sound

As Hecox (1975) points out, it is possible to estimate a series of neural thresholds for response to auditory stimuli depending upon the level in the nervous system at which the response is recorded. In infancy, differences in response thresholds at different levels may be amplified by differential maturity, as has just been described. Similarly, systems responsible for the behavioral responses studied may differ in their maturity as well as in the extent to which they are integrated with sensory mechanisms. Thus, another series of behavioral thresholds may be generated. It is best to keep in mind, then, that there is no one estimate of the infant's threshold or auditory capacity; the values obtained are ultimately dependent upon the measures being employed.

In this section, two areas of research will be reviewed. First, the data pertaining to the basic parameters affecting the infant's response to sound will be summarized. Second, a brief review of what is known about the infant's response to speech sounds will be given.

Psychoacoustic Studies of Infants

Sensitivity. Spears and Hohle (1967), reflecting the then current view, estimated the newborn's behavioral threshold to sound to be 60-90 dB higher than that of adults, with eyeblink the response measure. These authors suggest that this diminished sensitivity results from the presence of unabsorbed connective tissue within the middle ear cavity which would restrict movement of the ossicles. However, given the histological and electrophysiological data described above, such an explanation seems untenable.

The absolute thresholds obtained from infants seem to depend to a great extent on the response measure chosen. Northern and Downs (1974), for example, report a 90 dB threshold when testing newborns in a "noisy" room, with arousal from sleep taken as the criterion for response. Simmons (1973) obtained somewhat lower estimates of newborn sensitivity using the Crib-O-Gram, an automated device developed for detecting hearing loss. Each baby's motor and respiratory activity are automatically recorded while 30 test sounds (narrow-band noise) are presented. After testing 4,000 babies, Simmons reports that the average newborn will respond to 44% of signals presented at levels below 60 dB SPL. Whether newborns might be trained to respond to lower level sounds remains for future research to determine.

By 4-7 months, Northern and Downs (1974) report, an infant can localize a stimulus at 40-50 dB sounded to one side of the head. More recent research indicates greater sensitivity in this age range. Trehub, Scheider and Endman (Note 1) trained 6 month old infants to turn toward the source of a noise burst presented from loudspeakers located on either side of the infant. The infant is reinforced for a correct response by the activation of a mechanical toy. Using this technique, Trehub et al. report that the infant thresholds average about 20 dB over adult levels. In addition, these researchers find an elevation of infant thresholds at low frequencies. However, it is difficult to evaluate the latter finding given that the localizability of stimuli may vary with frequency (Green, 1976).

Perhaps the most sensitive paradigm developed for testing thresholds of infants 6-12 months old is the visually reinforced audiometry (VRA) technique (Wilson, Lee, Owen & Morre, Note 2). In this paradigm, the infant is trained to turn his head toward a visual reinforcer whenever he hears an acoustic stimulus. He is reinforced for doing so by the activation of the reinforcer, a mechanical toy, for a brief period. The stimulus can be presented via loudspeaker or through headphones which have been specially fitted to the infant's head to prevent slippage. The results of testing using this paradigm indicate two things. First, infant thresholds at 6 months are within 5-10 dB of adult levels. This finding is consistent with those of electrophysiological studies of low level neural responses. Second, the shape of the infant audiogram (threshold as function of frequency) parallels that of adults. This finding runs counter to those of Trehub et al. described earlier; the sources of this difference bear further investigation. It seems clear, however, that at least by 6 months of age, infant absolute sensitivity approaches adult levels.

A number of conclusions can be drawn from these studies. On the basis of the experiments with 6 month olds, it seems that observation of spontaneous responses to sound, such as localization, is not as sensitive to the infant's absolute threshold as some conditioning techniques. Thresholds determined using the VRA paridigm, for example, are consistent with electrophysiological measures. Unfortunately, comparable conditioning techniques have not been developed for use with younger infants. However, given the difference between spontaneous and conditioned performance in 6 month olds, we might expect that such techniques would show newborn behavioral thresholds to be close to the electrophsiological response thresholds, only 10-20 dB higher than that of adults.

Intensity Discrimination. The effect of increasing sound intensity on newborn behavior has been examined primarily in very general terms. Kessen et al. (1970) review the literature dealing with development in infancy and conclude, not too surprisingly, that more intense stimuli produce an increase in motor, cardiac and respiratory response among infants. Some more specific information is available, however. Stratton and Connolly (1770a), for example, report that louder stimuli evoked larger initial cardiac acceleration and more rapid habituation to repeated presentations in newborns. In addition, Turkewitz, Birch, Moreau, Levy and Cornwall (1966) found that 2 day old infants tended to turn their eyes away from an intense stimulus, but toward a less intense one. This response was found to depend on the infant's state of arousal, with high intensity stimuli presented just prior to feeding eliciting the greatest number of "avoidance" responses. Interestingly, Turkewitz et al. report that this pattern of results held only for stimuli presented to the right ear. Infants tended to turn toward the more intense stimulus when it occurred at the left ear, indicating a possible difference in sensitivity between the two ears.

It would appear, then, that newborns do respond differentially to sounds of different intensities. Moffitt (1973) demonstrated a comparable effect in older infants, 20-24 weeks of age. Moffitt found that dishabituation of cardiac deceleration in response to a 500 Hz tone burst occurred when the stimulus intensity changed from 15 to 25 dB above an ambient noise level of 60 dB SPL.

It is not known just how small a change in intensity can be detected by infants, though trained adult ovservers can easily discriminate changes as small as 1 dB. In addition, though Bartoshuk (1964) reported that the amplitude of cardiac response to sounds over 40 dB in intensity follows a power function similar to the loudness function for adults (Stevens, 1961), recent attempts to replicate these findings have been unsuccessful (Morse, 1973). Thus it is not clear how the infant's perception of loudness increases with stimulus intensity. It would be interesting to determine whether infants can use intensity information to guide their behavior. It might be possible, for example, to test intensity discrimination among older infants by using an adaptation of the VRA paradigm described earlier (Wilson et al, Note 2).

In summary, it does appear that the infant modulates his response according to sound intensity. It remains for future research, however, to establish the limit of intensity discrimination as well as the manner in which loudness grows with intensity in infancy.

Frequency Discrimination. Green (1976) describes the frequency analytic ability of the auditory system as its "single most salient characteristic" (p. 134). Von Bekesy's (1960) experiments demonstrated that the ear performs a spectrum analysis of sounds, and the limits of this analytic ability have been studied in classical psycho-physical (e.g., Wegel & Lane, 1924; Egan & Hake, 1950) and more recent temporal masking experiments (e.g., Houtgast, 1972) as well as in frequency discrimination tasks (e.g., Shower & Biddulp, 1931; Wier, Jesteadt & Green, 1977).

Early attempts to demonstrate frequency discrimination in infancy were not terribly successful. Leventhal and Lipsitt (1964), for example, examined motor and respiratory response to 200 and 1000 Hz tones. After habituation to the 200 Hz tone, an increase in response to the 1000 Hz tone was found not to be significant. More recent attempts to demonstrate dishabituation to a change in frequency have met with mixed success. Trehub (1973) employed what is known as the high amplitude sucking (HAS) paradigm, a technique frequently used to study speech discrimination in infancy. In this paradigm, infants are trained to produce high amplitude sucks on a blind nipple by reinforcing such sucks with the presentation of a sound. Over repeated presentations, the infant's sucking response habituates and discrimination is demonstrated by an increase in sucking rate, dishabituation, following a change in the sound. Trehub failed to demonstrate dishabituation in infants 4-17 weeks old when square wave stimuli changed from 100 to 200 or from 1000 to 2000Hz in fundamental frequency. Wormith, Pankhurst and Moffit (1975), however, did find dishabituation to a 500 Hz sinusoid following habituation to a 200 Hz tone using the same paradigm.

Other studies purported to show that infants are differentially responsive to certain frequencies. Eisenberg (1976), for example, reports that infants find signals over 4000 Hz in frequency "disturbing." Hutt et al. (1968) examined EMG responses of newborns to low frequency (70-2000 Hz) swuare wave stimuli and find that higher amplitude responses occur in the 125-250 Hz range. As Bench (1973) points out, however, the stimuli in this study were inadequately specified and it is possible that infants were responding to large high frequency components of the "low" frequency signals.

A recent study (Kessen, Levine & Wendrich, 1979) seems to indicate that 3 and 6 month old infants can not only discriminate among different frequency stimuli but can also reproduce them vocally. Infants in this study heard three tones, D, F and A above middle C, which were sung by their mothers or produced by pitch pipe. All babies responded by vocalizing on the presented pitch significantly often.

The latter study, along with Wormith et al.'s paper described earlier, indicate that at least by three months of age, infants are capable of frequency discrimination. However, the situation here parallels that in the area of intensity discrimination: while it is possible to conclude that infants can respond on the basis of frequency, the limits of this ability have not been established. Moreover, just as it is not known how loudness grows with intensity in infants, it is not known how the infant's perception of pitch is related to stimulus parameters.

To conclude this discussion of infant psychoacoustics, we can summarize briefly. Infant absolute threshold for sounds appears to approach adult levels by about 6 months of age. Furthermore, infants appear to be sensitive to changes in sound frequency and intensity. Detailed information regarding the infant's discriminative capacities, however, is sorely lacking.

This gap in our knowledge has a particular impact on the study of infant speech perception. Much evidence is available to support the contention that infants discriminate the basic sounds of speech in a manner which parallels adult perception. Speech sounds, however, differ along many dimensions, including frequency, intensity, duration and rate of change over time. The infant might use any of these as a basis for discrimination. Unfortunately, we have no way of knowing which of these the infant might actually use, since we know so little about the infant's ability to analyze sounds along any dimension. The possibility that the infant might distinguish between speech sounds on the basis of some relatively simple cue should be considered as we examine the date on infant speech discrimination.

Infant Speech Perception

A variety of studies have shown that infants are particularly responsive to speech (e.g., Friedlander, 1970; Hutt et al., 1968). Moreover, it has been demonstrated that an infant as young as three weeks of age distinguishes his mother's voice from a distorted version or from that of a stranger (Mills & Melhuish, 1974; Turnure, 1971; Jones-Molfese, 1977).

Two studies in particular have provoked a great deal of controversy about the infant's perception of speech. The first (Moffit, 1971) showed that 5-6 month old infants could discriminate the syllable [ba] from the syllable [pa], as indicated by dishabituation of cardiac response. Eimas, Siqueland, Jusczyk & Vigorito (1971) extended this finding with 1- to 4-month old subjects. Other studies (e.g., Mattingly, Lieberman, Syrdal & Halwes, 1971) had presented to adults synthetic speech syllables which differed in voice onset time (VOT), the time between the onset of voicing and the release of the initial consonant. They found that adults label all stimuli with VOTs below +25 msec as [ba] and all those with VOTs greater than +25 msec as the syllable [pa]. In addition, they demonstrated that adults cannot discriminate between syllables which fall within phonemic categories. This phenomenon, called categorical perception, has been found to characterize the adult's perception of consonant sounds. Using the HAS paradigm described above, Eimas et al. demonstrated that recovery from habituation in infants was greater for a given acoustic difference when two syllables were from different adult phonemic categories than when they were from the same category. They concluded that infants as young as 1 month of age also exhibit categorical perception of speech sounds, and that infants possess, probably from birth, a mechanism which allows them to process such sounds in a linguistically relevant manner. This mechanism was hypothesized to be based on neural feature detectors, units which respond to the critical differences between syllables. Since the differences between syllables were believed to be intimately related to articulation, moreover, the feature detectors were viewed as being exclusively linguistic in nature.

Subsequent research demonstrated categorical perception by infants of syllables varying along other dimensions (e.g., Eimas, 1974, 1975; Juszcyk & Thompson, Note 3). In addition, Trehub (1976) reported that infants exposed only to English could discriminate speech contrasts which occur in Czech, but which don't occur in English. Trehub and Rabinovitch (1972) found that discrimination of VOT occurred whether the syllables used were synthetically or naturally produced. Finally, it was shown that infants discriminate vowel sounds in a continuous, as opposed to categorical manner (Trehub, 1973; Swoboda, Morse & Leavitt, 1976), just as adults do (Mattingly et al., 1971).

All of these habituatin-HAS studies demonstrate that infants discriminate between members of different adult phonemic categories. However, arguing that the infant "labels" all within-category contrasts as equivalent amounts to arguing for the null hypothesis. Thus, in order to demonstrate categorical perception by infants, it is also necessary to show that they categorize syllables in the same way as adults do. Evidence for the infant's ability to categorize speech sounds by initial consonant has been obtained in another paradigm, sometimes called the visually reinforced infant speech discrimination (VRISD) paradigm. This technique involves some modifications of the VRA method described earlier. Recall that in VRA, a sound serves as a discriminative cue, indicating that reinforcement is available contingent upon the infant's turning his head toward the reinforcer. In VRISD, the cue for response is a change in a syllable which is presented repeatedly from the loudspeaker. Thus the infant can receive reinforcement whenever the syllable changes, even if the changed stimulus is within the same phonemic category. Using this paradigm, Eilers, Wilson and Moore (1977b) found that 6-8 month old infants place their phonemic boundary between +40 and +10 msec--in the same area as adults do. Thus it would appear that infants categorize phonemes in the same way as adults do. Researchers using the VRISD paradigm have also been able to train 6-8 month olds to ignore irrelevant variation in syllables such as speaker and pitch contour, while responding to phonemic contrasts (Kuhl and Miller, Note 4; Kuhn, Notes 5, 6, 7).

However, some of the data from VRISD studies argues against the notion that all phonemic boundaries are innately determined. Eilers, Wilson and Moore (1977a), for example, found that 6 month olds did not discriminate certain fricative contrasts, such as [fa] vs. [tha]. Holmberg, Morgan and Kuhl (Note 8) found that the [fa]-[tha] contrast could be learned by 6 month olds, but that many more training trials were required to reach criterion for that contrast in comparison to a [sa]-[sha] contrast. At any rate, it is clear that phonemic discrimination in infancy is not as automatic as initial findings indicated.

Other recent studies have forced a reappraisal of the view that linguistic feature detectors underlie phoneme perception in humans. First, categorical perception of several nonspeech sounds has been demonstrated in human adults (e.g., Cutting & Rosner, 1974; Pisoni, 1977) and in human infants (Jusczyk, Rosner, Cutting, Foard & Smith, 1977). Even more damaging to the linguistic feature detector hypothesis, however, were demonstrations of categorical phonemic discrimination in chinchillas (Kuhl & Miller, 1978) and in Rhesus monkeys (Morse, 1976). The location of "phonemic" boundaries in these species, moreover, are quite close to those observed in humans. Thus a more tenable hypothesis regarding categorical perception of speech sounds is that human language has evolved to take advantage of certain areas of heightened sensitivity characteristic of the mamalian auditory system (Kuhl, Note 9). In view of this hypothesis, it becomes important to describe the characteristics of the developing auditory system. In doing so, we may not only explain how infants process the sounds of speech, but may also shed light on adult speech perception by showing how the perception of speech sounds matures concurrently with other psychoacoustic processes.

RATIONALE OF THE PRESENT STUDY

The evidence against the linguistic nature of speech has led to renewed interest in describing the infant's psychoacoustic behavior. However, as has been made apparent here, almost no basic information is available on which to build. This study is intended as a first step in laying that foundation.

It was decided to try to establish the limits of frequency discrimination in infants 5-8 months old. Frequency discrimination was chosen for a number of reasons. First, it seemed likely that infants could be using frequency differences in discriminating certain speech sounds (e.g., vowels). Second, given the emphasis that has been placed on the frequency analytic characteristics of the auditory system, information regarding the development of such characteristics might have theoretical import for theories of hearing generally. Finally, the VRA/VRISD methodology, which is becoming widely used and has proven sensitive to infant capabilities, seemed particularly suitable for testing discrimination. Using the VRA/VRISD in combination with an adaptation of the one-up, two-down psychophysical staircase technique, Aslin and his colleagues have been able to determine VOT difference thresholds for infants in this age range (e.g., Aslin, Perey, Hennesy & Pisoni, Note 10). Tone bursts could readily be substituted for syllables within that paradigm. Given the growing use of the paradigm, furthermore, it seemed important to characterize it in terms of its ability to allow subjects to demonstrate their sensitivity to changes in a basic parameter of sound.

The purpose of this study, then, was to determine frequency difference thresholds, or difference limens (DLs) for infants 5-8 months of age. Prior to 5 months, infants are difficult to train; after about 8 months, they seem to lose interest quickly (Pisoni, Note 11). An adaptation of the VRA/VRISD paradigm was used to obtain thresholds. It was anticipated that this method would prove infants to be far better frequency analyzers than had previously been shown, especially since infants had discriminated speech syllables in VRISD which differ by fewer than 300 Hz in frequency. Information about frequency discrimination should add to our understanding of infant speech perception and of the development of the auditory system generally in infancy.

METHOD

Subjects

All 27 infants tested were Caucasion, from middle class homes and ranged in age from 4 mo 10 da to 8 mo 1 da ($\overline{X}$ = 6 mo 10 da). The names of potential subjects were obtained through the records of a Chicago hospital. Subjects were recruited by letter and telephone and were paid $5 for each session. Twenty-five percent of the parents contacted agreed to participate. Of these, data were obtained from 14 infants. The remaining subjects were not included either because they became fussy during training and testing (10 subjects) or because they did not learn the task (3 subjects). No differences in age, birth weight, current weight, health or performance on a screening test were found between the final subject population and subjects who did not complete the experiment (Appendix A).

Five adult subjects, unpaid volunteer graduate and undergraduate students served as a comparison group. One of these subjects had participated in other auditory experiments.

Stimuli

Sinusoids of 1000, 2000 and 3000 Hz in frequency served as standard stimuli. Tone bursts 500 msec in duration were presented monaurally to the right ear. The stimuli had a 50% duty cycle and bursts had a 20 msec rise-fall time. Stimulus level was 70 dB over thresholds of three adult subjects tested in the same laboratory. The maximum frequency difference generated was 96 Hz.

Apparatus

Waveforms were generated by a Wavetek (Model no. 136) voltage-controlled oscillator and lead through a rise-fall gate (Coulborn Instruments, S84-04) to an attenuator (Hewlett Packard, 350D), then through a matching transformer to a TDH-39 earphone. Stimulus frequency was monitored at the output of the oscillator on a Hewlett Packard (5381A) frequency counter. Two earphones were coupled to the ears by rubber pads and held in place by two elastic head bands.

The visual reinforcers used were a mechanical toy bear (Mambo the Bear Drummer, Son Ai Toys) and a mechanical toy dog (Plushy, Spaniel Series, Iwaya Toys). One of the two toys was chosen at random for each session, although the other toy was often substituted when the subject seemed to be losing interest. The reinforcer was enclosed in a smoked plexiglas box (Gray 2730), 3/16" in thickness and 12" on each side. A 40 W incandescent bulb was also located in the plexiglas box and was switched on with the toy to make it visible during the reinforcement period. The reinforcer was mounted on a small stand at the infant's eye level and placed 45° from midline 4 ft from the infant.

Procedure

Frequency changes were presented in a series of trials. The structure of a trial is illustrated in Figure 1. The infant hears the standard frequency tone bursts continuously. At trial onset, the frequency of the tone changes to the comparison level for 6 sec. If the infant turns toward the reinforcer (45° head turn) during the first 4 sec of this interval, he receives reinforcement for 2 sec. On blank trials, which occur interspersed with target trials during one stage of the experiment, no frequency change occurs and an infant is not reinforced.

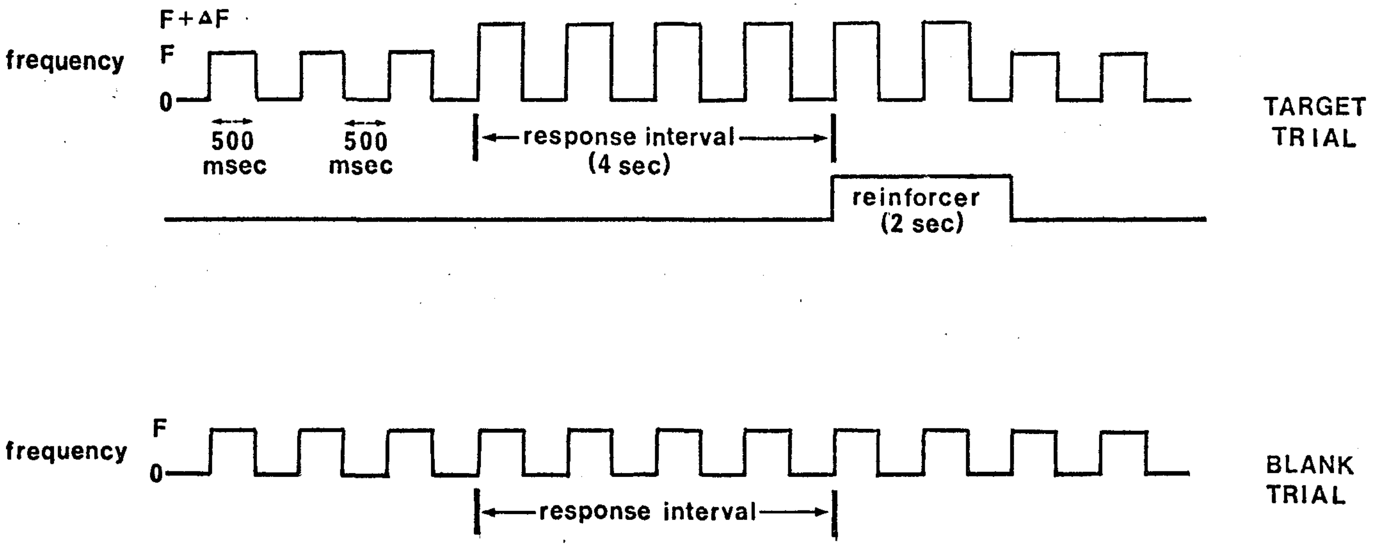

Figure 1. Trial structure

The layout of the laboratory is illustrated in Figure 2. The infant sat in his parent's lap at one end of a rectangular table, facing a one-way glass. One experimenter (T) sat to the infant's left and moved toys in from of the infant attempting to keep the infant's attention toward midline. The visual reinforcer stood to the infant's right. The infant's head turn was observed through the one-way glass by two observers (_01_ and _02_) in the next room. _01_ started a trial when she judged the infant to be in a "ready" state, attending to the toys and not fussing or crying. _01_ also controlled the frequency and intensity of the comparison stimulus and recorded the infant's performance. _01_ only recorded responses during a trial. _02_ could record a head turn at any time; responses noted by _02_ between trials were automatically recorded as false alarms. The two observers were separated by a barrier so that _02_ had no knowledge of when a trial was beginning. One experimenter was _01_ throughout the experiment (the author); six different assistants acted as _02_. Percent agreements on responses ranged from 91% to 100%.

On arrival at the laboratory, infants were made comfortable while the experimenter obtained information from the parent on the infant's age, mood, health, birth weight and current weight. A hearing screening test was then administered which consisted of ringing a bell on either side of the infant's head while he was seated in his mother's lap. Care was taken to keep the bell out of the infant's visual periphery. An observer scored the infant's response on the other side of the one-way glass. A 45° head turn toward the bell was scored as a positive response. Two trials on each side were given with presentation order random.

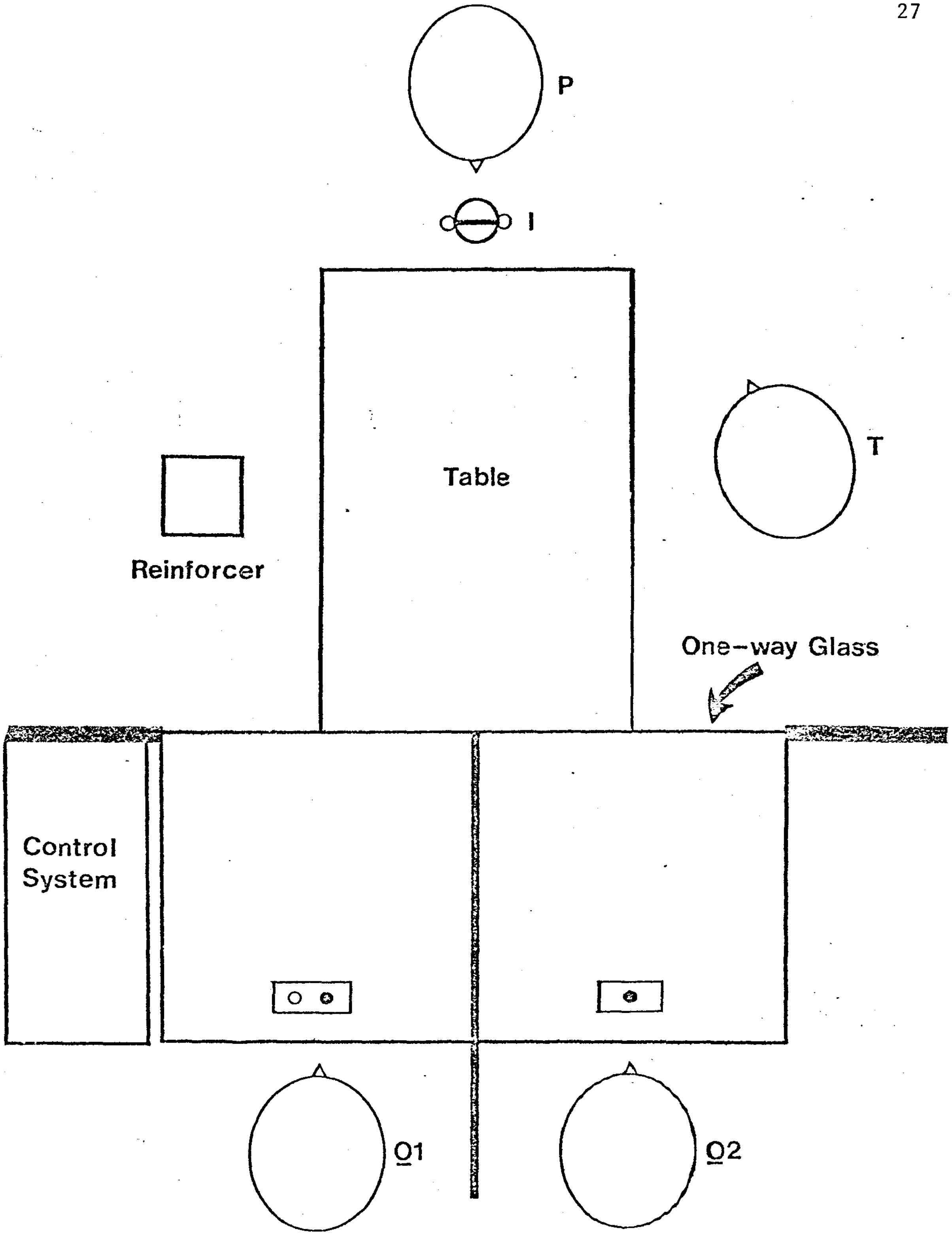

Figure 2. Laboratory layout. (P = Parent, I = Infant, T = Toy Waver, 01 = Observer 1, 02 = Observer 2)

Parent and infant were then settled in the subject room and the earphones fitted to the infant's head. The infant remained in his parent's lap throughout the training and testing. Although neither the parent nor the experimenter who remained with the parent and the child could hear the stimulus, the parent was asked to refrain from trying to influence the child's behavior with respect to the reinforcer.

The experiment consisted of two training phases and one testing phase (Table 1). During Stage 1, a frequency change of 96 Hz occurred on all trials, and the reinforcer was presented following each frequency change whether the infant turned toward the reinforcer or not. On initial trials, the comparison stimulus was also 2 dB more intense than the standard. Once the infant had anticipated the reinforcer by making a 45° head turn toward it during the 4 sec response interval immediately preceeding reinforcer onset on three consecutive trials, this intensity difference was eliminated. Stage 1 continued until the infant had anticipated reinforcer onset following the frequency change on another three consecutive trials.

During Stage 2, reinforcer onset was made ontingent upon the infant's turning during the response interval following a frequency change of 96 Hz. The infant was required to make 4 correct responses on 5 consecutive trials. In addition, during this stage, blank trials were interspersed with target or frequency change trials and the infant was required to refrain from turning on 4 or 5 consecutive blank trials in order to continue with testing. Target and blank trials occurred in random order; the observers were not aware of the type of trial occurring at any given time. However, after each trial, _O_1 could check the infant's progress on a series of counters which automatically recorded the number of trials of each type and the number of correct responses on each type of trial. A trial counter was reset to zero after two consecutive incorrect responses on trials of that type.

Table 1

Experimental Procedure

	TRIALS	REINFORCER	STIMULUS	RESPONSE CRITERIA
STAGE 1	100% target	all trials	$\Delta F = 96$ Hz $\Delta I = 2$ dB or $\Delta I = 0$ dB	3 consecutive anticipatory headturns at each level of ΔI
STAGE 2	50% target 50% blank	contingent on headturn	$\Delta F = 96$ Hz	4 of 5 correct on target trials and 4 of 5 correct on blank trials
STAGE 3	100% target	contingent on headturn	$\Delta F = 96$ Hz initially, varied in 3 Hz steps	2 correct → $\Delta F \downarrow$ 1 incorrect → $\Delta F \uparrow$ 2 incorrect → $\Delta F = 96$ Hz (probe)

The third stage of the experiment was the actual testing phase, during which thresholds were determined in an adaptation of the one-up, two-down staircase technique. During Stage 3, the comparison frequency was presented on all trials and reinforcer onset was contingent upon the infant's head turn. The initial frequency difference (ΔF) was 96 Hz. Following two consecutive correct responses at one comparison frequency. ΔF on the next trial was decreased by one step. Initial step size was 48 Hz and was halved for each succeeding ΔF reduction until a step size of 3 Hz was attained. The step size was then maintianed at that 3 Hz level. If the infant missed one trial, then ΔF was increased by one step. Following two misses, a probe trial (ΔF = 96 Hz) was inserted. If the infant turned on the probe trial, ΔF returned to the last level tested. If the infant missed the probe trial, testing was contined at 96 Hz until the infant again responded or until it was judged that the infant's state precluded further testing. Testing was continued until five reversals had been obtained or until the infant had ceased to respond. A typical response protocol is shown in Figure 3. Thresholds were calculated as the average of all reversals except the first two.

Two sessions (range 1-5 sessions) were typically required to obtain three thresholds from an infant. Each session lasted about 20 min and a single threshold determination required 30-60 trials. Frequencies were tested in the order 1000, 2000, 3000 Hz, since pilot work indicated that the subjects rarely provided stable thresholds when tested in the order 1000, 2000, 3000 Hz, since pilot work indicated that the subjects rarely provided stable thresholds when tested first on one of the higher frequencies. Subjects were retrained before testing at each frequency. The number of training trials required for each subject at each standard frequency are shown in Appendix B.

Adult comparison. Five adult subjects provided thresholds under essentially the same conditions as the infants. Adults sat in the same testing room and used the same headphones. They turned toward the reinforcer whenever they detected a change in frequency and the reinforcer was activated for 2 sec as feedback. Two observers recorded the adults's response, subject to the same rules as applied to the infants. The same training and testing procedure were also employed for the adults. Approcimately 10 min were required to obtain a stable threshold (30-40 trials).

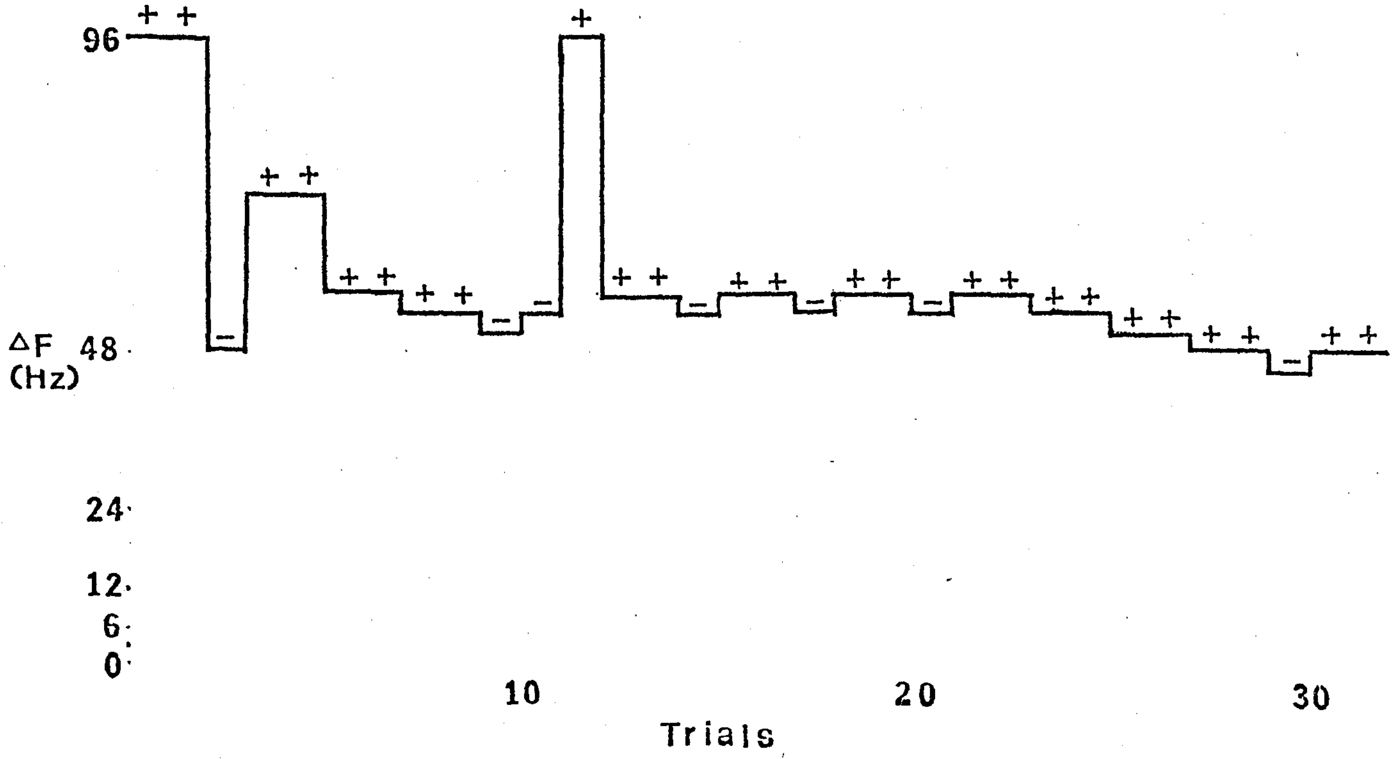

Figure 3. Typical infant response protocol. Standard frequency = 3000 Hz. Threshold in this case was 58.2 Hz.

RESULTS

It was important to show, first of all, that subjects were actually responding to the sound stimulus. Spurious thresholds might be obtained if infant false alarm rates were quite high: if the infant were turning toward the reinforcer repeatedly even when the frequency had not changed, it would be hard to conclude that he was actually responding to the frequency change when it did occur. We had attampted to control false alarm rates by employing a training procedure which included blank trials and requiring the infant to inhibit head turns on those trials before proceeding with testing. In addition, the presence of the experimenter playing with toys at the infant's midline was intended to control the number of false alarms. Because of the nature of the method employed to obtain thresholds, however, there is no way of estimating the number of opportunities for false alarms to occur during testing and traditional false alarm rates could not be computed. Simply presenting the numbers of hits and false alarms would be misleading since the time between trials when false alarms were counted was much greater than the duration of trials. Consequently, hit and false alarm "rates" were calculated as responses per minute for purposes of comparison.[1] These rates for each subject

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[1] $$\text{Hit rate} = \frac{\#\ \text{responses on trials}}{\#\ \text{trials} \times 4\ \text{sec}}$$

$$\text{False alarm rate} = \frac{\#\ \text{responses between trials}}{\text{time in testing--}\#\ \text{trials} \times 4\ \text{sec}}$$

at each standard frequency are listed in Table 2. Note that in each case, hits/min considerably exceeds false alarms/min. This finding argues against the hypothesis that thresholds are in fact spurious. In addition, with the exception of two infant subjects (DG & JC), false alarm "rates" are quite low, and no systematic differences as a function of age appear. Thus, we felt safe in concluding that our procedure had effectively controlled false alarms.

Once assured that our data did in fact reflect responses to the frequency changes, difference thresholds for each subject at each standard frequency were calculated. At least one threshold was available on 14 infants, but thresholds for all three frequencies were obtained for only 7 of these. For two subjects, thresholds at 1000 and 3000 Hz were obtained; the other five subjects provided data at 1000 Hz only. Thresholds for all subjects are shown in Figure 4.

As can be seen in Figure 4, infant thresholds at 1000 Hz ranged from 6 to 56 Hz, considerably better than had been found in earlier experiments. Moreover, while infant thresholds were found to be somewhat higher than those of adults, it is not uncommon to find differences of as much as 100% in adult DLs obtained from different subjects or different laboratories (Green, 1976). The age difference in threshold obtained, then, is within that range of variability.

Average thresholds for infants and adults clarify another aspect of these findings: the expected increase in DL with frequency occurs in the same manner for infants and adults (Figure 5). Moreover, these

Table 2

Hits and false alarms per minute

		1000 Hz		2000 Hz		3000 Hz	
	Subject	Hits/min	FAs/min	Hits/min	FAs/min	Hits/min	FAs/min
Infants	DG	4.5	3.6	8.5	1.9	6.4	2.6
	JC	5.7	2.2	6.7	1.2	5.2	2.2
	LL	1.8	1.6	5.6	0.6	4.8	0.6
	AO	6.4	1.4	6.2	0.8	7.0	0.6
	JZ	7.8	1.6	7.5	1.0	7.6	1.0
	MS	6.7	0.5	8.2	0.0	7.7	0.0
	KM	10.0	0.0	8.8	0.2	7.0	0.0
	SH	6.9	0.8	-	-	8.1	0.7
	SeH	8.4	0.9	-	-	8.2	1.4
	MSa	8.6	0.6	-	-	-	-
	GH	8.3	0.4	-	-	-	-
	RH	7.2	1.0	-	-	-	-
	HS	7.2	0.6	-	-	-	-
	AC	7.4	0.6	-	-	-	-
Adults	MP	8.5	0.0	7.4	0.2	7.4	0.0
	VS	8.3	0.4	7.5	0.0	8.0	0.5
	RS	8.2	0.0	6.8	0.0	7.0	0.2
	RT	7.6	0.3	6.8	0.4	8.0	1.6
	CS	7.8	0.0	6.7	0.8	8.5	0.0

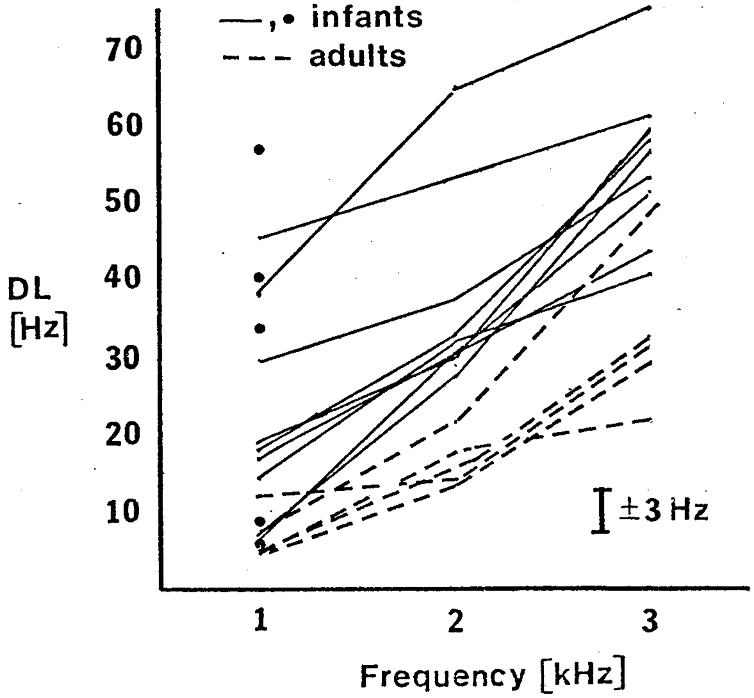

Figure 4. Individual subject thresholds as a function of frequency.

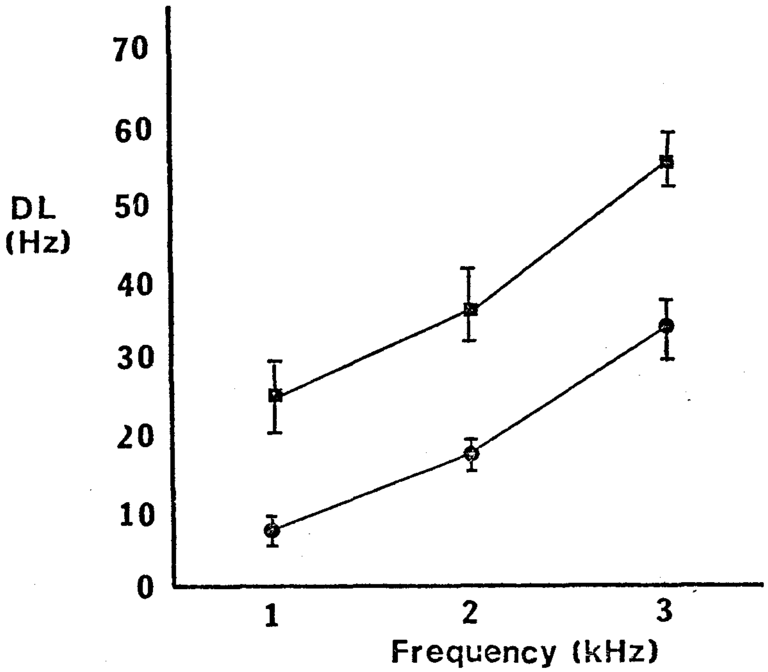

Figure 5. Average thresholds as a function of frequency for infants and adults (± 1 standard error).

curves are parallel to those obtained in a recent study of adult frequency discrimination (Wier et al., 1977) (Table 3). The results of this experiment, then, argue for at least a qualitative equivalence in the mechanisms controlling frequency discrimination in infants and adults.

It should be mentioned that no predictors of DL were identified in this study.[2] The infant's age, birth weight, current weight, stability of growth, health status and performance on the screening test were all found to be unrelated to the size of his difference threshold (Appendix B). Neither was the number of trials required for training related to the infant's performance during testing. The fact that the screening procedure did not predict success in the task would suggest that the procedure is not very effective. It can be noted, however, that this is the type of initial hearing screening device typically used in the newborn nursery and pediatrician's office. Our findings may indicate that this procedure actually gives little information about the infant's hearing capacity. On the other hand, it is unlikely that a major hearing impairment in in a middle class child who visits a doctor monthly would have gone unnoticed for 6 months. Therefore, it was improbable that we would recruit severely hearing impaired subjects, and we have no way of knowing how such infants might behave in the procedure.

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[2] One significant correlation emerged in this analysis, that between age and DL at 200 Hz ($r - .62$, $p < .05$). Recomputing the age-threshold correlations at 1000 and 3000 Hz for the seven subjects who were included in the 2000 Hz analysis yielded a signifcant correlation at 1000 Hz ($r = .85 < .01$) but not at 3000 Hz ($r = .31$, $p > .05$). A plausible explanation for this positive relationship between age and DL is not immediately apparent. Since the relationship does not persist when all 14 subjects are considered, it is possible that the significant correlation is a chance occurrence.

Table 3

Weber Fractions from this Experiment

and from Wier et al., 1977

	Frequency			
	1000	2000	3000	4000
Infants	.025	.018	.018	-
Adults	.0074	.0084	.0106	-
Wier et al.	.0013	.0012	-	.0028

DISCUSSION

Our findings demonstrate that infants are much better at detecting changes in frequency than has previously been shown. Their DLs, while slightly exceeding those of adult subjects in this study, are within the range of variability typically observed in tests of frequency discrimination. Moreover, infant and adult DLs increase with frequency in the same way. It can be argued, therefore, that frequency analyzing mechanisms in the auditory system are well-developed by the age of five months.

An examination of the adult psychoacoustics literature revealed that our subjects' thresholds were quite a bit higher than is typically observed. Our adult subjects were detecting approximately a 1% change in frequency while trained observers in standard psychophysical paradigms had been shown to detect changes of as little as .1% at this sensation level (e.g., Wier et al., 1977).

A number of factors might contribute to this difference. For example, our observers, with one exception, had not participated in other auditory experiments, and none of them were highly trained in frequency discrimination. More importantly, during testing, subjects in this experiment had no knowledge of when a frequency change might occur. Typical psychophysical experiments provide a signal to observers that a trial is about to begin. Our procedure, then, amounts to a vigilance task in which subjects must attend to each tone burst to decide whether or not a frequency change has occurred. Moray (1971) examined performance in a vigilance task in which observers detected frequency increments in a train of pulses 3000 Hz in frequency. For purposes of comparison, psychometric functions (percent correct as a function of frequency increment size) for his two observers are plotted in Figure 6 along with the adult psychometric function at 3000 Hz from this study, averaged over subjects. The performance of subjects in this experiment falls within the same range as that of Moray's subjects.

We were interested, however, in determining just how much of the difference between our results and those of Wier et al. (1977) was due to methodological differences. In order to estimate the size of that effect, it was decided to obtain DLs from our adult subjects under conditions comparable to shoe in Wier et al.'s study.

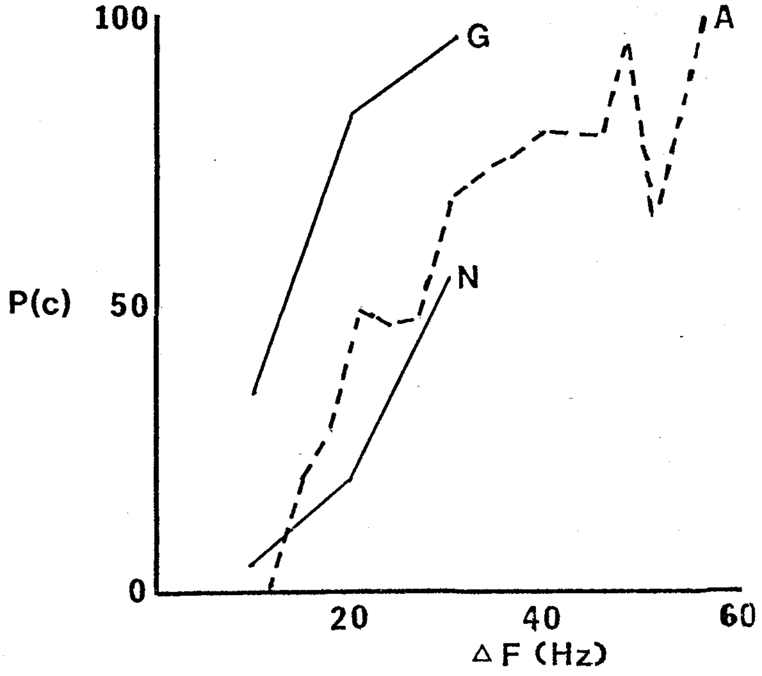

Figure 6. Average adult psychometric function (A) with functions for two subjects (G, N) in vigilance task, frequency = 3000 Hz (Moray, 1971).

EXPERIMENT II

Method

Four of the five subjects who had participated in the first experiment returned to the laboratory for Experiment II. Subjects were tested in a sound-attenuated room, and stimuli were presented via headphones. The procedure employed was a one-up, two-down two alternative forced choice (2AFC) procedure. A warning light 500 msec in duration occurred at the start of each trial. Each observation interval lasted 500 msec with a 10 msec rise-fall time. The two observation intervals were separated by a 500 msec pause. The observer had 1½ sec after the second observation interval to choose the interval which had contained the higher frequency signal. The correct response was then displayed for 500 msec. Stimulus presentation, response recording and feedback were all computer controlled.

Thresholds were obtained for standard frequencies of 1000, 2000 and 3000 Hz. Step sizes were 3 Hz at 1000 Hz, 5 Hz at 2000 Hz and 8 Hz at 3000 Hz. The stimulus level was 80 dB SPL. Each run continued until 7 reversals were obtained, averaging 35-50 trials. Two runs were obtained at each frequency. If the thresholds on these two runs differed by more than 1 step, a third run was obtained and the first discarded.

Results

Threshold was determined from each run as the average of the last five reversals. For each subject, the average of the thresholds from two runs at each frequency was used as the final estimate. These estimates are plotted in Figure 7, along with the average thresholds for these four subjects in the baby procedure and the average thresholds published by Wier et al. (1977).

The most striking aspect of these data is the decrease in threshold in the 2AFC procedure as compared with the vigilance-type baby procedure. The difference is on the order of 5-15 Hz, increasing with standard frequency. The theoretical limit of infant frequency discrimination, then, might be at least 10 Hz lower than the baby procedure estimates (Figure 8). It might be suggested, furthermore, that the effect of procedure would be greater for infants than adults.

Note also that the thresholds of subjects in this experiment are quite close to the values obtained by Wier et al. In fact, the one subject in this study (RS) who had had previous experience as an observer in auditory experiments performs at a level approximately equal to that reported by Wier et al. Therefore, at least some of the difference remaining between our observer's performance and that of Wier et al.'s subjects may be accounted for by general training effects.

Another aspect of these data which should be mentioned is the apparent frequency x procedure interaction: the effect of placing additional attentional demands on the subjects is greater as frequency is increased. No explanation for this effect is immediately apparent.

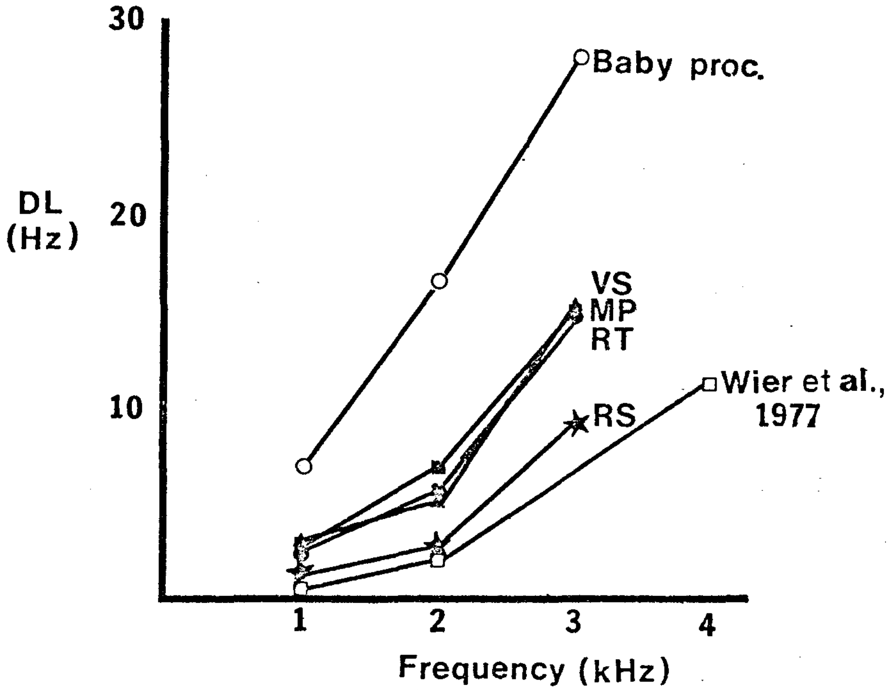

Figure 7. Individual threshold curves for adult subjects in 2AFC paradigm. (Baby proc. curve = average thresholds for these 4 subjects in head turn procedure. Lower curve represents average thresholds for 4 subjects reported by Wier et al., 1977.)

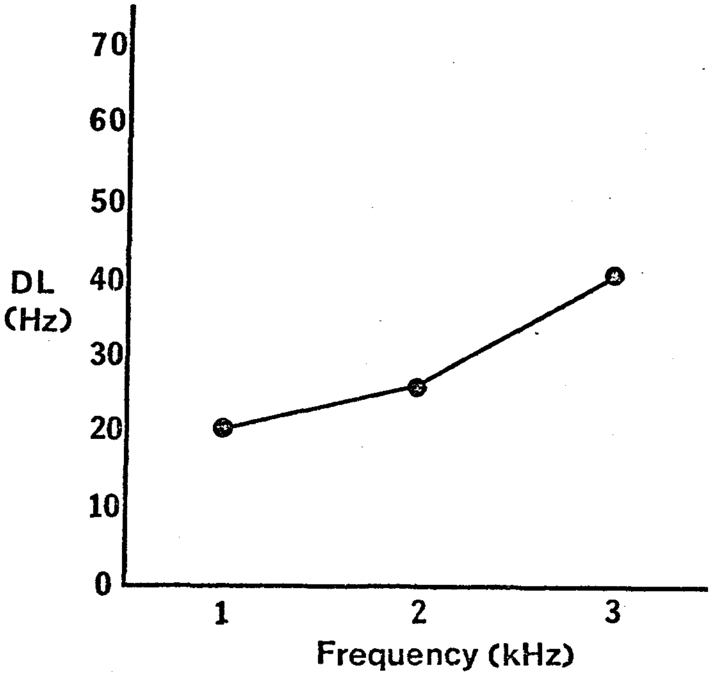

Figure 8. Average "corrected" infant thresholds. Correction made by subtracting difference between average adult threshold in baby procedure and average adult threshold in 2AFC procedure from average infant threshold at corresponding standard frequency.

GENERAL DISCUSSION

Infants in the age range tested here discriminate frequency at near-adult levels. Moreover, the increase in infant thresholds with frequency parallels that obtained with adults. A number of findings support the hypothesis that age differences in threshold result more from differences in performance criteria than from differences in the frequency selectivity or sensitivity of the auditory system. First, if the age difference in DL stems solely from a diminished sensation level among infants, we would expect that age difference to be even smaller than it actually is, since infant absolute thresholds are probably only 10 dB higher than those of adults (Wilson, Note 12). Wier et al. (1977) find a decrease in DL at 1000 Hz from 1.9 to 1.3 Hz when SL is increased from 40 to 80 dB. Furthermore, it might be noted that no systematic differences between infants and adults were found in the patterns of hits/min and false alarms/min. If these had been traditional hit and false alarm rates, this would argue against any differences in sensitivity. However, given the unorthodox nature of these response "rates" and the different methods used to control false alarm rates in the two age groups, any conclusions based on this finding must be tentative at best. It should be noted, though, that even if the age difference observed here reflects a relative lack of frequency selectivity in the infant auditory system, a difference on the order of 10 Hz is really quite small, given the variability in adult performance typically observed.

Since the threshold curves for infants and adults are parallel and assuming that the observed age difference results from a performance deficit among the infants, we can make a number of statements about the development of the auditory system. First, insofar as the response characteristics of the inner ear, and the basilar membrane in particular, determine the frequency analyzing capacity of the aucitory system, we would predict that these structures attain mature status within the first half year of life. Furthermore, immaturity of middle ear structures (e.g., greater compliance of the tympanic membrane discussed earlier) does not seem to have much effect on selective frequency response in the frequency range tested in this study. Finally, the increased latency and diminished amplitude of response noted at higher levels in the auditory system in infants within the first year do not appear to have a correlate in behavioral frequency discrimination. One might conclude, then, either that frequency discrimination is accomplished at a relatively low level in the auditory system or that it depends on neither the latency nor amplitude of the neural response. Given that the amplitude of the evoked response increases with signal level and that frequency discrimination worsens as signal level is decreased, the former explanation seems more plausible.

One implication of our finding of relatively fine frequency discrimination among infants is that information regarding frequency differences between speech sounds is available to infants in speech discrimination tasks. Frequency analysis could certainly account for the continuous (as opposed to categorical) discrimination of vowel sounds by infants reported by Trehub (1973) and by Swoboda et al.

(1976). The fundamental frequency of the voice has also been reported as one of several cues which distinguish voiced from voiceless stops (Agnello, 1975). While no single cue in a naturally occurring phoneme may be adequate to distinguish it from all other possibilities, our research forces the conclusion that frequency is available as a cue to infant listeners. An interesting possibility is that in consonants which may be distinguished by the frequency region of certain components (e.g., voiceless plosives/p,t,k/) infants might exhibit continuous discrimination, assuming they haven't yet learned the cut-off points of the frequency regions specifying different consonants for adults. Infant discrimination of such phonemes has not yet been examined.

At any rate, the variation of the VRA/VRISD paradigm which was employed in this study shows great promise as a method for investigating infant psychoacoustics. Instrumentation is relatively simple, experimenters can be trained quickly and a significant proportion of infants adapt readily to the procedure. Moreover, minor variations in the training procedure and in the type of stimulus used might prove effective in reducing the infant subject attrition rate. A further advantage of this technique is that older subjects can be run with essentially the same procedure, thus eliminating many procedural confounds in age comparisons. And most importantly, the head turn procedure has been shown to be far more sensitive than techniques such as the HAS paradigm in describing the infant's auditory capacity. It lends itself to the study of infant discrimination along a variety of dimensions including intensity, frequency, and frequency and amplitude modulation rates. Further research might turn to an examination of these and other dimensions.

In sum, this study represents an important first step in describing the development of one of the most salient characteristics of the human auditory system. As such, it reflects on the structural and physiological maturity of the auditory system in infancy and reveals one cue which may underlie the discrimination of speech sounds in early life. Future research should examine higher neural processes and uncover additional cues for infant speech discrimination.

SUMMARY

This study used an operant discrimination learning paradigm to determine frequency difference thresholds in 5- to 8-month old infants and in adults. Subjects were trained to turn their heads toward a mechanical toy and were reinforced for a head turn by the activation of the toy for 2 sec. Reinforcement was only available during the 4 sec period following a change in the frequency of a repeatedly presented tone burst. Thresholds were determined using a modified staircase technique in which the frequency difference was systematically decreased over trials until the subject no longer responded to the frequency change. The stimuli employed were sinusoids with standard frequencies of 1000, 2000, and 3000 Hz. The results of the experiment show infants to be much better frequency analyzers than had previously been demonstrated. Infants were able to discriminate changes in frequency of about 2-3%; adults in this paradigm could detect about 1% changes. The difference between adults and infants in thresholds is small in view of the variability typically observed in adult frequency discrimination tasks, and is discussed in terms of possible infant performance deficits. Much of the increase in threshold in this study relative to other adult psychophysical studies is shown to result from procedural effects. The results of this experiment are found to be consistent with other studies of the infant auditory system and may clarify some issues with regard to the processing of speech sounds in infancy.

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APPENDIX A

APPENDIX A

Comparison of Infant Subjects Participating in the Experiment with Those not Completing the Procedure

	Subjects Completing Procedure	Subjects Not Completing Procedure
Mean Age	6 mo 10 da	6 mo 11 da
Sex	7 M, 7 F	7 M, 5 F
Mean Birth Weight	7 lb 6 oz	7 lb 12 oz
Mean %ile	45	47
Mean Change in %ile, current - birth	-9.29	-9.25
Mean Performance in Screening	.77 correct	.76 correct
Colds?	1 yes 6 sniffles 7 no	1 yes 1 sniffles 10 no

APPENDIX B

APPENDIX B

Infant Subject Characteristics

I. Infant characteristics

			Weight (lb-oz)						Screening (#responses/#trials)	
		Age	Birth		Current		Current -			
Subject	Sex	(mo-da)	weight	%ile	Birth	%ile	Birth %ile	Cold?	Left	Right
DG	M	7-16	7-12	75	19-06	50	-25	sniffles	2/2	2/3
JC	M	4-26	6-13	25	12-13	10	-15	sniffles	0/2	2/2
LL	F	8-1	8-0	75	21-07	90	+15	no	2/2	2/2
KM	F	6-6	8-12	90	17-15	75	-15	sniffles	1/2	2/2
JZ	M	4-21	7-8	50	16-00	50	0	sniffles	2/2	2/2
MS	M	5-18	7-15	75	15-06	75	0	no	2/3	1/3
AO	F	8-1	8-01	75	15-13	75	0	yes	3/3	2/3
SH	F	5-23	4-10	10	12-00	10	+10	no	0/2	1/2
SeH	M	5-23	4-10	25	12-15	25	+25	sniffles	2/2	2/2
GH	M	5-2-	7-11	25	14-15	25	-50	no	1/2	0/2
MSa	M	7-22	7-10	25	17-00	25	-25	sniffles	1/2	0/2
HS	F	5-27	6-01	25	12-06	25	+15	no	1/2	2/2
AC	F	5-20	9-01	90	18-01	90	0	no	2/2	2/2
RH	F	6-3	8-05	50	14-08	50	-25	no	2/2	2/2

	# Training Trials			# Testing Trials			Frequency Difference Threshold (Hz)					
							1 kHz		2 kHz		3 kHz	
Subject	1 kHz	2 kHz	3 kHz	1 kHz	2 kHz	3 kHz	X	SD	X	SD	X	SD
DG	22	16	14	26	25	48	29.5	.41	37.5	3.24	53.0	8.15
JC	17	14	15	17	26	25	7.3	.43	27.5		57.0	3.24
LL	15	14	14	16	16	21	37.7	3.32	65.0	5.79	75.0	9.00
KM	18	14	15	18	15	28	18.5	1.41	30.0	3.13	58.2	1.47
JZ	30	16	15	18	15	28	6.8	.75	30.8	1.22	51.6	8.19
MS	30	17	14	16	13	17	14.3	1.67	31.5	.75	40.1	4.16
AO	20	15	14	26	25	23	18.0	1.84	32.1	1.50	57.6	1.80
SH	20	-	15	21	-	16	17.0	2.83	-	1.53	43.3	3.34
SeH	20	-	15	11	-	21	45.5	6.75	-	-	58.0	5.82
GH	20	-	-	18	-	-	40.2	1.84	-	-	-	-
MSa	25	-	-	14	-	-	33.8	.75	-	-	-	-
HS	35	-	-	19	-	-	57.0	2.12	-	-	-	-
AC	27	-	-	30	-	-	9.0	4.42	-	-	-	-
RH	41	-	-	26	-	-	7.0	1.87	-	-	-	-

II. Correlations between Subject Variables and Thresholds

Variable	Correlation 1 kHz	 2 kHz	 3 kHz
Age	.03	.62*	.30
Change in Weight %tile	.11	.50	.18
Weight %tile	.40	.54	.37
# training trials	.11	.21	.19
N	14	7	9

*$p < .05$

III. Adult Thresholds

	Frequency Difference Threshold (Hz)					
	1 kHz		2 kHz		3 kHz	
Subject	$\bar{X}$	SD	$\bar{X}$	SD	X	SD
RS	5.0	.71	17.5	2.23	21.5	2.55
VS	5.0	.71	13.5	10.45	28.9	6.48
MP	5.8	2.83	16.5	1.06	32.3	5.62
RT	12.3	1.82	14.5	.71	30.9	.73
CS	9.0	1.22	21.4	3.25	48.0	7.22

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The dissertation is therefore accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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