Development of Frequency Perception in Infants and Children

Élaboration d'une perception des fréquences chez les nouveaux-nés et les enfants

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Abstract

Research using behavioural methods to study the development of frequency perception is reviewed. Four aspects of frequency perception are considered: sensitivity, discrimination, masking, and critical bandwidths. Implications for clinical practice and possible underlying mechanisms mediating developmental changes in performance are discussed.

Résumé

Est passée en revue la recherche qui se sert des méthodes comportementales pour étudier la perception des fréquences. Quatre facettes de la perception des fréquences sont examinées: la sensibilité, la discrimination, le masque et les bandes critiques. Sont également discutées les incidences de la perception des fréquences pour la pratique clinique et les mécanismes sous-jacents possibles servant d'intermédiaire dans les modifications évolutives apportées au rendement.

Introduction

Frequency perception is a fundamental capacity of the auditory system and influences our auditory experience in numerous ways. For example, the ability to analyze sound into its frequency components allows us to listen to one instrument out of many being played in an orchestra or to attend to a conversation with one person while others around us are talking simultaneously. In fact, various components of language usage are dependent upon frequency perception, such as our ability to discriminate vowels, consonants, and combinations of phonemes. Also, the ability to detect frequency differences is essential to perceiving variations in intonation, which communicate subtle elements of meaning in speech. Frequency analysis also gives rise to our perception of pitch and thereby influences our ability to recognize and appreciate music. Even our ability for sound localizations influenced by sound frequency (Mills, 1972). For example, the localization of a sound along the vertical axis depends upon spectral cues (Gardner & Gardner, 1973; Morrongiello, 1987; Roffler & Butler, 1968). Finally, normative data on frequency perception are necessary to detect hearing impairments or the onset of hearing loss which may result from age, accident, illness, or exposure to ototoxic drugs.

This review will address four aspects of frequency perception: *hearing sensitivity, discrimination, masking,* and *critical bandwidths.* This review is limited to research on the development of frequency perception in human infants and children using behavioral testing methods. Physiological methods, such as heart rate and evoked potentials, also have been used successfully to assess frequency perception (e.g., Moffitt, 1971; Picton & Hillyard, 1974; Morrongiello & Clifton, 1984) but will not be discussed here (for a review see Aslin, Pisoni, & Jusczyk, 1983). Because research is constrained by methodology, we will begin with a discussion of relevant behavioural techniques used in the study of frequency perception with infants and young children. These include psychophysical procedures for stimulus presentation and testing techniques using behavioural response measurement.

Psychophysical Methods

The two classic psychophysical procedures (Fletcher, 1940) are the *Method of Constant Stimuli* (MCS) and the *Method of Limits* (ML). These two procedures are used to estimate an individual's level of sensitivity to a stimulus. Two types of thresholds can be measured: the *absolute threshold* and the *difference threshold.* The absolute threshold is the lowest intensity level of a stimulus that an observer can just detect reliably. The difference threshold is the smallest difference between two stimuli (e.g., intensity levels or frequency difference) that an observer can discriminate reliably. Both methods have been applied to the study of frequency perception in infants.

Method of Constant Stimuli

In the MCS, the subject is with presented a predetermined number of stimuli at a set number of intensity levels. The intensity levels are chosen so that the lowest level(s) can never be detected and the highest level(s) can always be detected; this range is usually determined by pilot testing. The goal is to determine the subject's sensitivity level, defined as the lowest intensity level that is detected on 50% of the trials on which that level is presented (Gescheider, 1985). To test adults, each of the pre-determined intensity levels is presented several times in random order. Because infants will not tolerate many trials, however, the MCS is generally not a good choice for measuring individual thresholds in infants (Trehub, Bull, Schneider, & Morrongiello, 1986). However, group thresholds can be measured using this method by pooling data from a number of infants to identify the stimulus intensity level that is detected by the group on 50% of the trials. Usually infants are grouped according to age so that developmental trends in threshold estimates can be examined (e.g., Trehub, Schneider, & Endman, 1980).

The Method of Limits

The ML presents a series of stimuli that begin at either a very high (i.e., a level that is easily detected) or a very low (i.e., a level that is impossible to detect) intensity level. Subsequent trials are increasingly less (or more) intense until the observer is no longer able (or becomes able) to detect the stimulus. Ascending and descending presentations are alternated until a set number of reversals of both types of series has been completed. The absolute threshold is defined as the average of the points of reversal (i.e., the intensity level at which the subject changed from being able to detect the stimulus to being unable to detect the stimulus, or the reverse).

To determine the difference threshold with the ML two stimuli are presented on each trial. One stimulus is the standard stimulus and remains constant. The other stimulus is the comparison stimulus. In an ascending series, the comparison stimulus is less intense than the standard initially and becomes more intense with each trial. The reverse is true for a descending series. Generally, a subject detects a difference between standard and comparison stimuli for several trials, then is unable to detect a difference for one or more trials, and then is able to detect a difference once again. Trials for which a subject is unable to detect a difference comprise the interval of uncertainty. The interval of uncertainty is measured by subtracting the intensity of the comparison stimulus detected just prior to entering the interval of uncertainty from the intensity level detected immediately following the interval of uncertainty. The difference threshold is half the absolute value of the interval of uncertainty (Gescheider, 1985).

The ML requires fewer trials to obtain a threshold than the MCS and is therefore preferable for measuring individual thresholds in infants, particularly since attrition rates due to poor state tend to increase with increasing numbers of trials. For estimating group thresholds, however, either procedure can be used; thresholds obtained using the MCS and ML tend to be very similar (Trehub et al., 1986).

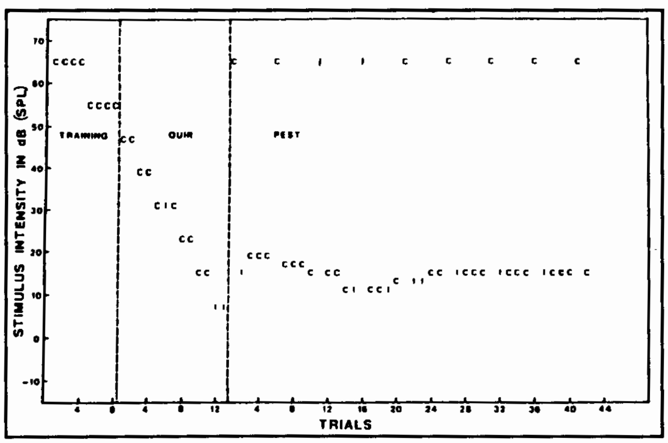
The Staircase Procedure

A modification of the ML that has become popular is *the staircase procedure* (Cornsweet, 1962). Variations of the staircase procedure have been developed but the basic method is the same in each case. It consists of presenting stimuli in either an ascending or descending series like the ML, but then terminating the series when the subject first detects (or fails to detect) a stimulus. Often two consecutive responses indicating a change in detection of a stimulus relative to preceding trials are required to terminate a series. Ascending and descending series alternate, each one beginning when the other is terminated. This alternation is continued until the direction of the series has reversed a number of times. Rules govern termination and the number of reversals. These allow the examiner to bracket the subject's threshold so that any further directional change would result in only a 1 to 2 dB change in stimulus intensity. Thus, the number of reversals is dependent upon both the subject's performance and on the rules specific to the methodology being used. Approximately two to 10 reversals is typical and reliability increases with an increased number of reversals. The threshold is the average of the intensity levels at which detection of the stimulus changed.

The staircase method is more efficient than the classic ML because less time is spent on trials in which the stimulus is either easily detected or impossible to detect. Thus, threshold can be measured in fewer trials. Using the traditional ML, Gescheider (1985) provides a sample session for an adult that required 71 trials. By contrast, Trehub et al. (1986) using the staircase method required only an average of 40 trials to test infants. This reduction in the number of trials results in significantly lower attrition rates, particularly with infants. Consequently, variations of the staircase procedure are used frequently in infant testing (Levitt, 1971; Berg & Smith, 1983; Olsho, 1983, 1985; Sinnott, Pisoni, & Aslin, 1983).

One staircase procedure developed specifically for estimating individual thresholds in infants is PESTI (Parameter Estimation by Sequential Testing in Infants; Trehub, et al., 1986). PESTI is an adaptation of PEST, developed by Taylor and Creelman (1967) for use with adults. PESTI is used to find the intensity level at which the probability of a correct response is equal to a pre-selected value (e.g., 75% chosen by Trehub et al., 1986). The number of correct responses over successive trials at a given intensity level is tabulated and compared with an expected number. The expected number is calculated as N x P, where N is the number of trials and P is the pre-selected value (e.g., 0.75). If the absolute value of the difference between the actual and expected number of correct responses equals or exceeds the pre-selected criterion value, the intensity of the stimulus is changed on the next trial. For example, the expected number of correct responses after 2 trials would be 2 x 0.75 or 1.5. If the actual number of correct responses was 1, then the absolute value of the difference between actual and expected values is 0.5, which is less than the criterion value of 0.75. Thus, no change in intensity is warranted. If, however, an incorrect response was made on the first trial, then the absolute value of the difference between actual (0) and expected (0.75) values would equal 0.75, and an increase in intensity would be made on the next trial. Decisions regarding the magnitude of intensity change from trial to trial are based on the preceding sequence of reversals (i.e., change in direction of stimulus magnitude) and continuations (i.e., stimulus magnitude changed in the same direction from one trial to the next) according to a series of pre-set rules (see Trehub et al., 1986). A sample PESTI session is shown in Figure 1.

Figure 1. A sample PESTI session from a 6-month-old infant. Correct responses are designated by C and incorrect responses by I. During training, QUIR (quickly into range) serves to focus quickly in on the threshold range. In PESTI, every fourth trial is a catch trial (from Trehub et al., 1986; reprinted with the permission of Ablex Publishing Corporation and the first author).



Trehub et al. (1986) suggest several advantages of the PESTI procedure. They tested 6-month-olds and found that attrition rates were relatively low and that group thresholds obtained with PESTI were comparable to those obtained with the MCS. Individual thresholds were obtained after only 20 to 25 trials without sacrificing accuracy. The relative efficiency of the PESTI method makes it particularly well-suited for testing infants in a clinical setting.

When using a staircase procedure, it is important to include both probe and catch trials (Sinnott et al., 1983). *Probe trials* present a signal well above threshold (i.e., the infant can hear the sound easily) and are included to assess the infant's level of attention throughout the session. If the infant fails to respond to a certain number of probe trials, it suggests that the infant is not attending to the task or is unable or unwilling to perform the required response and, consequently, the threshold is considered inaccurate (Berg & Smith, 1983). When measuring absolute thresholds, *control* or *catch trials* in which the stimulus is not presented are used to assess the incidence of random responses. When measuring difference thresholds, the control trial is one in which the comparison stimulus is equal to the standard stimulus; that is, there is no difference. Control trials are essential for determining the degree to which an infant's responding is under stimulus control and are used to separate sensitivity from a simple tendency to produce the desired response independent of whether the stimulus was detected. If a response occurs on a catch trial, the infant is sometimes given a rest period before testing resumes, and if responding to catch trials exceeds a certain level, testing is terminated (Sinnott et al., 1983).

Probe and catch trials are essential components of Signal Detection Theory (SDT; Tanner & Swets, 1954). SDT acknowledges that a subject's performance on a test of sensitivity is affected not only by sensitivity per se, but also by nonsensory factors such as motivation, interest, attention, and so on. Thus, experiments conducted according to SDT yield two measures of the subject's performance. One measure, *d'*, reflects the subject's sensitivity and the other measure, *beta*, is an index of the influence exerted by nonsensory factors.

Signal detection theory compares the incidence of responses when a signal was presented (i.e., hit rate) with the incidence of responses when no signal was presented (i.e., false alarm rate). The proportion of hit rates and false alarm rates can be converted to d' and beta scores using published tables (Elliott, 1964). A combination of high hit rate and low false alarm rate indicates a high level of sensitivity. A high hit rate alone is not sufficient evidence for high sensitivity because if the false alarm rate is also high, then the subject failed to discriminate between signal and no-signal trials and simply displayed a high response rate (e.g., Weir, 1976). Thus, one benefit of SDT in both clinical and research settings is the potential to evaluate the influence of sensory and nonsensory factors on performance.

SDT is often applied to Yes/No psychophysical paradigms in which a proportion (e.g., 50%) of trials present a signal and the remaining trials do not. The frequency of responses to no-signal trials is used to calculate a false alarm rate while the hit rate is determined by the frequency of responses on signal trials. For a discussion of this and other applications of SDT see Gescheider (1985).

Behavioural Response Measures

High Amplitude Sucking Technique

Behavioural studies of infant frequency perception have examined three types of perceptual processes: hearing sensitivity, frequency discrimination, and detection of a signal in the presence of background or masking noise. One of the first behavioural response measures used to investigate frequency discrimination was the high-amplitude sucking (HAS) technique (e.g., Trehub, 1973). In HAS, the first step is to measure the infant's baseline rate of sucking by calculating the frequency of sucking for a specified time period (e.g., 1 minute). During this period, a criterion level of sucking is established such that the pressure of the infant's sucks at that level would be sufficient to activate the stimulus during the testing phase. Following this, a stimulus is presented contingent upon sucking at the criterion level until the infant is habituated to the stimulus, that is, until sucking rate falls to some pre-determined level. The habituation criterion is usually some proportion of the infant's highest sucking rate. For example, Trehub (1973) defined habituation as 33 1/3% of the infant's highest sucking rate maintained for 2 consecutive seconds, while Wormith, Pankhurst, and Moffitt (1975) used 25% of the highest sucking rate held for 2 seconds as their habituation criterion. After habituation occurs, a second stimulus is presented. If the sucking rate resumes to a high level (i.e., dishabituation occurs), the infant is said to have discriminated the two sounds (see Jusczyk, 1985, for a discussion of necessary control groups).

One advantage of the HAS paradigm is that it relies on a response that can be executed by nearly all young infants. However, there also are some disadvantages. First, because infants older than 4 months generally will not suck on a non-nutritive nipple, the sucking paradigm can only be used for a narrow age range (i.e., under 4 months), making it impossible to compare thresholds obtained with this method across a number of different ages. Also, HAS requires a specialized apparatus generally not available in most clinical settings. For these reasons, HAS is no longer used very often (for a complete review of HAS see Jusczyk, 1985).

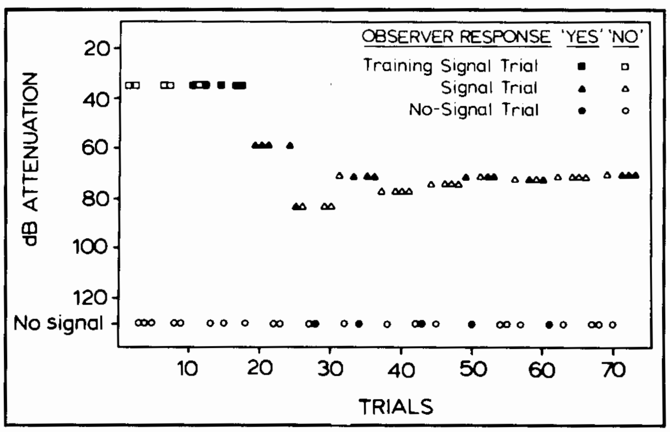
Observer-Based Psychophysical Procedures

Currently, a more common procedure for evaluating frequency perception in very young infants is the *observer-based psychoacoustic procedure* (OPP) developed by Olsho and her colleagues (Olsho, Koch, Halpin & Carter, 1987) for testing infants 4 weeks of age and older. Because young infants have a limited response repertoire coupled with large individual differences in motor skills, Olsho's procedure does not require a particular response. Instead, any response is acceptable. Responses typically include eye widening, changes in rate of sucking on a pacifier, head turns toward or away from the sound, and general alerting or quieting. On each trial, the examiner observes the baby's behaviour and, on the basis of those observations, decides whether or not a signal was presented. This method is a Yes/No procedure in which the observer decides whether a signal was presented ("yes") or not ("no"). Signal and no-signal trials occur equally often and are used to evaluate the observer's ability to distinguish detection responses from the baby's random behaviour.

The OPP requires a training phase in which the signal is presented well above threshold to enable the observer to become familiar with the typical responses to sound of the baby being tested. Feedback is provided during training and testing to facilitate the observer's judgements on subsequent trials. If the observer judges correctly that a signal was presented, then some type of reinforcer (e.g., toy waved in front of baby) is presented to encourage the baby to reproduce on subsequent sound trials whatever response was judged by the observer to be indicative of signal presentation. On no-signal trials, if the observer correctly judges that a signal was not presented, no reinforcement is given. Figure 2 shows a sample session using OPP.

Olsho and her colleagues (Olsho et al., 1987) were successful in testing infants under 6 months of age using OPP and found that the PEST rules for stimulus presentation worked well. A threshold could be obtained within the infant's attention span; a separate session needed for each threshold obtained. An average of 22 training trials was required for 3- and 6-month-olds to evaluate pure tone detection. To test frequency discrimination, an average of 19 training trials was needed for 3-month-olds, and an average of 17 for 6-month-olds. The data obtained for 6-month-olds

Figure 2. A sample OPP session from a 6-month-old using a 500 Hz stimulus (from Olsho et al., 1988; reprinted with permission from the American Institute of Physics and the first author).

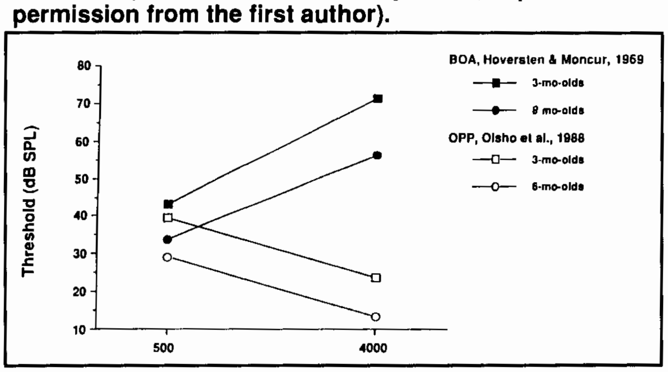


with OPP were compared with data obtained using the well established conditioned head-turn technique and close agreement was found.

OPP has both advantages and disadvantages for clinical use. The advantages include low attrition rates and its use with infants across a wide age range. Thus, thresholds obtained at an early age can be compared to those at older ages using the same procedure. One possible disadvantage is that if the observer judges that a signal was not presented when in fact a signal was presented, one cannot conclude that the infant did not hear the sound. Also, infant responses may vary as a function of stimulus parameters such that responses to low intensity sounds may be too subtle for an observer to detect. Thus, one may underestimate threshold for some infants.

Olsho's procedure is somewhat similar to behavioural observation audiometry (BOA) which was developed for use by audiologists in testing infants under 6 months of age. However, there are key differences between the two procedures: (1) BOA does not control for examiner bias, while OPP requires all those involved in the test session to wear masking headphones, unless stimuli are presented via earphones (in which case the testers would be unable hear the signal); (2) OPP uses reinforcement to maintain the infants' attention and to shape their responses; and (3) threshold estimates for infants presumed to have normal hearing vary greatly as a function of which procedure is used (see Kuhl, 1985). Werner and Feeney (1990) compared thresholds for 500 and 4000 Hz tones obtained with OPP (Olsho, Koch, Carter, Halpin, & Spetner, 1988) with thresholds obtained with BOA (Hoversten & Moncur, 1969). They found a substantially lower threshold for the 4000 Hz stimulus when the OPP was used, presumably due to the effectiveness of reinforcement in maintaining and controlling the infants' responding. Figure 3 shows this comparison.

Figure 3. Comparison of thresholds obtained using OPP and BOA (from Werner & Feeney, 1990; reprinted with permission from the first author).



Conditioned Head-Turn Technique

One of the most widely used methodologies for studying frequency perception in older infants is the conditioned head-turn technique (Moore, Thompson, & Thompson, 1975; Schneider & Trehub, 1985, Schneider, Trehub, & Bull, 1980; Olsho, 1984). Babies as young as 4 months will turn their heads in the direction of a sound (Muir & Clifton, 1985) but the head turn response cannot be conditioned until 5 to 6 months of age (Moore et al., 1975). The conditioned head-turn technique is advantageous because it can be used with a wide age range, attrition rates are low, it is non-invasive, and infants typically will complete as many as 30 to 40 trials in a single session, which usually is sufficient to provide a threshold estimate.

In this procedure, the infant sits in an infant seat or on the mother's lap facing away from her. The infant then is conditioned to execute a head turn in response to a stimulus according to an operant conditioning paradigm. When a sound is presented and the infant head turns in the direction of the sound, some type of visual reinforcement is presented at the location of the sound source. If the infant does not turn toward the sound (i.e., turns away from the sound or makes no head turn at all), a time-out period (usually about 4 seconds) is introduced before beginning the next trial.

The conditioned head-turn technique can be applied to both the two alternative forced-choice and the Yes/No psychophysical procedures. In the forced-choice procedure, sounds are presented to the left or right of the baby's midline, with an equal number of trials at each location. The examiner must decide whether the baby executed a head turn to the left or right of midline. A reinforcer is activated if the head turn was in the direction of the sound source. This method works well with babies age 5 to 21 months and can be used to assess sensitivity (Schneider & Thorpe, 1990; Sinnott et al., 1983; Trehub et al., 1980), discrimination (Olsho, 1983), and masking (Bull, Schneider, & Trehub, 1981; Nozza, 1987; Olsho, 1985).

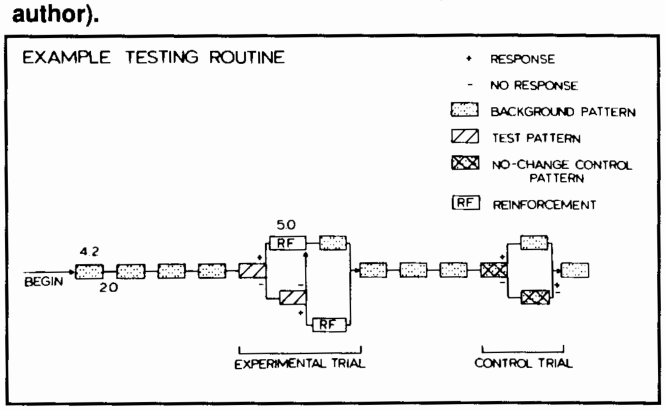
To measure sensitivity using the forced-choice procedure, sounds of one or more centre frequencies are used as stimuli. Each frequency is presented at different intensity levels. If the infant turns reliably in the direction of the sound for a particular frequency at a particular level, the infant is said to be sensitive to that combination of frequency and intensity. It is also possible to use this technique with earphone presentation (Berg & Smith, 1983). Earphone presentation may be preferable in clinical settings when the sensitivity of each ear needs to be evaluated.

To measure discrimination using the two alternative forced-choice procedure, a standard stimulus of a particular centre frequency is presented on all trials. On signal trials, the stimulus alternates between the standard and a comparison of a different centre frequency, and the infant is trained to execute a head turn when a change in frequency occurs. To measure masking, a signal of a particular centre frequency is presented continuously from loudspeakers to the infant's right and left. A masking stimulus with overlapping frequencies but a higher intensity level is then added to the output of one speaker, and the baby is conditioned to head turn in the direction of the signal.

When using the Yes/No or Go/No Go technique (Moore & Wilson, 1978) in conjunction with the conditioned head-turn procedure, the infant is conditioned to execute a head turn (i.e., "Go") if the signal is presented and not to respond (i.e., "No Go") if the signal is absent. Typically, the baby sits on a parent's lap facing the examiner. The examiner waves a toy in front of the infant to centre the head prior to the onset of a trial. When a trial begins, the examiner watches for the infant's response. When measuring sensitivity, signal and no-signal trials are presented. If a signal is presented on a trial, a reinforcer is activated if the baby makes a head turn. No reinforcer is activated if a signal is not presented. When measuring discrimination, infants are reinforced for responding to changes in the frequency of a signal within a trial. The examiner always knows when a trial begins but is blind to the type of trial. A sample test session using the Go/No Go procedure is shown in Figure 4.

The Go/No Go technique can be used to measure either sensitivity or discrimination. When sensitivity is measured, the infant is conditioned to head turn reliably on trials in which the signal is presented and not to respond on no-sound or control trials. Examining how response rate varies with signal intensity allows one to obtain a threshold estimate (i.e., the lowest signal intensity for which the infant responded reliably above the spontaneous response rate observed on no-signal trials). When discrimination is measured, a signal

Figure 4. A sample session using the Go/No Go procedure (from Morrongiello, 1986; reprinted with the permission of Ablex Publishing Corporation and the author).



of a particular frequency is presented repeatedly as a background stimulus and the baby is conditioned to execute a head turn when the frequency of the signal changes; no response is expected on no-change control trials. Thus, if the baby head turns reliably to a change in frequency, then the baby is said to be able to discriminate these frequencies (Olsho, Schoon, Sakai, Turpin, & Sperduto, 1982).

The Go/No Go technique also can be used to assess signal detection in noise. Background noise is presented continuously during the test session and the signal is either presented or not presented on each trial. If the infant head turns consistently when the signal is presented and does not respond on no-signal trials, one can conclude that the infant was able to detect the signal in the presence of the noise. More than one stimulus can be evaluated in the same test session simply by presenting signals of different frequencies or different intensities on some trials. It is usually best to duplicate some trials so that the infant is allowed more than one trial to demonstrate detection of each stimulus to allow for random fluctuations in responding.

Except for HAS, there are some important methodological considerations common to all behavioural response procedures. The essential factors are reinforcement, use of masking headphones, training to criterion, and length of the response interval. Research has shown that the use of reinforcement is crucial in estimating infant thresholds (Trehub, Schneider, & Bull, 1981). Reinforcement helps to maintain the infant's attention and thus permits a greater number of trials than would be possible without it. Trehub, Schneider, and Bull (1981) compared infant thresholds obtained with and without reinforcement and found substantially lower thresholds when reinforcement was used. Several types of visual reinforcement have proven effective, such as a mechanical toy enclosed in a darkened Plexiglas box that is lit when the child turns toward the sound (Schneider, Trehub, Morrongiello, & Thorpe, 1986) or an array of Christmas lights set in black styrofoam (cf., Morrongiello, Fenwick, & Chance, 1990; Morrongiello & Rocca, 1987).

When using behavioural techniques, it is essential that adults involved in the testing are unable to bias the infant's responding in any way. This is accomplished by wearing masking headphones that prevent detection of the signal (e.g., Trehub & Schneider, 1983). Another important factor is the length of the response interval. The examiner must decide whether to allow the baby an unlimited time interval in which to execute a response (i.e., an open-ended delay between trials) or whether to set a fixed amount of time for a response to occur. Trehub, Schneider, and Bull (1981) compared thresholds obtained using an unlimited versus a fixed response interval and found that when an unlimited interval was allowed, lower thresholds were obtained. Some infants are slow to respond on some trials but respond correctly when given ample time (e.g., 2 to 5 seconds). The use of an unlimited response interval, then, can accommodate these infants without sacrificing the accuracy of threshold estimates. However, use of an unlimited response interval may lengthen the duration of each trial and, consequently, limit the number of trials that can be presented within the infant's attention span.

When using either the observer-based or the conditioned head-turn procedure, a training phase usually is presented before testing begins. In the training phase, sounds are presented well above threshold so that the examiner can be sure that the infant can detect the sound. The training phase is used to demonstrate the task to the infant and to ensure that the infant is capable of making the desired response and learning the contingency. Also, when using the observer-based procedure, the training period enables the examiner to become familiar with the responses typical of each baby. In both procedures, infants usually must meet a training criterion before proceeding to testing (e.g., four correct responses within five trials). Infants who fail to meet the training criterion cannot provide threshold estimates and are excluded from a study (e.g., Trehub & Schneider, 1983)

Some Recommendations for Clinical Applications

Methodological advances achieved in the study of infant audition do not always lend themselves to direct implementation in a clinical audiology setting. For example, often in the clinical setting there are more limited resources available to meet electronic and related technical needs. Nonetheless, knowledge gained about the significance of certain aspects of the testing context and procedures can be applied clinically to enhance the reliability and validity of infant tests.

First, it is essential that the testing chamber be free of unnecessary items (e.g., unused equipment, toys, etc.) in order to minimize distractions to the infant during testing and also to enhance the homogeneity of the sound field (e.g., effects of reverberation on performance). If directional responding is required, it is imperative that visual distractions be balanced on each side of the baby (e.g., loudspeaker and toy on each side), even if both sides are not used in testing. Failure to do so often results in infants' developing a bias for turning to the side in which something interesting is available to see.

If no-signal (i.e., control) trials are not included in testing, one is very likely to overestimate an infant's capabilities because of the frequency with which they look toward the toy throughout the session. Similarly, responses on sound trials are more likely to occur if the infant is always rewarded for a response, potentially resulting in an overestimation of the infant's capabilities. Ideally, in the clinic, no-signal trials should be interspersed with signal trials to assess the infant's level of random responding. A comparison of performance on these two types of trials can provide a more informed judgement of the infant's true hearing sensitivity. Including both trial types would allow the clinician to use d' scores to evaluate sensitivity and response bias separately. Infants who score very well by head turning on signal and not turning on no-signal trials are more selectively responsive than those who turn often on both types of trials. Also, inclusion of an occasional probe trial (i.e., signal presented well above threshold level) will ensure continued exposure to reinforcement and will provide an index of the infant's interest in the task and willingness to perform the desired response. If the infant fails to respond on a probe trial, the examiner may either terminate testing or give the infant a break. Boredom or unwillingness to respond poses threats to the validity of results obtained from continued testing.

Throughout testing it is essential that the parent holding the baby wear headphones to prevent biasing of the infant's performance. In our experience, parental biasing can occur in very subtle but significant ways (e.g., gently bouncing the baby and then pausing briefly when a signal is presented). If the parent is required to entertain the baby between trials, then some procedure should be implemented to let the parent know that a trial is occurring but not the type of trial (i.e., probe, no-signal, signal). Presenting a beep over the parent's headset or turning on a light signal (out of the baby's line of sight) at trial start might be some easy ways to give the parent a warning signal to stop entertaining the baby.

Finally, reinforcement is useful both to condition the infant to produce the desired response and to maintain attention, thereby permitting longer testing sessions than would be possible without it. The most common reinforcer is a mechanical toy. However, in our experience some infants, particularly younger ones, respond negatively to the abrupt, loud onset of such a toy. Consequently, we have found that connecting the toy to the power source via a potentiometer (i.e., a dimmer-type switch) is very useful. It enables us to moderate the abruptness of the onset and the speed at which the toys operate. As an added bonus, operating the toys at decreased power levels greatly prolongs their life. Another reinforcer that is easy to implement and extremely effective in recruiting attention is a set of miniature Christmas lights set in styrofoam (painted black) arranged in different geometric designs (see Morrongiello & Rocca, 1987). A brief 4 to 5 second presentation of the lights has been used successfully in auditory testing with 6- to 18- month-old infants. In summary, careful selection of both the testing environment and procedures is essential to maximize the infant's cooperation and the reliability and validity of the hearing assessment.

Review of Research Findings

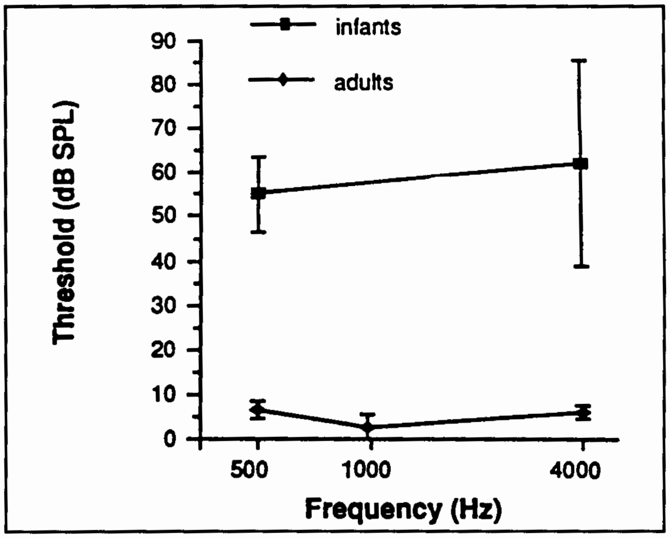
Hearing Sensitivity

Hearing sensitivity refers to an observer's ability to detect the presence of an auditory stimulus. Sensitivity is affected by the frequency of a sound, regardless of the listener's age. However, age-related changes in sensitivity are known to occur. In general, sensitivity improves with age from birth to adulthood. However, the rate and degree of change in sensitivity vary as a function of sound frequency.

Evidence from research conducted during the first few weeks after birth suggests that very young infants are more sensitive to lower than to higher frequencies (Hutt, Hutt, Lenard, von Bernuth, & Muntjewerff, 1968; Eisele, Berry, & Schriner, 1975; Weir, 1976; Werner & Feeney, 1990; Werner & Gillenwater, 1990). In addition, a few studies (e.g., Weir, 1976) have found that very young infants exhibit low rates of responding to sound in general, which could be taken to suggest difficulty in using behavioral measures to estimate hearing sensitivity at young ages. Werner and Gillenwater (1990), however, point out that although the developmental trend obtained from studies of very young human infants showing a progression from low to high frequency sensitivity is consistent with data obtained from studies of non-human species (Rubel, 1978), the finding of low sensitivity overall is not. They suggest that behavioural techniques used previously have not been sufficiently sensitive to detect sensitivity to sound in very young infants.

In an effort to provide a more sensitive assessment of hearing sensitivity in very young infants, Werner and Gillenwater (1990) used the observer-based psychoacoustic procedure (cf., Olsho et al., 1987). Pure tones with centre frequencies of 500, 1000, and 4000 Hz were presented to infants aged 2 to 5 weeks via a probe tube inserted into the ear canal. At 500 Hz, sensitivity approached the level of 3-month-old infants. Similarly, at 1000 Hz, the threshold obtained from infants was 25 dB, which corresponds closely to the 1000 Hz thresholds obtained previously for both 3- and 12-month-olds. At 4000 Hz, however, infants did not respond reliably to tones presented under 65 dB SPL (Olsho, et al., 1988). Thus, the greatest limitation in very young infants' sensitivity to sound occurred at relatively higher frequencies, with sensitivity to lower frequency sounds approaching that of older infants. Weir (1976) has suggested that the young infants' improved sensitivity for lower, relative to higher, frequencies may represent an adaptive mechanism in that their auditory system is maximally sensitive to the predominant frequencies of adult speech. A comparison of some threshold estimates obtained from adults and 2- to 5-week-old infants is shown in Figure 5.

Figure 5. Pure tone thresholds for 2- to 5-week-old infants and adults. No threshold could be obtained for infants at 1000 Hz (from Werner & Gillenwater, 1990; reprinted with the permission of Ablex Publishing.

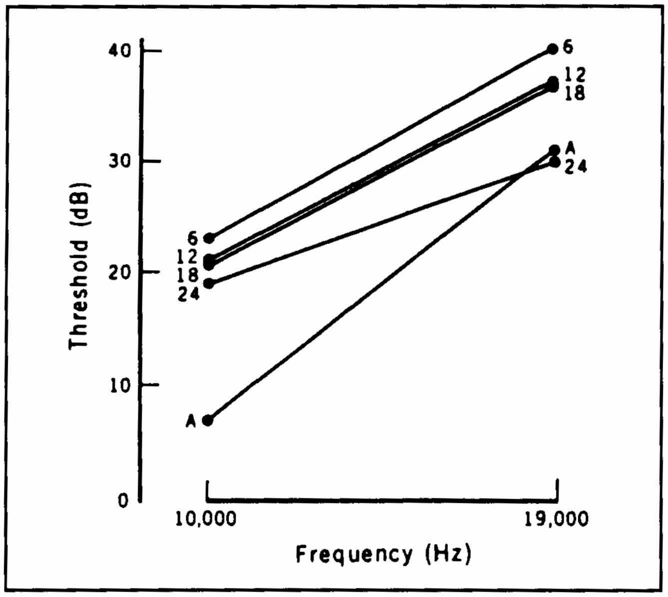


As indicated by the findings of Werner and her colleagues (Werner & Gillenwater, 1990; Werner and Feeney, 1990), improvements in high frequency sensitivity occur during the first several weeks after birth. Following this period, however, evidence from a number of studies suggests greater sensitivity for higher, relative to lower, frequency sounds, with converging thresholds for infants and adults at very high frequencies.

Schneider et al. (1980), using a two alternative forced-choice procedure, determined thresholds for 6-, 12-, 18-, and 24-month-olds and young adults (mean age=26 years) for 1/2 octave-band noises centred at 10,000 and 19,000 Hz. For the 10,000 Hz stimulus, results indicated that adults had significantly lower thresholds, indicating greater sensitivity, than infants. No significant differences were found between 6 and 24 months, however, with infants in each of the four age groups tested displaying thresholds 12 to 16 dB higher than those of adults. By contrast, results for the 19,000 Hz stimulus indicated a substantial decrease in the discrepancy between infant and adult thresholds. In fact, the disparity disappeared completely for the 24-month-olds and was greatly reduced for the three other age groups. Figure 6 provides a comparison of infant and adult thresholds for these high frequency stimuli.

Trehub et al. (1980) used a two alternative forced-choice conditioned head-turn procedure to determine 6-, 12-, and 18-month-olds' thresholds for detecting octave-band noises. The 6-month-olds had higher thresholds than the older infants and adults when frequencies of 200 Hz or less were used. For frequencies of 4000 Hz and 10,000 Hz, however, thresholds for the three infant groups were similar and

Figure 6. High frequency thresholds for 6- to 24-month-olds and adults (from Schneider et al., 1980; copyright 1980 by AAAS, reprinted with permission).



also converged with adults' thresholds. Thus, both Schneider et al. (1980) and Trehub et al. (1980) concluded that age-related changes in frequency sensitivity from 6 months are limited primarily to lower frequencies.

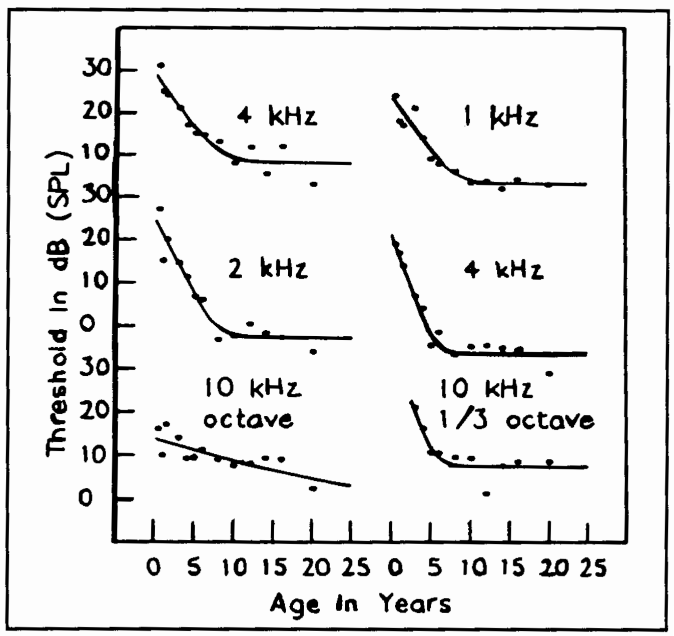
In contrast to the findings reported above, Berg and Smith (1983), used the Go/No Go conditioned head-turn technique with pulsed pure tones and found that 6- to 18-month-olds did not show lower thresholds for higher frequencies when tested with stimuli of 500, 2000 and 8000 Hz. Similarly, Moore and Wilson (1978) also used the Go/No-Go procedure to evaluate thresholds for 6- and 12-month-old infants using warbled tones of 500, 2000, or 4000 Hz and found no evidence for reduced sensitivity to lower frequencies for either age group. These discrepancies in results across studies may reflect differences in stimulus selection, measurement, or related factors, such as the use of headphone presentation at some ages. For example, Berg and Smith used pulsed pure tones in a free field at some ages, which can result in a highly variable distribution of sound pressures in a room (Dillon & Walker, 1982; Morgan, Dirks, & Bower 1979). Also, Berg and Smith's use of an A-weighted scale rather than a C or Linear scale for measuring sound pressure level likely underestimated the actual SPL for the 500 Hz stimulus (Peterson & Gross, 1972). Finally, use of a headphone with infants can itself contribute to variation in threshold estimation (Moore & Wilson, 1978).

Despite the few inconsistencies in results of studies examining thresholds of infants 6 months and older, most studies indicate less discrepancy between infant and adult thresholds at higher frequencies. Research with older children similarly indicates greater changes in low frequency sensitivity (Schneider et al., 1986; Trehub, Schneider, Morrongiello, & Thorpe, 1988). In a study of pre-school children, Schneider et al. (1986) found evidence of improvement in sensitivity throughout the age range of 3 to 5 years for frequencies centred at 400, 1000, 2000, 4000, 10,000, and 20,000 Hz. For all but the 20,000 Hz stimulus, continued increases in sensitivity were evident beyond 5 years of age when thresholds were compared with those of young adults (mean age of 20 years). However, 5-year-olds' sensitivity was superior to that of adults at 20,000 Hz, indicating that there is a decline in sensitivity prior to adulthood for very high frequencies.

To extend these findings Trehub et al. (1988) assessed frequency sensitivity in children aged 6 to 16 years. Their data indicated that maximal sensitivity for 400 and 1000 Hz stimuli is reached at 10 years of age; for 2000 and 4000 Hz stimuli at 8 years; for 10,000 Hz stimuli at 4-5 years; and for the 20,000 Hz stimulus, maximal sensitivity is reached at 6 to 8 years followed by a decline to adult levels during adolescence. Finally, both Schneider et al. (1986) and Trehub et al. concluded that throughout childhood the rate and extent of improvement in frequency sensitivity is considerably greater for lower frequencies than for higher frequencies. Shown in Figure 7 are infant, child, and adult thresholds for stimuli ranging from 400 to 10,000 Hz.

While one might argue that age-related changes in sensitivity reflect changes in motivation to perform the task,

Figure 7. Thresholds as a function of age for octave-band stimuli centred at .4, 2 and 10 kHz and 1/3 octave-band stimuli at 1, 4 and 10 kHz (from Trehub et al., 1988; reprinted with the permission of Academic Press, Inc. and the first author).



Schneider et al. (1986) point out that if the motivation hypothesis were correct, then the magnitude of improvement with age would be equal across different frequencies. As can be seen in Figure 7, this is not the case for infants and children aged 6 months to 5 years.

Because age-related changes in sensitivity cannot be explained simply as an artifact of changes in motivation, other mechanisms must be responsible. Schneider et al. (1986) suggest that changes in the structure and mechanics of the ear and in neural processing may contribute to age-related changes in frequency sensitivity. For example, the small size of the pinnae and external auditory canal in infants, relative to adults, may provide a partial explanation for why high frequencies are more easily detected than low frequencies in infants and young children, since the smaller pinnae and ear canal would resonate at a higher frequency (Trehub, Schneider, Morrongiello, & Thorpe, 1989). Furthermore, changes in the mechanical properties of the middle ear structures and the cochlea could account, at least in part, for the observed developmental changes in frequency sensitivity. For example, as discussed by Schneider et al., there is evidence of developmental changes in cochlear mechanics in some non-human species, and it is possible that similar changes occur in humans. Specifically, evidence from studies of embryonic and hatchling chickens (Rubel, 1978; Rubel & Ryals, 1983) suggests that, with age, the locus of the peak of a travelling wave shifts from the base toward the apical end of the cochlea for any given frequency. Furthermore, changes in the tonotopic organization of brainstem auditory nuclei occur late in embryonic development resulting in different neurons having maximal sensitivity to different frequencies at different ages (Lippe & Rubel, 1983).

In addition to changes in the mechanics of the ear, Schneider et al. (1986) suggest that improvements in the efficiency of neural coding may contribute to age-related changes in frequency sensitivity. They argue that threshold experiments involve the detection of a signal within a background of internal physiological noise and, therefore, age-related improvements in performance may be related to changes in the ability of subjects to separate a signal from noise at the neural coding level.

Frequency Discrimination

The ability to discriminate frequencies is an important skill for communication and music perception. Speech perception requires frequency discrimination skills because each word is made up of several phonemes represented by different frequencies. Thus, we learn to interpret spoken utterances based on complex combinations of different frequencies.

Similarly, frequency discrimination is essential for music perception. Our ability to appreciate the combinations of notes that make up a piece of music is largely dependent upon our ability to resolve frequency differences. Literature on frequency discrimination using musical stimuli and on pitch perception per se will not be reviewed in this paper. A discussion of infants' discrimination of musical patterns is provided by Trehub (1985), and Clarkson and Clifton (1985) discuss infant pitch perception.

Using the HAS procedure, Wormith et al. (1975) found that infants as young as 1 month of age were able to discriminate between pure tones of 200 and 500 Hz. Trehub (1973) tested 4- to 17-week-old infants using the HAS paradigm. Stimuli consisted of vowel pairs (i.e., [a] & [i]; [i] & [u]), vowel-consonant pairs (i.e., [pa] & [pi]; [ta] & [ti]), or pure tone pairs (i.e., 1000 & 2000 Hz; 100 & 200 Hz; 200 & 1000 Hz). Infants could discriminate two speech stimuli, however, they failed to discriminate pure tones. These results may indicate that fundamental differences exist between the processes underlying the perception of speech and pure tones. Alternatively, speech sounds may be more reinforcing for infants than tones, resulting in higher sucking rates during the dishabituation phase for speech than for tones.

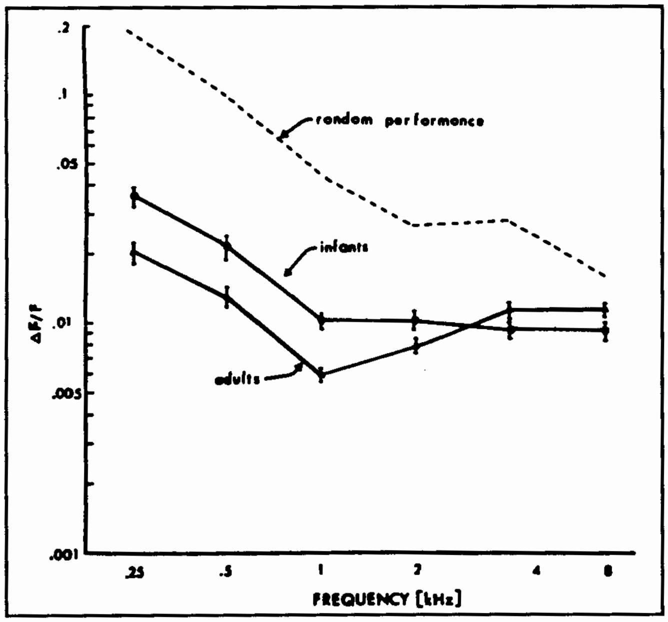
Reasons for the discrepancy in results between the studies of Trehub (1973) and Wormith et al. (1975) are not clear. Wormith et al. suggest that differences in infants' state may be responsible because they discarded the data of 32 infants who were not in an awake and alert state throughout testing. Trehub discarded infants' data only if they failed to reach a criterion level of sucking or if they cried persistently. Thus, the infants included in Wormith et al.'s analysis may have been in a more optimal state for testing and, consequently, yielded evidence of better frequency discrimination. Obviously, these suggestions point to some essential considerations for effective clinical appraisal of infants' frequency discrimination abilities. Using behavioural measures necessitates infants be in an alert and quiet state.

Using a conditioned head-turn procedure, Olsho et al. (1982) tested 5- and 8-month-old infants' and young adults' abilities to discriminate frequency changes in pure tones of 1000, 2000, and 3000 Hz. Results indicated that infants had higher difference thresholds at all three frequencies when compared to adults. The infants detected frequency changes of approximately 2%, while adults detected changes of approximately 1%.

In a related study, Olsho (1984) determined frequency difference thresholds (or difference limens) for 5- to 8-month-old infants and adults for a wider range of frequencies, tone bursts of 250, 500, 1000, 2000, 4000, and 8000 Hz. At the higher frequencies (i.e., 4000 and 8000 Hz), there were no significant differences between infants and adults.

However, at the lower frequencies, difference limens for infants were twice those of adults. These results are depicted in Figure 8.

Figure 8. Frequency-difference thresholds for 5- to 8-month-olds and adults (from Olsho, 1984; reprinted with the permission of Ablex Publishing Corp. and the author).



Olsho (1984) argues that the differences obtained between infants' and adults' discrimination abilities at the lower frequencies are too great to be accounted for solely by differences in sensitivity to high versus low frequency, although she does acknowledge that such differences in sensitivity may exist. The developmental trend reflecting increased discriminability for higher versus lower frequencies with age-related improvements for the lower frequencies may reflect earlier development of the basal as compared to the apical end of the cochlea because the base is maximally sensitive to high frequencies and the apex to lower frequencies. Based on this evidence, Olsho suggests that the mechanisms responsible for frequency discrimination (e.g., hair cells and associated nerve fibres in the cochlea) may mature earlier for higher frequencies.

Masking

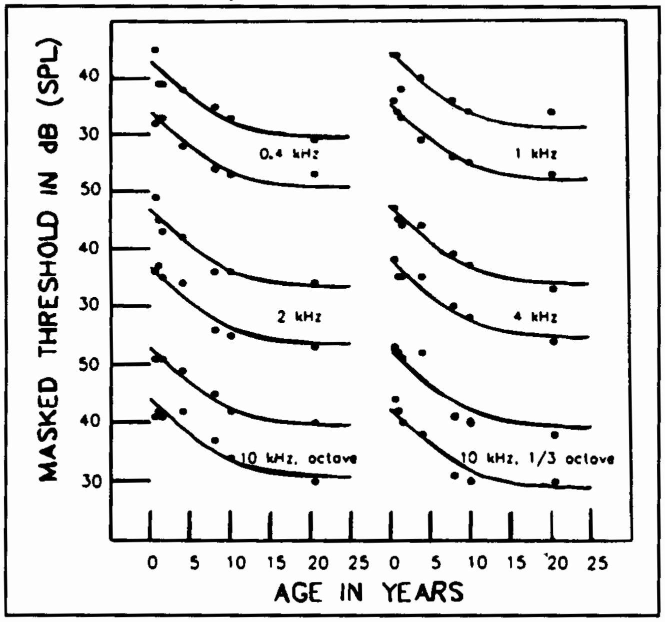
Adults are capable of attending to a particular frequency while ignoring other frequencies occurring simultaneously. Although the auditory system is remarkably adept at detecting a specific frequency among many frequencies, there are instances in which the ability to do so is hampered to such an extent that one sound makes it difficult or impossible to hear another sound. This phenomenon is known as *masking*. For example, when listening to a speech inside a classroom, noise from outside heard through an open window will reduce the listener's ability to detect what the speaker is saying (Houtgast, 1981).

Studies of masking can provide information about the auditory system's ability to select or filter relevant auditory information from a background of irrelevant noise. In masking experiments the listener is required to detect one sound (the signal), while another interfering sound (the masker) is presented simultaneously. The signal and the masker share overlapping frequencies. Masking experiments usually begin by evaluating the listener's threshold in quiet (i.e., no background noise) and then determining the threshold for the signal with the masker present. The difference between the two thresholds equals the amount of masking produced by the masker. If there is no difference between the two thresholds, then the masker had no effect and the listener was able to ignore its presence in detecting the signal. If the threshold-in-noise is elevated, however, then the masker caused a decrement in the listener's ability to detect the signal and, thus, frequency analysis of the signal was incomplete or failed (Green, 1976).

Bull et al. (1981) measured thresholds for adults and infants to evaluate whether masking occurs in the infant auditory system and whether there are developmental changes in the amount of masking produced in a given listening situation. Bull et al., using a 4000 Hz octave-band signal, tested 6-, 12-, 18-, and 24-month-olds using a two alternative forced-choice procedure. Thresholds were determined for two levels of the masking noise (42 dB and 60 dB) and compared to thresholds for adults with the same levels of masking noise. Threshold shifts were obtained for all ages when the masker was changed from 42 to 60 dB. For both infants and adults, threshold elevation was comparable to the elevation of the amplitude of the masking noise (i.e., 18 dB). However, infant thresholds were 16 to 25 dB higher than those of adults at both levels of the masking noise and in the absence of the masker.

Further evidence for infant-adult differences in masked thresholds comes from Nozza and Wilson's (1984) experiment in which 6- and 12-month-old infants and adults were presented with pure tones of 1000 and 4000 Hz in the presence of a masker and in quiet. Results indicated that infant thresholds were elevated relative to adults and that there were no differences between the two infant groups. Furthermore, there was greater similarity between infants and adults for the 4000 Hz tone than for the 1000 Hz tone. This finding concurs with the results of sensitivity and discrimination studies in showing a greater discrepancy between infant (i.e., 6 months or older) and adult performance at lower than higher frequencies.

Figure 9. Masked thresholds for two masker levels (0 and 10 dB) as a function of age for octave-band noise centred at .4, 2, and 10 kHz and 1/3 octave-band noise at 1, 4, and 10 kHz (from Schneider et al., 1989; reprinted with permission from the American Institute of Physics and the first author).



Schneider, Trehub, Morrongiello and Thorpe (1989), using octave-band noises centred at 400, 1000, 2000, 4000, and 10,000 Hz, obtained masked thresholds for 6.5-month-olds, and 1-, 1.5-, 4-, 8-, 10- and 20.5-year-olds. As can be seen in Figure 9, for all test frequencies, thresholds were elevated with the masker present, but the degree of elevation declined with age. When the centre frequency was 10,000 Hz, the difference between thresholds measured in quiet and in the presence of background noise was equal across all ages tested. By contrast, for the lower frequencies, the difference between the two thresholds increased with age. The authors suggest that changes in ear resonance, maturation in basilar membrane sensitivity to lower frequencies, and improvements in the mechanical efficiency of the ear, all of which would lower the unmasked threshold, may account for age-related increases in the difference between masked and unmasked thresholds at the lower frequencies.

Nozza (1987) compared infants' and adults' abilities to detect a binaural signal in noise using a situation referred to as "binaural release from masking." Binaural release from masking occurs when a signal that was previously masked is rendered detectable by presenting the signal so that it is out of phase, rather than in phase, at the two ears. The improvement in detectability (i.e., reduction in threshold) when the signal is changed from in to out of phase is referred to as the Binaural Masking Level Difference (BMLD). To test the effects of phase differences at the two ears on detectability, infants 6 to 11 months and adults were presented broadband signals centred at 500 Hz via earphones. Infants demonstrated improved detectability with the out of phase signals relative to in phase signals. However, the magnitude of the improvement in detectability with the out-of-phase signal was not as great for the infants as for the adults, even with adjustments made for differences in thresholds between the infant and adult groups. Nozza suggests that these findings indicate that the central auditory nervous system in infancy is not sufficiently developed for fine analysis of interaural phase differences. He suggests that developmental changes in the ability to analyze interaural phase information may be related to the increase in myelination that occurs postnatally in neural fibres. Consistent with this explanation, research by Olsen and Noffsinger (1976) with multiple sclerosis patients showed that decreased myelination can cause reduced BMLDs.

Masking operates not only when attempting to detect a signal in noise, but also when listening to speech in the presence of other sounds. Trehub, Bull and Schneider (1981) tested the ability of infants and adults to detect a speech phrase presented in the presence of background noise. They used the same procedure and the same levels of background noise used by Bull et al. (1981) and found a 10 dB difference between the masked thresholds of infants and adults. They suggest that the difference in the threshold reduction for infants versus adults in the two studies is likely due to the use of a more complex signal (i.e., speech) in the second study and that, because speech has energy spread over a broad range of frequencies, the detection of speech could depend upon detection of its most salient frequency components. More recently, Nozza, Rossman, Bond, and Miller (1990) found similar results when comparing infants' and adults' thresholds for detecting speech in noise. Thus, infants may not hear all the sounds that adults hear when a great deal of background noise is present and, consequently, the development of communication skills may be hampered for infants reared in very noisy environments.

To account for differences in masked thresholds between infants and adults, explanations based on changes in the mechanical effectiveness of the ear cannot be invoked because mechanical changes should improve both the detection of the signal and of the masking noise (for a discussion see Schneider et al., 1989). Thus, other explanations for age-related improvements in the ability to detect a signal in noise are needed. Because any improvements in the auditory system that develop in a linear fashion would affect detection of a signal and a masker similarly, Schneider et al. argue that a non-linear change in auditory processing must account for age-related improvements in detecting a signal in noise. Specifically, they suggest that nonlinear changes in the neural representation of sound amplitude in the central auditory system may account for the lower signal-to-noise ratio required for the detection of a masked signal with increasing age.

Critical Bandwidth

Closely related to the study of masking is the notion of the critical band or bandwidth. Fletcher (1940) used the notion of the critical bandwidth to explain the phenomenon of masking, particularly the finding that a signal is masked most effectively by noise containing frequencies that overlap with the signal. Fletcher suggested that the auditory system operates as though it contains a series of bandpass filters with overlapping centre frequencies. Thus, when a listener tries to detect a signal within noise, the filter with the centre frequency closest to that of the signal would be invoked. The filter would act to reduce the effects of the noise by allowing the frequencies closest to the signal to pass through the filter while eliminating other frequencies that fall outside the filter. The more narrow a filter, the greater would be its effectiveness in filtering out background noise because only a narrow range of frequencies would be allowed to pass through the filter. Fletcher used the term "critical bandwidth" to refer to the bandwidth of the filter and the term "critical band" to refer to the notion of an internal series of bandpass filters in the auditory system.

Experiments have provided support for the notion of critical bands in audition by showing that increasing the band of noise up to a certain width produces an increase in the attenuating effects on the signal, while increases beyond the critical bandwidth produce no additional effects (Greenwood, 1961; Swets, Green, & Tanner, 1962). Thus, Fletcher's (1940) notions that the auditory filter excludes frequencies outside its critical bandwidth and that only a narrow band of frequencies similar to the signal contribute to the masking effects of the noise have been supported.

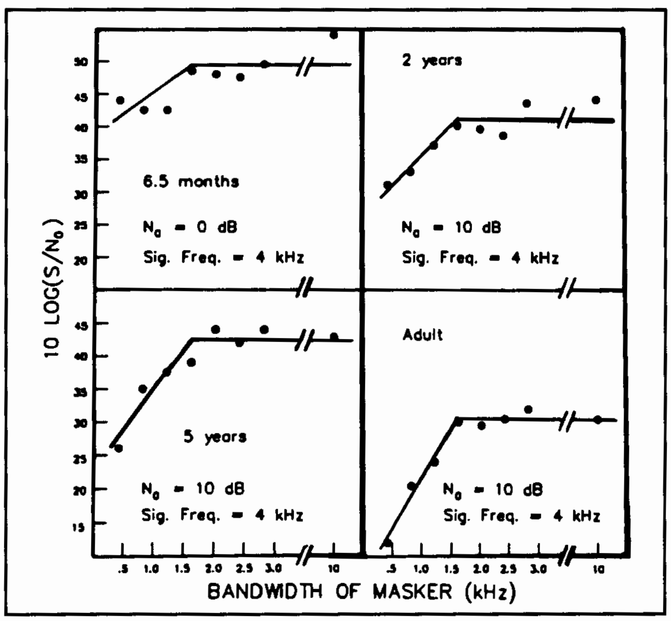
Except at the very low frequency regions of hearing (i.e., 200 Hz and less), the critical bandwidth increases with frequency between 500 and 20,000 Hz, corresponding in width to approximately a 1/3 octave in adults (Scharf, 1970). Because a narrow filter allows fewer of the frequency components of the background noise to pass through the filter and consequently mask the signal, a critical band wider than 1/3 octave would result in more difficulty in perceiving accurately a signal in noise (Moore, 1982). Thus, if the critical band were larger than 1/3 octave in infants, infants would show a deficit, relative to adults, in detecting a signal within a background of complex (broadband) frequencies.

The width of the auditory filter is important to speech perception. For example, in order to process formants in the speech signal, the frequencies of the formants must be resolved. Furthermore, in order to detect speech in noise, the listener must be able to discriminate the frequencies in speech from the frequencies in the noise (Green, 1976; Irwin, Stillman & Schade, 1986; Schneider et al., 1989; Aslin et al., 1983).

Developmental studies have shown that the critical bandwidth undergoes age-related changes from infancy to adulthood. Schneider, Morrongiello, and Trehub (1990) measured the size of the critical band in 6.5-month-olds and 2-, 5-, and 20.5-year-olds using 1/3 octave-band signals centred at 800 and 4000 Hz. Consistent with Fletcher's (1940) results, they found that for all ages and both frequencies tested, masked thresholds increased with bandwidth until a critical width was reached beyond which no further increases were obtained. Furthermore, although their results indicated that the auditory filter was wider in infants and children than in adults, the developmental change was relatively small. Specifically, they found that for children aged 2 years and older, the size of the critical band is no more than 50% larger than it is for adults. Masked thresholds for a 400 Hz stimulus obtained at different ages are shown in Figure 10.

Irwin et al. (1986), using signals centred at 500, 1000, and 3000 Hz at six different notch widths (change in frequency/frequency equal to approximately 0, .05, 0.1, 0.2, 0.3, & 0.4), studied the critical bandwidth in children aged 6 and 10 years and young adults. Their results provided evidence for a narrowing of the auditory filter related to

Figure 10. Thresholds as a function of effective bandwidth of the masker for a 4 kHz signal at different ages (from Schneider et al., 1990; © 1990 by the American Psychological Association, reprinted by permission).



increasing age such that, on average, the 6-year-olds showed a wider filter than either the 10-year-olds or the young adults. Furthermore, consistent with research on auditory sensitivity, discrimination, and masking, a larger child-adult difference in the size of the critical band was obtained with the 500 Hz signal than with the higher frequencies. There was also a significant interaction between age and notch width, such that the difference between the signal-to-noise ratio required by 6-year-olds and adults was greatest at the widest notch width. However, similar to the results of Schneider et al. (1990), age-related differences in critical bandwidths at all test frequencies and notch widths were of relatively small magnitude. Thus, although changes in the width of the critical band may have some bearing on developmental changes in masked thresholds, it is apparent that additional mechanisms, such as changes in the central auditory system, must also contribute to age-related improvements in sensitivity to masked stimuli.

Summary

The present review provides a developmental perspective on various aspects of frequency perception including sensitivity, discrimination, masking and the notion of the critical band. The principal findings regarding frequency sensitivity highlight a developmental progression from birth to adulthood. Initially, neonates and very young infants are more sensitive to lower than higher frequencies and show less discrepancy with adult thresholds at the lower frequencies, with improvements in high frequency sensitivity proceeding during the first month of life. Beyond this period, infants' sensitivity is greater for higher than for lower frequencies, with less discrepancy between infant and adult thresholds evident at higher frequencies. Throughout childhood, improvements in sensitivity occur, with decreases in thresholds occurring at a greater rate and extent for low than for high frequencies. However, for very high frequencies (i.e., 20,000 Hz), maximal sensitivity occurs during childhood, at approximately 7 years, with a decline in sensitivity prior to early adulthood.Just as infants beyond the first few months of life are more sensitive to sounds of high frequencies, infants also are able to discriminate more easily between high frequency than low frequency sounds, with a greater discrepancy between difference thresholds of infants and adults occurring at lower frequencies.

Studies of masking and critical bandwidths also indicate age-related improvements in the functioning of the auditory system. Specifically, adults are superior to infants in detecting a signal in the presence of background or masking noise particularly at lower frequencies. Also, there is some evidence that the width of the critical band becomes more narrow with age. Both of these findings suggest that the auditory system in infants is not as adept at filtering out noise that may interfere with detection of an auditory signal or speech sounds.

In addition to specific research findings regarding the development of frequency perception, this review considers a variety of behavioural techniques used in the study of auditory functioning in infants. Important methodological considerations for use in the clinical appraisal of infant audition are highlighted. Specific recommendations for clinical application of research findings include the following: (1) the use of masking headphones by parents and observers in the sound booth; (2) the use of catch trials to compare the rates of responding to signal and no-signal trials; (3) the use of probe trials to assess the infant's willingness and ability to perform the required response; (4) an awareness that minor variations in the type of stimulus used and the manner of presentation can result in major changes in infants' responsiveness (e.g., fixed versus unlimited response time, duration of the stimulus); (5) the use of earphones for assessing aspects of frequency sensitivity; (6) the use of reinforcement both to condition the infant to produce a required response and to maintain attention for longer testing sessions. Although our knowledge of the mechanisms responsible for developmental trends in frequency perception is limited, possible mechanisms have been suggested. These include age-related changes in: the size of the pinnae and external ear canal; the mechanics of the middle and inner ear; neural efficiency and processing; and the central auditory system.

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