A COMPARISON OF THRESHOLD AND SUPRATHRESHOLD
MEASUREMENT OF TEMPORAL INTEGRATION
IN NORMAL AND COCHLEA-IMPAIRED EARS

by

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ABSTRACT

The present study was undertaken in order to investigate temporal integration at threshold and suprathreshold levels in normal-hearing and cochlea-impaired subjects, and also to examine the effect of frequency on the amount of integration for each group. Thresholds for 500- and 20-msec tone pulses were established in a Bekésy tracking procedure by 20 subjects with normal hearing acuity and 20 subjects with noise-induced hearing loss. The amount of threshold shift between the long- and short-duration tones, or temporal integration, was examined as a function of subject group and signal frequency (500 Hz and 4000 Hz) both in quiet and in the presence of a white noise masker. Results of this study showed that the two groups could be differentiated by the mean threshold shift between the two tone durations, although overlap between groups was marked. The amount of integration observed for the group with normal hearing was frequency-dependent in both quiet and masked conditions. The group of subjects with cochlear impairment exhibited normal integration values at 500 Hz, where no hearing loss was present, and significantly smaller than normal values at 4000 Hz, where they demonstrated cochlear pathology. The masker altered the amount of temporal integration of the hearing-impaired group at both signal frequencies, while the normal subjects were unaffected by the presence of the masker at 4000 Hz. Critical ratios which were calculated from the masked thresholds showed
larger values for the hearing-impaired group than the normal-hearing group. The present results support the use of brief-tone audiometry in the clinical assessment of cochlear impairment. However, the group overlap in performance which was demonstrated in this study indicates that an individual's performance using this assessment must be interpreted cautiously. That is, a subject cannot be reliably assigned to either group in this experiment when the amount of integration falls within the region of overlap.
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CHAPTER 1

1. INTRODUCTION

A concept of recent interest in the differential diagnosis of hearing impairment is that involving the relation between threshold of audibility and stimulus duration. The manner in which the ear sums acoustic energy over time is known as temporal integration and the clinical application of threshold-duration relationships has become known as brief-tone audiometry (Harris, Haines, and Myers, 1958).

Theoretical interest in the concept of the auditory system as an energy-integrator began with the description provided by Hughes (1946) of the time-intensity relationships observed in normal-hearing persons. Garner (1947b) and Garner and Miller (1947) also provided data on this phenomenon. It was observed that as the duration of an auditory signal is decreased, its intensity must be increased in order to maintain audibility. Perfect integration occurs when a 3 dB increase in signal intensity is required to maintain audibility each time signal duration is halved. This amounts to a 10 dB shift in threshold for each decade (i.e. log unit) change in duration. Observation of this phenomenon is limited to durations less than approximately 200-500 msec. Typically (depending on frequency), at durations longer than 500 msec threshold does not change.

While the above threshold-duration relationship is demon-
strated in persons with normal hearing acuity, it has been noted that cochlear impairment alters this relationship (Miskolczy-Fodor, 1953; Harris et al., 1958; Sanders and Honig, 1967; Wright 1968b; Hattler and Northern, 1970). The 10 dB shift in threshold per log unit change in duration which is typical of normal hearing persons is reduced to less than 6 dB in persons with cochlear pathology. This observation has shown the diagnostic potential of temporal integration data in the clinical evaluation of cochlear function.

Miskolczy-Fodor (1953) was one of the first to document the reduction in temporal integration in impaired ears. He reported that the atypical integration demonstrated in cochlear pathology accompanied the symptom of loudness recruitment, and suggested that different pathologies might exhibit different integration patterns. The study of Harris et al. (1958) did not support Miskolczy-Fodor's data correlating the symptoms of atypical integration and recruitment but confirmed the clinical potential of temporal integration data in the diagnosis of cochlear pathology.

Despite the growing body of literature concerning temporal integration, it has not yet been fully incorporated into the audiologic test battery. This is partially due to the lack of agreement concerning the specification of stimulus parameters for use in a clinical setting. These parameters include stimulus duration, stimulus frequency, and psychophysical
testing procedure. In addition, there is some conflicting
evidence in various studies concerning the existence of
frequency dependence in temporal integration. Other variables,
such as masking, require further investigation in order to
provide a better understanding of the process involved in audi­
tory temporal integration. The present study provides more
data bearing on some of the factors influencing threshold­
duration relationships in both normal and impaired auditory
systems.
CHAPTER 2

2. LITERATURE REVIEW

2.1 PSYCHOPHYSICAL PROCEDURES FOR THE INVESTIGATION OF TEMPORAL INTEGRATION

A variety of psychophysical procedures are feasible for the study of temporal integration. The early literature concerning this phenomenon typically reports the use of the classical procedures such as method of adjustment and method of limits (Garner, 1947a, 1947b; Garner and Miller, 1947; Harris et al., 1958; Plomp and Bouman, 1959; Elliott, 1963). In the more recent clinical investigations of threshold-duration relationships a conventional psychophysical tracking procedure has commonly been employed (Wright, 1968, 1969; Hattler and Northern, 1970; Martin and Wofford, 1970; Sanders, Josey, and Kemker, 1971). Other procedures which have been less commonly used include forced-choice tracking, constant stimuli and confidence rating (Bilger and Feldman, 1969; Chamberlain and Zwislocki, 1970).

Tracking is an attractive method of choice for clinical use of brief-tone audiometry since this procedure has already been established as a powerful diagnostic tool in audiology. Békésy audiometry (Békésy, 1960) is based on psychophysical tracking and has proven to be a reliable procedure for
determining threshold as well as having a variety of other clinical applications. The Bekésy audiometer is easily adapted for brief-tone audiometry by the addition of circuitry to provide control of stimulus duration.

An advantage which the tracking method has over the classical methods is the amount of time required for establishing threshold. The latter methods, particularly the method of limits, require repeated measurements for reliability and may involve lengthy testing sessions. In a tracking procedure, thresholds can be obtained reliably in a few minutes and the subject is presented with a relatively easy task. The success of brief-tone audiometry in the clinical test battery may be affected by the factors of time and task-difficulty and they deserve important consideration.

The method of adjustment and method of limits have been chosen for both clinical and theoretical investigations of temporal integration. The method of limits, however, has not been popular in brief-tone studies and has been used seldom with hearing-impaired subjects. The method of adjustment has received more frequent use and has become the most popular alternative to the tracking method. Gengel and Watson (1971) and Richards and Dunn (1974) have compared subjects' performance under these latter two procedures. It is apparent in the literature that method of investigation may influence test results. Conflicting data have been reported on frequency dependence in
temporal integration and part of this conflict has been attributed to testing procedures used. Gengel and Watson (1971) compared the performance of normal-hearing subjects and hearing-impaired subjects with the tracking procedure and method of adjustment and found different results for the normal subjects with each procedure. They discussed the need for a standard clinical procedure to avoid the differences in test interpretation which would arise on the basis of different test procedures.

Richards and Dunn (1974) suggested that reliability of threshold measurements is an important consideration in brief-tone audiometry and that a method of investigation be chosen which could provide a high degree of test-retest reliability. Their study involved a comparison of the reliability of Bekésy tracking and method of adjustment. Included in the investigation was a comparison of two attenuation rates of the tracking method. Their results showed no significant change in threshold as a function of measurement procedure or attenuation rate. Although no difference was found, they recommended that tracking be the preferred clinical procedure, due to the ease of the task and relatively short testing time involved.

Despite the number of psychophysical procedures which are suitable for the investigation of temporal integration, it is evident that method has introduced a source of variation in the existing data. While these variations are interesting
from a theoretical perspective, they have caused some disagree­ment in the standardization of a clinical protocol for brief­tone audiometry.

2.2 STIMULUS PARAMETERS

Regardless of the psychophysical procedure used in the in­vestigation of temporal integration, certain stimulus parameters must be given consideration. These include rise-fall time and specification of stimulus duration. In the case of tracking, repetition rate and attenuation rate must also be carefully chosen.

Artifacts are introduced into the experimental paradigm when the duration (and hence rise-fall time) of the stimulus is sufficiently short that, in the course of turning the tone pulse on and off, unwanted transient energy appears. This energy, causing audible clicks, may be detected by the subject and can alter thresholds significantly (Wright, 1967). Frequency spread from tone pulses increases as stimulus duration decreases, making rise-fall time a very important consideration. There is a limit, however, to how much increase in rise-fall time is possible when the desired duration of the tone is very short. Choice of a rise-fall time is necessarily related to how duration is defined.

Many different rise-fall times have been employed in brief-
tone studies. In order to determine the effect of shaping the stimulus envelope, Dallos and Johnson (1966) obtained auditory thresholds for eight listeners at 1000 Hz with rise-fall times which varied from 0-40 msec. They found that when the overall energy content was held constant, changes in rise-fall time did not affect threshold. This allows some choice in rise-fall suitable for brief-tone audiometry. Wright (1978), however, suggests that rise-fall time should not be less than 5 msec to ensure adequate elimination of transient energy. He reported an experiment in which normal-hearing subjects tracked the audible artifacts of tones where rise-fall time varied from being instantaneous to 5 msec. It was found that at 5 msec intensity had to be increased to levels greater than 100 dB before the transients could be detected. For clinical testing, Wright suggested that a rise-fall time of 10 msec be adopted.

When rise-fall time is not instantaneous, duration must be carefully defined. However, there has been no consistency in the literature on the specification of signal duration. To overcome the ambiguity in stating both rise-fall time and stimulus duration, Dallos and Olsen (1964) suggested the concept of equivalent duration. The equation they devised to describe the equivalent duration of a short tone burst is:

\[ t = \frac{2r}{3} + P \]

where \( t \) represents equivalent duration in milliseconds, \( r \) is the rise-fall time (where both rise and fall are equal), and \( P \) is the peak time of the tone burst. The equivalent durations
computed from this equation maintain the same energy content as a tone burst with instantaneous rise-fall times.

In temporal integration studies, the choice of stimulus durations has been widely spread. Durations as short as .5 msec and as long as 10 seconds have been used (Plomp and Bouman, 1959). Practical limitations have posed some constraints on what durations are clinically feasible. Due to the need for rise-fall ramps to reduce transient energy, a minimum duration of 10 msec has been suggested by Wright (1978). A maximum desirable duration is 500 msec. Beyond 500 msec little integration takes place. However, a number of investigators have attempted to specify the point at which temporal integration ceases (Harris et al., 1958; Goldstein and Kramer, 1960; Sanders and Honig, 1967; Counter, 1974; Yonovitz, Mitchell and Clark, 1978). This point has been called the critical duration. The notion of critical duration was introduced by Harris et al. (1958) to describe the point on the temporal integration function where the abcissa is crossed by a straight line fitted to the data. This point was a measure of where stabilization of threshold occurred. Sanders and Honig (1967) also used the term critical duration which they described as the duration beyond which no observable threshold change takes place. For normal-hearing persons, this point was established at approximately 150 msec. Goldstein and Kramer (1960) had previously reported that, in normal-hearing persons, integration could take place
up to 2 seconds. An investigation by Counter (1973) of both normal-hearing and cochlea-impaired subjects showed that no specific critical duration could be defined for the normal group, but the cochlea-impaired group showed a definite termination of integration at approximately 100 msec. In a unique procedure devised to provide a direct measure of critical duration as well as a temporal summation function, Yonovitz et al. (1978) allowed normal-hearing subjects to track threshold by controlling the duration of the tone burst rather than its intensity. Burst width could be varied between 10 and 800 msec while the experimenter controlled stimulus frequency and intensity. The critical durations obtained with this procedure were consistent with the values obtained by Sanders and Honig (1967). This procedure also was found to be a feasible method for obtaining threshold-duration functions.

A parameter which must be given consideration when threshold-duration functions are obtained with pulsed tones, is repetition rate. In clinical use of brief-tone audiometry, repetition rate is frequently established with respect to the longest test tone to be used in the procedure as well as the silent interval which will occur between successive tone pulses. The silent interval must be sufficiently large to allow isolation of neural excitation initiated by each tone pulse and should thus be at least 200 msec in duration (Zwislocki, 1960). This would theoretically allow a maximum repetition rate of 2.5
per second if the duration of the longest tone used was 200 msec. Wright (1978) prefers to use a repetition rate of one per second given that the longest tone in his ideal clinical procedure is 500 msec. Repetition rate should be maintained at a fixed value for all durations sampled in a brief-tone experiment in order to eliminate the potential confounding of rate with duration.

A final consideration in stimulus parameters is attenuation rate. Wright (1978) suggests that in brief-tone audiometry, the attenuation should be set at 2.5 dB per second since this is the conventional rate used in Bekésy audiometry and by maintaining this rate results from the two procedures may be used together in diagnosis. Martin and Wofford (1970) had suggested that a lower attenuation rate might increase the precision of the test, although Richards and Dunn (1974) found no difference between a 1 dB per second and 2 dB per second attenuation rate except that the latter rate appeared more reliable.

2.3 **THE PHYSIOLOGICAL BASIS OF TEMPORAL INTEGRATION**

The physiological basis of temporal summation in the auditory system is not clearly understood. Many of the early investigations described hypotheses which attempted to account for the manner in which the ear integrates acoustic energy. Garner and Miller (1947) hypothesized that the process of
integration is linear with time. Inherent in their proposal was the notion that the ear is a perfect integrator above a certain minimum duration. This would result in a threshold decrease of 3 dB for each time that signal duration is doubled. To test their hypothesis, they examined the change in masked threshold for four frequencies over eight signal durations from 12.5 msec to 2 seconds. The data indicated that the ear integrated linearly up to a maximum time of 200 msec. That is, threshold changed by 10 dB for each log unit change in duration. Above 200 msec integration still took place but it was not linear. Although masked thresholds were used in this study, Garner and Miller assumed that the observed relations would also hold for quiet thresholds.

In a further study of threshold-duration relationships, Garner (1947b) stated the hypothesis that the rate of temporal integration of energy is dependent on the frequency band of energy to be integrated. Thus, duration would be proportional to energy only when all the energy available for integration would fall within a narrow band of frequencies. When the energy fell into a wider band of frequencies, integration would still occur but less change in threshold would occur as duration changed. Garner's ideas were based on the observation that as the duration of a tone becomes very short the bandwidth of energy increases. Intensity would have to be raised to compensate for not only a loss in total energy but also for the spread of that energy over a greater bandwidth. Bandwidth of the energy
was defined as being inversely proportional to the duration of the tone. In the course of shortening the duration of a tone, total energy would decrease while bandwidth increased. Garner examined these ideas by obtaining threshold-duration functions at 250, 1000 and 4000 Hz. The shape of the functions for the 1000 and 4000 Hz stimuli were similar and showed linear integration over the durations tested, but at 250 Hz the change in threshold was unexpectedly small when stimulus duration decreased. This finding was explained in terms of the energy splatter associated with the 250 Hz tone. Garner suspected that energy was available to the more sensitive frequencies in the normal hearing sensitivity curve and contributed to threshold.

While early investigations of temporal integration were concerned with describing the relationship between intensity and duration, there were few speculations made about the locus of the mechanism involved with integration. Zwislocki (1960) suggested that the process most likely occurred beyond the cochlea at a higher neural level. His reasoning for a higher level was based on the observation that the neural activity which is recorded from the first-order cochlear neurons fails to show gradual build-up as would be expected in the process of integration. In developing his theory of auditory temporal summation, Zwislocki made the assumption that the decay of excitation in the auditory system is exponential. At the threshold of audibility, the time constant of the exponential decay
was estimated to be on the order of 200 msec. This value may be used as a lower limit for the silent interval between successive tone pulses in the measurement of temporal integration.

It is unclear how a higher level integrative mechanism could account for the psychophysical data showing depressed threshold-duration functions associated with cochlear pathology. In an attempt to clarify this matter, Wright (1968a) proposed that the results which are typical of cochlear impairment do not reflect a disturbance in the integration process itself but are, rather, the result of rapid signal adaptation at the level of the cochlea. Adaptation would limit the energy input available for summation at a higher level. Wright suggested that rapid adaptation occurs with long-duration stimuli in cochlear pathology.

Jerger et al. (1958) observed an adaptation effect in subjects with cochlear pathology when thresholds were obtained in a Bekésy tracking procedure for continuous tones. A comparison made between thresholds for continuous and interrupted tones showed that, while no threshold change occurred with the interrupted signals, a shift of 8 dB was observed after three minutes of tracking the continuous tone. Threshold remained stable after this time in contrast to subjects with retrocochlear pathology who demonstrated further threshold shift. These observations support the notion that adaptation at the level of the cochlea may be related to reduced temporal integration functions in subjects with cochlear pathology when the stimulus has sufficient duration.
Gersuni (1965) also supports the contention that the locus of temporal integration is beyond the cochlea. However, he prefers to assume that there is not just one neural level involved but, rather, several successive levels. He also suggests different types of summation for brief intense sounds compared to long weaker stimuli and states that there must be spatial summation involved as well as temporal summation. Although spatial summation is a probable contributing factor in the integration of acoustic energy, it has not been systematically evaluated in the literature concerning brief-tone audiometry and deserves further attention.

2.4 BRIEF-TONE AUDIOMETRY IN THE CLINICAL DIAGNOSIS OF AUDITORY PATHOLOGY

Brief-tone audiometry has gained support as a useful tool in the differential diagnosis of auditory pathology. Studies of temporal integration with hearing-impaired subjects have described the shape of the integration function which typifies a variety of auditory pathologies. Together with other audiometric tests, brief-tone audiometry can provide useful diagnostic information to the clinician.

The strength of brief-tone audiometry lies in its ability to reveal cochlear pathology (as opposed to other sensorineural pathologies). Numerous investigators have observed that the temporal integration function in a cochlea-impaired listener is
significantly depressed in comparison to functions obtained with normal listeners (Miskolczy-Fodor, 1953; Harris et al., 1958; Sanders and Honig, 1967; Wright, 1968b). Typically, a threshold-shift of less than 6 dB is observed in these subjects when signal duration is changed by a log unit.

Attempts have been made to correlate aspects of the temporal integration function with specific types of cochlear pathology but it does not appear that brief-tone audiometry can differentiate between types of cochlear impairment. Sanders and Honig (1967) reported that there was no consistent relationship between etiology of the cochlear disturbance and the results of brief-tone testing. The temporal integration functions of fourteen subjects with diagnosis of Meniere's disease, acoustic trauma, and presbycusis did not reveal striking differences. Correlations have been reported, however, between the degree of hearing loss and amount of threshold shift as duration is shortened (Elliott, 1963; Young and Kanofsky, 1973; Pedersen and Salomon, 1977; Wright, 1978). It has been reported that as hearing loss increases, amount of temporal integration decreases. This finding has led to the suggestion that temporal integration may be dependent on the sound pressure level acting on the cochlea (Gengel, 1972).

While cochlear disturbance is reflected in the small amount of threshold shift between long and short duration tones, it has been found that retrocochlear lesions have no effect on the temporal integration function (Sanders et al., 1971). Similarly,
it has been reported that conductive hearing impairment does not alter the function (Wright and Cannella, 1969). Conductive impairment, affecting the middle ear structures would not be expected to alter the higher level integration process. To examine this matter, Wright and Cannella artificially induced conductive hearing loss in a group of normal-hearing subjects by occlusion of the external auditory meatus. Threshold-duration functions were obtained before, during, and after simulation of conductive impairment. No change in the integration functions was observed at any of these times. Results were also obtained for a subject with a pure conductive loss who demonstrated a normal temporal integration function. In the case of a mixed hearing loss where both the middle ear and cochlea are involved, Wright and Cannella found that the integration function reflected only the cochlear component of the loss.

Although conventional audiometric tests are able to identify a hearing loss as of sensorineural origin, special tests are usually necessary in order to determine whether the loss is sensory (that is, cochlear) or neural (affecting the auditory nerve elsewhere). Brief-tone audiometry is able to make this kind of distinction. Sanders et al., (1971) found that subjects who had confirmed lesions affecting the eighth nerve could be distinguished from subjects with cochlear impairment by the shape of the integration function. The former group showed
threshold-duration functions which were similar to those obtained from normal-hearing persons. Thus, if a patient demonstrated a sensorineural loss in conventional audiometric testing, brief-tone audiometry could establish if the loss was cochlear or neural by the presence of a normal or depressed integration function.

A further possible clinical use of brief-tone audiometry is in the diagnosis of a temporal lobe lesion. Wright (1978) observed that a 15 dB threshold shift may be demonstrated in patients with temporal lobe lesions in the ear contralateral to the lesion. This finding may not be demonstrated at all frequencies, however, and results should be interpreted cautiously. A 15 dB shift in threshold may also be shown by a malingering patient. In general, accurate diagnosis can be made when brief-tone audiometry is used in conjunction with other audiometric tests.

2.5 THE FREQUENCY EFFECT IN TEMPORAL INTEGRATION

Perhaps the greatest source of conflict in the literature concerning temporal integration is the effect that frequency has on the threshold-duration function. Generally, the effect which has been described is that there is a decrease in amount of integration as stimulus frequency increases. There is some difficulty in attempting to resolve the issue largely because of the great variability in the manner in which temporal integration
has been examined. There has been no consistency in the choice of psychophysical procedure, range of frequencies tested, or number of durations sampled. The influence of each of these factors on the results is difficult to ascertain.

Psychophysical procedure has received the most speculation as the cause of the conflicting results concerning frequency. However, an examination of the literature which involves a variety of psychophysical procedures for measuring temporal integration fails to reveal any consistency in this matter. The majority of data obtained with the classical psychophysical procedures is in support of frequency dependence, although there is inconsistency here as well. Chamberlain and Zwislocki (1970) investigated the influence of procedure in a study which used six psychophysical methods: adjustment, limits, constant stimuli, tracking, forced-choice, and confidence rating. The slope of integration was found to change with frequency for all procedures except tracking and forced choice. Bilger and Feldman (1969) also examined the comparison between threshold-duration functions obtained with three different methods: tracking, forced-choice, and a "yes-no" procedure. Results for the first two procedures, as in the study of Chamberlain and Zwislocki, showed no change with frequency, while the "yes-no" procedure revealed different functions for different frequencies. On the basis of these two studies, it would seem possible that the tracking method lacks
the sensitivity in identifying frequency dependence which other methods have been able to establish. It is also possible that there is no dependence and the observed effect is an artifact of the other methods. The studies of Wright (1967, 1968b) which involved a tracking procedure, also failed to show a frequency effect. However, not all studies which used a tracking procedure reported the absence of frequency dependence. Hattler and Northern (1970) found a frequency effect in the data for their normal subjects and Olsen and Carhart (1966) found a difference in the slope of integration between low and high frequencies.

Campbell and Counter (1969) proposed that there is a lower frequency limit for the observation of temporal integration which is related to the upper limit of periodicity pitch. They suggested that both temporal integration and periodicity pitch are neural in nature and are based on a temporal analysis which takes place beyond the cochlea. However, they believed that the two processes were related in a way which made them mutually exclusive and hence the upper frequency limit for periodicity pitch would also serve as the lower limit for temporal integration. In both a "yes-no" adaptive procedure and tracking procedure the threshold-integration function was investigated for 125-, 175-, and 1000-Hz tones. No integration of energy was observed at 125 Hz and it was concluded that 100-200 Hz was the lower frequency limit for temporal
integration. Watson and Gengel (1969) suggested that the lack of threshold change with short-duration stimuli at 125 Hz was due to the enhanced detection of energy at other frequencies over which the energy had spread. To test this possibility, they incorporated a masker into the paradigm of Campbell and Counter to prevent detection of the signal energy at other frequencies. Their results showed that it was, indeed, likely that energy spread had influenced the results of Campbell and Counter since significant integration was found at 125 Hz. It would appear, then, that the use of a masker or appropriate rise-fall time is desirable in the study of temporal integration where energy spread may be available to contaminate the results.

The lack of consistency regarding the influence of frequency in temporal integration is an important issue to be resolved in order to allow brief-tone audiometry to become useful as a clinical tool. Since no resolution of this issue is available at the present time, further research is warranted to elucidate the matter.

2.6 THE USE OF MASKING IN THE STUDY OF TEMPORAL INTEGRATION

Masking noise has been used in the study of temporal integration to serve two general purposes. First, it has provided a means to prevent energy spread at short durations from being
detected by the listener. The second use has been to allow suprathreshold (that is, supra-quiet) measurement of temporal integration.

Hattler and Northern (1970) utilized an ipsilateral white noise masker with cochlea-impaired subjects to investigate what effect a minimal amount of masking would have on the temporal integration function. They suggested that masking may be desirable in some cases where threshold may be influenced by bands of transient energy which appear with short tone pulses. Their masking stimulus was broad-band noise presented at a level which would shift threshold by only 5 dB from the value obtained in the quiet. The results of this investigation showed that threshold had shifted slightly in the presence of the masker although the shape of the threshold-duration function was unchanged. It was concluded that it would be advisable to use a masker when the occurrence of transient energy is probable. A closer examination of their data, however, indicates that the effect of the masker is to increase the amount of threshold shift between the longest and shortest tones even though slightly. The use of a higher level masker might indicate whether this trend is significant and can also be observed in normal-hearing persons.

A masking paradigm can also be used to study suprathreshold measurement of temporal integration. Gengel (1972) stated the possibility that reduced temporal integration in cochlea-
impaired ears is a reflection of the higher signal levels needed to reach threshold. To examine this, the integration functions of four normal-hearing subjects were obtained in the presence of a masking noise. The masker was introduced to raise threshold to a level which is characteristic of moderate to severe cochlear hearing loss. The results showed threshold-duration functions which are typical of normal-hearing persons, rather than cochlea-impaired persons. This finding suggested that increased stimulus level is not the factor responsible for the reduced temporal integration observed in subjects with cochlear pathology. However, Gengel compared his masked data to those of Watson and Gengel (1969) which were obtained in quiet and this makes it difficult to interpret the effect of masking. An inspection of the data from these two studies indicates that the shape of the integration function is largely unchanged in the masked condition but, similar to the Hattler and Northern study (1970), the masker appears to cause a slight increase in the amount of threshold shift between the long-and short-duration tones. This observation appears to be worthy of further investigation.

2.7 THE EFFECT OF A FATIGUING STIMULUS ON THE THRESHOLD-DURATION FUNCTION

Measurement of temporal integration has been made after exposure to a fatiguing stimulus in order to ascertain whether
the pattern of temporal integration typically observed in cochlear pathology can be demonstrated in normal ears during recovery from auditory fatigue. Jerger (1955) obtained threshold-duration functions for twelve normal-hearing subjects at quiet threshold with a 4000-Hz signal. Subjects were then exposed to thermal noise presented at a level of 110 dB SPL for two minutes. After this time the threshold shift was measured for tones of different durations. Pre-exposure integration values were found to demonstrate the normal time-intensity relationship while post-exposure thresholds showed a decrease in the threshold shift between the tones of long and short duration, which is characteristic of persons with cochlear pathology. Threshold measurements obtained at 1, 3, 9, and 12 minutes post-exposure demonstrated a gradual recovery to pre-exposure threshold levels as post-exposure time increased. The findings of this study illustrated that the effect of intense noise stimulation on the cochlea was identical to the altered time constant of integration associated with hearing loss of cochlear origin. This also confirmed that a normal-functioning cochlea is necessary for normal integration of acoustic energy.

In a similar type of experiment, Henderson (1969) examined the temporal integration function of chinchillas before and after exposure to a fatiguing noise stimulus. Functions obtained before exposure for a 2000 Hz tone were similar to
those obtained for human subjects. The chinchillas were then given three hours of exposure to an octave band of noise centered at 2000 Hz at a level of 105 dB SPL. At intervals following the exposure, thresholds were measured. The 12 dB difference between the long- and short- duration tones in the pre-exposure testing was reduced to zero at four minutes after the three hours of noise. This difference increased as post-exposure time increased. Complete recovery of the threshold-duration function was complete after three weeks. These findings concur with Jerger's results for human subjects and show that the integration of energy is reduced when noise-induced temporary threshold shift occurs in the auditory system.

2.8 SUPRATHRESHOLD MEASUREMENT OF TEMPORAL INTEGRATION

There are other means to investigate the temporal integration function at suprathreshold levels in addition to the use of masking. These means include measurements of stapedial reflex thresholds and the use of loudness balancing.

The threshold-duration relationships observed at auditory threshold have also been observed with stapedial reflex testing. The threshold at which the reflex occurs is elevated when stimulus duration is decreased. This observation was reported by Djupesland and Zwislocki (1971), who found a 35 dB shift in reflex threshold for a 2000 Hz tone in normal listeners when
stimulus duration was reduced from 1000 msec to 10 msec. This is considerably steeper than the usual 10 dB per decade shortening.

Woodford, Henderson, Hamernik, and Feldman (1975) reported similar findings, extending the data to more frequencies. They investigated threshold-duration functions of the acoustic reflex in ten normal-hearing subjects and three persons with cochlear impairment, at stimulus frequencies of 500, 1000, 2000, 3000, and 4000 Hz. The integration functions of the normal-hearing subjects were found to be much steeper than the functions typically obtained at auditory threshold, which is consistent with the findings of Djupesland and Zwislocki (1971). The reflex threshold-duration functions obtained for the cochleaudi-mpaired subjects were flattened in comparison to the normals, a trend which is also observed at auditory threshold. In addition to these findings, Woodford et al. reported a frequency effect in their data. Thresholds for the 500- and 1000- Hz stimuli produced a shallower integration function than the higher frequencies. This finding is in contrast to the frequency effect observed at auditory threshold where the lower frequencies usually produce the steepest function. In this study, the 4000 Hz stimulus produced the steepest function for both the normal and sensorineural-impaired subjects.

Contrary to the findings of Woodford et al., Stelmachowicz and Seewald (1977) found that the slope of integration at reflex
threshold was similar for both normal-hearing and cochlea-impaired persons. Their data were obtained using 20 normals and 20 subjects with cochlear pathology, numbers which they felt may have accounted for the differences in the findings of Woodford et al. who used only three cochlea-impaired and ten normal subjects. At auditory threshold, however, Stelmachowicz and Seewald observed differences between the two groups which are consistent with the literature demonstrating flatter functions for cochlea-impaired subjects. The results of this study suggest the possibility that cochlea-impaired subjects may integrate acoustic energy differently at threshold and suprathreshold levels.

A loudness-balancing procedure was used by Pederson and Poulsen (1973) to obtain measurements of suprathreshold temporal integration. Monaural and binaural loudness balancing was performed for 1000 Hz tone pulses of various durations by presbycusisic subjects at levels of 75 and 95 dB SPL. Although inter-subject variation was great, results showed no reduction in temporal integration from expected normal values. The loudness balances at 95 dB resulted in a temporal integration function similar to that observed for normals at auditory threshold while at 75 dB, the function was found to be steeper than normal. These results are in contrast to data reported by Pedersen and Elberling (1973) for presbycusisic subjects who showed reduced temporal integration when measured at auditory
threshold. Again it appears that integration may occur dif­
ferently at suprathreshold levels.
3. **OBJECTIVES**

It is apparent from the literature that there are several matters in the research concerning temporal integration which deserve further attention. Among these are the establishment of a standardized clinical procedure for brief-tone audiometry, further investigation of the frequency effect, and more detailed study of the influence of masking on the threshold-duration function.

The clinical procedure advocated by Wright (1978) for examining temporal integration diagnostically appears to be a suitable paradigm for use with the hearing-impaired. The tracking procedure can be used to establish threshold reliably within a few minutes and the patient can easily be familiarized with the task. A two-duration comparison also appears to be an adequate measure of temporal integration differences. Since few studies have attempted previously to validate this procedure, the present study will adopt Wright's paradigm for examining temporal integration with both normal and cochlea-impaired listeners. If more investigations are made with similar procedures, standardized data may become available to warrant the use of brief-tone audiometry as a reliable diagnostic test of cochlear function.

It will also be the aim of this study to make more data available concerning the frequency effect in temporal integration. With measurement of both threshold and suprathreshold
integration in normal and hearing-impaired subjects, it is hoped that the data may reveal information useful in the explanation of the conflicting data which exist in the literature.

A final purpose of the present research is to examine the effect of masking on the temporal integration function. The existing literature dealing with masking and integration does not as yet, supply an adequate description of a masker's effect. The study of Hattler and Northern (1970) used only minimal masking with a sensorineural population and revealed a small increase in the amount of threshold shift between long- and short-duration tones. Gengel's study (1972) also showed such an increase but these data were obtained for a very small sample of normal listeners and the increase can only be measured with respect to data from another study. Since masking allows a suprathreshold measurement of temporal integration, it is the aim of this study to compare the amount of threshold shift observed at both auditory and masked threshold. The data of Stelmachowicz and Seewald (1977), as well as Pederson and Poulsen (1973), suggest that suprathreshold integration of acoustic energy involves a somewhat different process than the integration which is measured at auditory threshold.
4. **METHOD**

4.1 **SUBJECTS**

Two groups of subjects were selected to participate in this experiment, one group of normal-hearing persons (N), and one group of persons with noise-induced hearing loss (NIHL). The N group consisted of 20 males between the ages of 21 and 33 with a mean age of 25.6 years. Eight of these men were employees in the building at the Workers' Compensation Board of British Columbia (WCB). The other 12 were patients at the WCB Rehabilitation Centre who were being treated for injuries unrelated to hearing. There was no known history of ear pathology or prolonged exposure to noise in any of these subjects. For inclusion in this study, it was required that their pure-tone thresholds at the octave frequencies from 250 Hz to 8000 Hz be 15 dB HL (ANSI, 1969) or better.

The NIHL group consisted of 20 males between the ages of 49 and 69 with a mean age of 59.8 years. All were claimants at the Hearing Branch at the WCB. The criteria for selection of these subjects included good health, no known incidence of middle ear pathology and a history of prolonged exposure to industrial noise. Requirements for inclusion in the group were thresholds of 20 dB HL or less at 500 Hz and thresholds of 50-70 dB HL at 4000 Hz, with no irregularities in the slope of
the curve plotting loss as a function of frequency.

In addition to these 2 groups of subjects, 11 other WCB claimants, whose pure-tone thresholds did not meet the criteria specified above, were used in the experiment. Thresholds of these subjects were greater than 20 dB HL at 500 Hz and/or greater than 70 dB HL at 4000 Hz. Otherwise they were similar to the NIHL group in all respects. The data from these 11 subjects were combined with those of the 20 NIHL subjects for a certain part of the analysis where noted.

4.2 APPARATUS

The apparatus used in this experiment consisted of a Grason-Stadler audiometer, model 1701, to which an electronic switch was adapted for control of stimulus duration. A block diagram of the apparatus is shown in figure 1. The experiment was conducted with the subject seated in a sound-insulated test booth, IAC model 11-330, at the Hearing Branch of the WCB in Richmond, B.C. Stimuli were delivered monaurally through a TDH-49 earphone.

4.3 STIMULI

The stimuli consisted of pure tones at the frequencies 500 Hz and 4000 Hz, and a white noise masker. The bandwidth of the masker was limited by the response of the earphone. The spectrum level of the noise was calculated to be 52.7 dB with a bandwidth of 5370 Hz.
Figure 1. Block diagram of the apparatus.
Intensity level of the masker was fixed at 90 dB SPL and it was presented ipsilaterally to the tonal stimuli. Duration of the pure tones was either 500 msec or 20 msec and was determined in the manner suggested by Dallos and Olsen (1964), where $t = \frac{2r}{3} + P$. In this equation, $t$ refers to time, $r$ represents the rise-fall time and $P$ is the peak time. Rise-fall time for both the 500 msec and 20 msec tones was six msec.

4.4 Procedure

Threshold measurements were made with a psychophysical tracking procedure. Each subject tracked a total of eight thresholds, with each threshold being determined for a different condition of stimulus frequency, duration, and masking. The stimulus was pulsed monaurally at a repetition rate of approximately one per second. Attenuation rate of the signal was 2.5 dB per second, and the direction of change was controlled by the subject with a hand switch. All subjects tracked four thresholds in quiet followed by four thresholds in the presence of the continuous white noise masker. Presentation order of the four combinations of stimulus frequency and duration was randomly determined within each of the quiet and masking conditions.

Subjects were familiarized with the task in a practice trial prior to the beginning of the experiment. Both the frequency and duration of the stimulus tone used in this practice
trial were different from those used in the experiment. In each of the experimental trials, subjects tracked the stimulus until a total of 12 threshold crossings were made. The first two crossings were discarded in the determination of threshold. The threshold was defined as the average of the 10 points at which the attenuator made a reversal. Total testing was completed in an average of 15 minutes.
5. RESULTS

The mean thresholds for the 500- and 20- msec tones were calculated for each subject group at the 2 stimulus frequencies in both the quiet and masked conditions. These values are presented in Table 1. The amount of threshold shift between the long- and short-duration tones, or temporal integration, is depicted in a histogram in Figure 2 with bars representing each of the experimental conditions. Preliminary examination of the data indicated that there were differences in the amount of temporal integration between groups, frequencies and masking conditions. A series of t-tests were computed to determine the significance of these differences. These results are shown in Table 2.

The amount of temporal integration in the N group and NIHL group were significantly different at 4000 Hz, as expected, with threshold shift between the long- and short-duration tones for the N group being 7.3 dB, and 4.1 dB for the NIHL group. At 500 Hz, where thresholds for the NIHL group fall in the normal hearing range, there was no difference between groups (8.6 dB for the N group and 8.0 dB for the NIHL group).
Mean thresholds and threshold shift by tone duration and frequency in quiet and masked conditions for each subject group.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Duration (Msec)</th>
<th>Mean Difference (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>20</td>
<td>11.30</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>2.70</td>
</tr>
<tr>
<td>4000</td>
<td>20</td>
<td>10.00</td>
</tr>
<tr>
<td>4000</td>
<td>500</td>
<td>2.70</td>
</tr>
<tr>
<td>500</td>
<td>20</td>
<td>72.10</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>60.80</td>
</tr>
<tr>
<td>4000</td>
<td>20</td>
<td>74.60</td>
</tr>
<tr>
<td>4000</td>
<td>500</td>
<td>67.50</td>
</tr>
<tr>
<td>500</td>
<td>20</td>
<td>18.00</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>10.00</td>
</tr>
<tr>
<td>4000</td>
<td>20</td>
<td>64.40</td>
</tr>
<tr>
<td>4000</td>
<td>500</td>
<td>60.30</td>
</tr>
<tr>
<td>500</td>
<td>20</td>
<td>74.00</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>64.30</td>
</tr>
<tr>
<td>4000</td>
<td>20</td>
<td>78.50</td>
</tr>
<tr>
<td>4000</td>
<td>500</td>
<td>72.70</td>
</tr>
</tbody>
</table>

**NIHL**

**Quiet Condition**

**Masked Condition**
Figure 2. Histograms showing amount of threshold shift for each group, frequency, and condition. Note: N=normal; P=noise-induced hearing loss; Q=quiet; M=masked; 5=500 Hz; 4=4000 Hz.
### TABLE 2

Results of the 12 t-tests

<table>
<thead>
<tr>
<th>t-tests</th>
<th>conditions</th>
<th>t</th>
<th>df</th>
<th>p&lt;.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>500 Hz, quiet</td>
<td>0.97</td>
<td>38</td>
<td>N</td>
</tr>
<tr>
<td>vs.</td>
<td>500 Hz, masked</td>
<td>2.69</td>
<td>38</td>
<td>Y</td>
</tr>
<tr>
<td>NIHL</td>
<td>4000 Hz, quiet</td>
<td>5.23</td>
<td>38</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>4000 Hz, masked</td>
<td>1.86</td>
<td>38</td>
<td>Y</td>
</tr>
<tr>
<td>500 Hz</td>
<td>normal, quiet</td>
<td>2.17</td>
<td>19</td>
<td>Y</td>
</tr>
<tr>
<td>vs.</td>
<td>normal, masked</td>
<td>7.14</td>
<td>19</td>
<td>Y</td>
</tr>
<tr>
<td>4000 Hz</td>
<td>NIHL, quiet</td>
<td>7.56</td>
<td>19</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>NIHL, masked</td>
<td>5.60</td>
<td>19</td>
<td>Y</td>
</tr>
<tr>
<td>quiet</td>
<td>normal, 500 Hz</td>
<td>3.87</td>
<td>19</td>
<td>Y</td>
</tr>
<tr>
<td>vs.</td>
<td>normal, 4000 Hz</td>
<td>0.14</td>
<td>19</td>
<td>N</td>
</tr>
<tr>
<td>masked</td>
<td>NIHL, 500 Hz</td>
<td>2.82</td>
<td>19</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>NIHL, 4000 Hz</td>
<td>1.98</td>
<td>19</td>
<td>Y</td>
</tr>
</tbody>
</table>

**Note:** Y = significant, N = not significant; level of significance based on one-tailed test.
In the masked condition the differences between groups were significant at both test frequencies. The masking appears to have affected the 2 groups differently at 500 Hz increasing the .6 dB difference observed in the unmasked condition to a difference of 1.6 dB when masking was introduced. At 4000 Hz the difference between groups decreases from 3.2 dB to 1.3 dB in the presence of the masker although the difference is still significant.

A frequency effect was observed in the normal group for both unmasked and masked conditions. The amount of threshold shift between the 500- and 20-msec tones was significantly different between the 500 Hz and 4000 Hz signals. As seen in Figure 2, this difference is more apparent when masking is introduced and in both conditions shows greater threshold shift for the 500 Hz tone. In the case of the NIHL group, a frequency effect is also apparent. This difference is in the direction expected on the basis of the hearing loss at 4000 Hz. The presence of cochlear pathology at this frequency results in a threshold shift of 4.1 dB (in the quiet condition) compared with 8.0 dB at 500 Hz where hearing is within normal limits.

The presence of the white noise masker significantly affected the amount of threshold shift between the tones of long and short duration for all conditions except 4000 Hz for the N group. In each of these cases, threshold shift became
greater when masking was introduced. However, at 4000 Hz the mean threshold shifts for the normal-hearing subjects were 7.1 dB and 7.3 dB under quiet and masked conditions respectively.

On the basis of contentions made by various investigators about the relationship between amount of hearing loss and absolute hearing threshold (Elliott, 1963; Pederson, 1977; Wright, 1978), an investigation was made of such a relationship in the present data. For this analysis, the data of the 11 subjects described earlier, who did not meet the experimental criteria, are included to provide a wider distribution of hearing levels. The data for 500 Hz are not included since hearing thresholds at this frequency are normal or near normal for the 32 subjects. In Figure 3 absolute thresholds for the 4000 Hz tone are plotted as a function of the threshold shift which occurs when duration is decreased from 500 msec to 20 msec. A significant correlation of negative -.63 was found between these 2 variables.

The group overlap in the integration data is reflected in Figures 3 to 5 which display histograms showing the number of subjects who demonstrated various amounts of threshold shift between the long- and short-duration tones. The amount of overlap between groups is greater at 500 Hz than 4000 Hz, as expected, due to the absence of hearing loss at this frequency.
Figure 3. Threshold shift as a function of absolute threshold at 4000 Hz for 20 N subjects (●) and 31 NIHL subjects (◆).
Figure 4. Histograms displaying number of subjects

Threshold Shift (DB)

500 Hz

4000 Hz
Figure 5. Histograms displaying number of subjects with corresponding amounts of threshold shift in the masked condition for N group (□) and NIHL group (■).
However, it is apparent that there is no one frequency or masking condition in which the 2 groups are easily separated on the basis of threshold shift. That is, one can expect to see a normal-hearing person with a threshold shift "typical" of (i.e. near the mean for) cochlear pathology and vice versa.

A final analysis of the data was made with measurement of the critical ratio at masked threshold. These values appear in Table 3. It can be seen that an increase in signal duration has a corresponding increase in critical ratio for both groups. In all cases, the values are larger for 4000 Hz than for 500 Hz. The NIHL group has larger critical ratios than the N group for each duration and each frequency. Also the difference between groups is smaller at 20 msec than at 500 msec. It appears that there is a difference in the way in which both groups process signals of long duration compared to short duration.
### TABLE 3

Critical ratio in dB by subject group as a function of signal duration.

<table>
<thead>
<tr>
<th>Subject Group</th>
<th>Frequency</th>
<th>Signal Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
<td>500</td>
</tr>
<tr>
<td>500 Hz</td>
<td>30.9</td>
<td>19.6</td>
</tr>
<tr>
<td>Normal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 Hz</td>
<td>31.4</td>
<td>24.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise-induced</td>
<td>500 Hz</td>
<td>32.8</td>
</tr>
<tr>
<td></td>
<td>4000 Hz</td>
<td>35.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29.5</td>
</tr>
</tbody>
</table>
6. DISCUSSION

6.1 SUMMARY OF RESULTS

The results of this study showed that:

(1) groups of normal-hearing persons could be distinguished from groups of persons with noise-induced hearing loss on the basis of temporal integration.

(2) there is great variability in the data which results in overlap between the two subject groups.

(3) there is greater threshold shift between the tones of long and short duration at 500 Hz than at 4000 Hz.

(4) the masker differentially affects the amount of threshold shift at the two test frequencies.

(5) there is a negative correlation between absolute threshold and threshold shift.

(6) the critical ratios obtained from the masked threshold data show larger values for the group with cochlear pathology than for the normal-hearing group.

6.2 DIAGNOSTIC SENSITIVITY OF BRIEF-TONE AUDIOMETRY

The finding that the normal and cochlea-impaired group means could be differentiated by measurement of temporal integration is consistent with reports in the literature that brief-tone audiometry might be sufficiently sensitive to allow identification of cochlear lesions (Miskolczy-Fodor, 1953; Harris et al, 1958; Sanders and Honig, 1967; Wright, 1968b). However, it
does not support this possibility in that group overlap is so extensive, despite the difference in means, that no attempted diagnostic use in individual cases is justified as yet. The study leaves open the possibility that by training subjects, the separation of groups might be large enough to allow diagnostic use in individual cases. The findings that the NIHL group had normal temporal integration at 500 Hz where they demonstrated no hearing loss, but reduced integration at 4000 Hz where they demonstrated cochlear pathology, also shows the diagnostic potential of brief-tone audiometry.

The results of this study also show that a 2-duration comparison as suggested by Wright (1978) has sufficient sensitivity to differentiate the group means of normal and cochlear-lesion subjects. Wright previously tested 50 normal-hearing subjects at six durations from 10 to 500 msec and compared the threshold shift to that obtained when only two durations (20 and 500 msec) were used. The 6-duration and 2-duration procedures yielded the same mean values and standard deviations indicating that two durations are suitable for clinical use. A 2-duration comparison also allows brief-tone audiometry to be performed in less time than a sampling of several durations would require. This increases its appeal in clinical applications. Wright (1978) cautioned about the clinical use of only two durations until data is available concerning the differences of hearing-impaired persons on two versus six durations.
While the present study did not purport to examine such a difference, it showed that two durations were sufficient to differentiate between groups of normal-hearing subjects and subjects with cochlear impairment.

6.3 THE ISSUE OF FREQUENCY DEPENDENCE

The shift in threshold between the tones of long and short duration was found to be slightly greater for the N group at 500 Hz than at 4000 Hz. While this difference was very small in quiet, it was accentuated in the masked condition. The observation of a frequency effect in temporal integration has been reported many times in the literature and has been discussed primarily as being a possible result of the psychophysical procedure used (although no suggestions have been offered to explain why one method should reveal or create the effect and not another). The tracking procedure generally has failed to reflect frequency-dependent results (Wright, 1968b; Bilger and Feldman, 1969; Chamberlain and Zwislocki, 1970). It is uncertain whether the decrease in temporal integration which is noted with increase in frequency is related to certain other factors instead of, or in addition to, being related to the method of investigation. It has been suggested for instance, that the decreased temporal integration for high frequencies might be related to the presence of subclinical cochlear lesions in the normal-hearing subjects used (Campbell and
Counter, 1969; Barry and Larson, 1974; Wright, 1978).

Barry and Larson (1974) present some data which may be relevant to this suggestion. The temporal integration functions of children, both normal-hearing and cochlea-impaired, were obtained using a modified method of limits for the octave frequencies from 500 Hz to 4000 Hz. The amount of threshold shift measured for the normal children was similar at all frequencies. That is, the frequency effect reported in most studies using a procedure other than tracking was absent in the children examined in this study. These results gave increased plausibility to the proposal of Campbell and Counter which presented the possibility that the frequency effect may be due to subclinical cochlear pathology in adult subjects. Similar speculations have been made by Sanders and Honig (1967) and Wright (1978). It could be reasoned that the children exhibit no frequency effect because their cochleas are relatively unimpaired. Since it has been reported that the higher frequencies show the least amount of integration, it is not unreasonable to suppose that most apparently normal-hearing adults may have subclinical deterioration of the basal end of the cochlea. Although the subjects in the present study exhibited hearing thresholds less than 15 dB HL and were generally less than 30 years of age, it is, nevertheless, possible that they had some cochlear deterioration not measurable in standard pure-tone audiometry. It is feasible to make such a speculation since persons are often exposed to excessive noise
in the course of daily activities. Bredberg (1968) also has provided data based on histopathologic studies which show the presence of degeneration in some of the sensory cells in the cochlea which is believed to occur near the third decade of life. While such reasoning is speculative in describing the effect of frequency in temporal integration, it could, nevertheless, be a contributing factor. Further studies with children may provide more data in support of such a possibility. In any case, more experiments are needed to convert these speculations into proposals with some practical utility.

Further indication that cochlear dysfunction may be identified by brief-tone audiometry when hearing thresholds are within normal limits is given by Hans, Henderson, and Hamernik, (1975). These investigators induced permanent threshold shift of various degrees in chinchillas and compared pre- and post-exposure threshold shift between 500- and 20-msec tones. The pre-exposure values were comparable to those of normal-hearing persons, while the post-exposure threshold shifts were depressed. However, the amount of decrease in the post-exposure condition appeared to be unrelated to amount of permanent threshold shift. Histopathologic study of the chinchillas used in their study showed that there was a correlation between the amount of permanent threshold shift and degenerated inner hair cells, while the threshold shift between long and short duration tones was correlated with reduction of outer hair cells.
These findings are consistent with the possibility that an atypical temporal integration function observed for a person with normal hearing threshold levels may be an indication that there is degeneration of outer hair cells in the cochlea. Again, this is merely a speculative interpretation but certain investigators such as Wright (1978) are in favour of such an explanation to account for the conflicting results which exist concerning frequency.

6.4 MASKING AND TEMPORAL INTEGRATION

The use of a masker in the present study enabled a comparison to be made of both threshold and suprathreshold measurement of temporal integration. The amount of threshold shift between the long- and short-duration tones was found to vary between masked and quiet conditions at the two test frequencies. This appeared to affect the two groups differently. In the case of the normal-hearing group, the threshold shift increased by almost 3 dB at 500 Hz in the presence of the masker, while no significant change was observed at 4000 Hz. The hearing-impaired group showed an increase in threshold shift at both test frequencies in the presence of the masker. However, the threshold shift remains smaller for the NIHL group than the N group at suprathreshold levels. The trend observed in the data for the hearing-impaired group suggests that the amount
of integration is approaching normal values. With the exception of the 4000 Hz data in the case of the N group, it appears that suprathreshold integration may generally yield larger amounts of threshold shift between tones of long and short duration. This observation is consistent with data obtained by other investigators at suprathreshold levels. Djupesland and Zwislocki (1971) found as much as a 35 dB shift in reflex threshold as duration was varied from 1000 msec to 10 msec. The data of Hattler and Northern (1970) as well as those of Gengel (1972) also show indications of larger integration values at masked threshold. There is no consistency, however, in the manner in which suprathreshold measurement of integration affects the normal versus hearing-impaired groups. Stelmachowicz and Seewald (1977) found that the amount of threshold shift was equal for the normal and hearing-impaired groups at suprathreshold levels and differed only at auditory threshold. In the present study, the NIHL group produced the same amount of threshold shift with masking both for the 500 Hz signal, where their hearing is normal, and also for 4000 Hz, where they show evidence of cochlear pathology. It remains unclear why no change in temporal integration took place at 4000 Hz for the N group when the masker was present. It is proposed that future investigation of integration at masked threshold should include more masker levels and signal frequencies to determine whether the masker differentially affects
integration at various frequencies and/or whether its affect is level dependent.

The general increase in threshold shift which the cochlea-impaired group shows in the present study as well as in previous investigations of suprathreshold temporal integration may involve an alteration of the adaptation effect which Wright (1968) has proposed to be responsible for the reduced integration in cochlea-impaired ears. It has been hypothesized for diagnostic purposes that cochlear pathology is more reliably identified at threshold rather than suprathreshold levels (Feldman, 1976). If more rapid adaptation than normal is responsible for the reduced ability of the cochlea-impaired ear to integrate the energy of a long-duration signal, then it is possible, judging from the evidence, that at suprathreshold levels such unduly rapid adaptation does not occur. This would account for the reports in the literature which show a normal slope of integration for cochlea-impaired persons when measured at suprathreshold levels.

6.5 RELATIONSHIP BETWEEN HEARING LOSS AND THRESHOLD SHIFT

The correlation between absolute threshold and threshold shift which was observed in this study at 4000 Hz is consistent with reports of other investigators (Elliott, 1963; Young and Kanofsky, 1973; Pedersen and Salomon, 1977; Wright, 1978). Elliott (1963) found correlations of -.74 and -.79 for the
500- and 4000-Hz tones respectively. Young and Kanofsky (1973) found that the amount of threshold shift for their subjects with sensorineural pathology was correlated with absolute threshold. At 4000 Hz the correlation obtained in their study was -.87. Wright (1978), however, reported a weak correlation for a group of subjects with noise-induced hearing loss when absolute threshold was compared to the threshold difference between tones of 500 msec and 20 msec. The chinchilla study discussed earlier (Hans et al., 1975) did not reveal a correlation between the absolute threshold which resulted from permanent damage and amount of temporal integration. These conflicting reports in the literature make it difficult to ascertain whether the degree of hearing loss is reflected in the amount of threshold shift.

6.6 DATA VARIABILITY

An important aspect of the temporal integration data which must be considered in the clinical application of brief-tone audiometry is the variability which has been observed for both normal-hearing subjects and those with cochlear pathology. In the present study the overlap between amount of threshold shift exhibited by the two groups under all conditions of frequency and masking, as shown in Figures 4 and 5, is noteworthy. At 500 Hz the overlap is expected since the NIHL group has normal
hearing levels at this frequency. However, 40% of the NIHL subjects had threshold shifts which fell below the levels for the N group at 500 Hz (7dB or greater). The overlap between groups at 4000 Hz is greater than would be expected on the basis of absolute thresholds. A higher percentage of the normal-hearing subjects had threshold shifts which fell within 2 dB of the NIHL mean than the cochlea-impaired group had threshold shifts which fell within 2 dB of the N mean (40% vs. 5%). In the masked condition, the amount of overlap is similar between the two groups.

The variability found in the data is consistent with the contention that the normal-hearing subjects in this study may have subclinical cochlear disturbances. Barry and Larson (1974) showed that there was virtually no overlap between the normal-hearing and the deaf children at 1000 and 2000 Hz and that there was very minimal overlap at 500 and 4000 Hz. Thus the separation between normal and impaired subjects is more apparent in the data for children as compared to adults. This definite separation of scores may also be related to the fact that the children had normal hearing while the deaf children had hearing losses generally greater than 70 dB HL across the entire frequency range. In contrast to this, the hearing-impaired subjects used in the present study had more variable levels of hearing loss.

Sanders, Josey and Kemker (1971) found a great deal of
overlap in the data of their three groups of subjects who represented normal-hearing, cochlear pathology, and eighth nerve lesions, respectively. While such results are discouraging, they point out the necessity to consider this variability and overlap of the scores in any effort to use brief-tone audiometry as a test for the diagnosis of cochlear-hearing loss. To make diagnostic use of brief-tone measurement of integration it is more important that the integration scores of the impaired subjects fall away from the normal mean than it is that the scores of the normal-hearing subjects may fall well up in the range of cochlear impairment. Such appears to be indicated by the data in the present study, which supports the potential diagnostic value of brief-tone audiometry and also suggests that many normal-hearing persons give evidence of subclinical cochlear disturbances.

6.7 CRITICAL RATIO

Measurement of the critical ratio was made in this study in order to compare the data with those reported by Gengel (1972) and Simon (1963). Gengel suggested that examination of the critical ratio for signals at different durations may aid in understanding the relationship between slope of the integration function and the manner in which long-duration signals are processed in the auditory system. On the basis of Wright's
model of rapid physiological adaptation which affects the signals of long duration, Gengel suspected that the critical ratios of the hearing-impaired subjects might be normal at short durations but not at long signal duration. Alternately, he speculated that the critical ratios might be larger than normal at both long and short durations. In his study, he found that for subjects with normal hearing and tones of 200 msec or greater, the size of the critical ratio increased with frequency. This change with frequency was removed, however, when the data for each frequency at 10 msec were compared. At this short duration, the critical ratios appeared to be independent of frequency. Gengel interpreted this as an indication that the integration function is related to the processing of long-duration signals as Wright (1978) suggested. He also speculated that the critical ratios of persons with cochlear pathology might also be similar across frequencies at short duration if it were the case that the reduced temporal integration function of these persons was due to rapid physiological adaptation. However, Gengel did not investigate this matter with hearing-impaired subjects.

Simon (1963) speculated that the decreased temporal integration observed in recruiting ears was correlated with an increase in bandwidth within which integration takes place. He examined this possibility by calculating the critical ratio obtained at masked threshold for normal and recruiting ears.
At the frequency where recruitment was present, he found a larger critical ratio than he found for normal ears at that frequency. The similarity of critical ratios at short duration, across frequency, as Gengel reported, was not found in Simon's study. This matter is difficult to interpret from the present study, since the NIHL group had normal hearing at 500 Hz and evidence of cochlear pathology only at 4000 Hz. However, the findings of the present study are consistent with Gengel's data showing that the 4000 Hz signal consistently yielded larger critical ratios than the 500 Hz signal. The largest values were obtained by the NIHL group at 4000 Hz, which is consistent with Simon's suggestion concerning enlarged bandwidth in cochlea-impaired ears (which he did not directly test). The critical ratios of the N group are all larger than those obtained by Gengel. There is, however, a better correspondence with Simon's data at 4000 Hz for the normal-hearing and cochlea-impaired groups in his and the present study. The data from the present study support Gengel's speculation of enlarged critical ratio for cochlea-impaired subjects at both long and short duration. The critical ratios of the NIHL group were larger than for normals at all frequencies and all durations. Even at 500 Hz where no pathology is reflected in the audiograms of the NIHL group the critical ratios were larger than normal. However, it is noteworthy that the difference between groups is larger for the long duration
than for the short duration signals.

The differences which have been noted between long- and short-duration tones for normal versus cochlea-impaired subjects suggest that the two groups are more alike in how shorter tones are processed in the cochlea. Fastl (1977) presents some interesting data in regard to this. In his investigation of temporal integration, Fastl used a noise masker to simulate a hearing loss in a normal-hearing subject. The simulated loss was achieved with a bandstop filter and matched the audiometric configuration of a cochlea-impaired subject with an abrupt drop at 3000 Hz. A comparison of the amount of integration was made for the two subjects. The threshold shift between long- and short-duration tones at 3000 Hz showed a significant difference between the ear with simulated loss and the cochlea-impaired ear. As Gengel (1972) found, the ear with the simulated loss produced a slope of integration similar to what would be expected in a person with normal hearing while the impaired subject showed very little integration. At frequencies where the cochlea-impaired listener had little hearing loss, functions for both subjects were similar. As indicated earlier, the two subjects were matched in audiometric configuration. Although this match was achieved with 300 msec tones, a striking difference was found between the subjects when threshold comparisons were made across the frequency range for tones of 3 msec duration. That is, an audiogram
obtained with 3 msec tones revealed a configuration quite un-
like that obtained with a 300 msec tone. These results suggest
that the reduced integration typically reported for cochlea-
impaired subjects may be directly related to an altered mode
of processing for either the signals of long duration or
those of short duration.

6.8 CONCLUSION

It appears that brief-tone audiometry is a potentially
useful diagnostic test of disturbance at the level of the
cochlea. The two durations examined in this study are suffi-
cient to disclose cochlear pathology. The frequency depen-
dence of the temporal integration function, however, is a
matter which deserves further attention. It appears to be
not so much an effect of psychophysical procedure but also a
possible "early warning sign" of cochlear dysfunction unde-
tectable in conventional pure-tone audiometry. Suprathreshold
measurement of temporal integration by use of masking appears
to yield results unlike those obtained at quiet threshold
levels, and masking affects the normal and cochlea-impaired
subjects differently. Further studies utilizing masking with
both normal and cochlea-impaired subjects is warranted in order
to provide a more comprehensive set of data to show the re-
lation between masking and the intensity-duration function.
Such data may enable a better understanding of the mechanism
underlying temporal integration of acoustic energy.
REFERENCES


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