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AN INVESTIGATION OF THRESHOLD AND SUPRA-

THRESHOLD TEMPORAL INTEGRATION

APPROVED BY

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DISSERTATION COMMITTEE

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AN INVESTIGATION OF THRESHOLD AND SUPRA-THRESHOLD TEMPORAL INTEGRATION

CHAPTER I

INTRODUCTION

The detection and the loudness of acoustic signals are dependent upon several factors including the frequency, intensity, and duration of the signals. Kucharski (1928) was the first to report a relationship between signal duration and auditory sensitivity. He reported that as the duration of an acoustic signal is decreased below a critical time, the intensity of the signal must be increased in order to elicit a threshold response. A similar phenomenon is observed in studies of the loudness of acoustic signals. Bekesy (1960) in a study first reported in 1929, found that loudness decreased as the duration of the signal was decreased below a critical time.

Temporal integration and temporal summation are terms which are used interchangeably to describe the effect of signal duration on threshold sensitivity and loudness. A graphic representation of temporal integration displays the intensity required to obtain threshold or a specified loudness level at various signal durations. The abscissa denotes signal duration in seconds or milliseconds (msec) while the ordinate denotes signal amplitude in decibels.

Temporal integration functions are described by their slopes and their critical durations. The slope of the temporal integration function is identified by the decibel change in signal intensity for a tenfold change in signal duration. The critical duration refers to the upper duration limit of the sloping portion of the function.

The slope of the threshold temporal integration function for normal-hearing subjects is theoretically 10 dB per decade change in signal duration (Zwislocki, 1960). Several recent investigators (Dallos and Olsen, 1964; Dallos and Johnson, 1966; Olsen and Carhart, 1966; and Wright, 1968), however, suggest that the slope is between 6 and 8 dB per decade change in signal duration. This slope is most generally confined to signal durations between 10 msec and 200 msec. Two-hundred msec, therefore, is the commonly reported critical duration. Auditory sensitivity does, however, continue to change beyond these limits, but at a reduced rate above 200 msec and at an increased rate below 10 msec (Garner, 1947 ; Green, Birdsall, and Tanner, 1957; Olsen and Carhart, 1966; Counter and Tobin, 1969).

A wide range of values is reported for the slope of the suprathreshold temporal integration function. Generally, it is found to be slightly less than the slope of the threshold temporal integration function. The critical duration of the suprathreshold temporal integration function ranges from 25 msec (Zwislocki and Sokolich, 1972) to 1100 msec (Berglund and Berglund, 1967). This wide range of values assigned to the critical duration of the suprathreshold temporal integration function results from the instructions to the subjects and the diverse psychophysical procedures employed in these investigations as well as different methods of specifying signal durations. Further, the definition of the critical duration differs among investigators and is often vague and confusing. According to Zwislocki's (1969) theory of loudness summation, the critical duration is 100 msec for moderate and high suprathreshold signals.

Although temporal integration has been investigated extensively since the early work of Kucharski and Bekesy, conflicting and sometimes confusing reports are found in the literature concerning the slope and critical duration of the temporal integration function at threshold and suprathreshold levels. The empirical evidence is at times inconsistent with the theories of temporal integration proposed by Zwislocki (1960, 1969). Threshold and suprathreshold temporal integration have not been investigated systematically over a wide range of signal intensities using the same sample of normal-hearing subjects. An investigation of this nature would provide information regarding the effect of signal presentation level on the temporal integration function. The data obtained from such an investigation could also be compared with predictions based upon Zwislocki's theories.

This study was designed to investigate the temporal integration function for a 1000 Hz pure tone at presentation levels from threshold to 90 dB SL in a group of normal-hearing subjects. There are several reasons to hypothesize that the temporal integration function is altered by presentation level. First, empirical evidence from several independent investigators indicates that the threshold and suprathreshold temporal integration functions differ with regard to slope and critical duration. Second, Zwislocki (1960, 1969), in his theories of threshold and suprathreshold temporal integration, proposes that the critical duration becomes shorter at moderate and high suprathreshold levels. These theories are based on the results of related psychoacoustic and physiologic studies. Third, the contraction of the middle ear muscles at high presentation levels is known to alter the loudness of acoustic signals (Reger, 1960; Loeb and Riopelle, 1960). Recent evidence (Djupesland and Zwislocki, 1971) suggests that the threshold of the reflex is elevated as signal duration is decreased. It might be anticipated that these two phenomena would interact to reduce the slope of the temporal integration function for loudness at high presentation levels. Finally, it has been demonstrated that normal-hearing subjects and patients with cochlear pathology perform in a similar manner when certain auditory tasks are presented at relatively high hearing levels, yet they perform differently when these same tasks are presented at low sensation levels. The return to "normal-loudness", evidenced by complete recruitment on the Alternate Binaural Loudness Balance (ABLB) test (Fowler, 1928; Reger, 1936) and the results obtained with the Short Increment Sensitivity Index (SISI) are two examples of this behavior (Jerger, Shedd, and Harford, 1959; Young and Harbart, 1967). An important factor determining the responses obtained on these two tests by subjects with normal hearing and patients with cochlear pathology appears to be the level of energy reaching the cochlea. When the eighth nerve and central auditory pathways are intact, the responses obtained by these two groups of subjects are similar once the level of energy in the cochlea exceeds a certain magnitude, provided, of course, that this level exceeds the threshold sensitivity of the hearing impaired patients.

It is also documented in the literature that patients with cochlear pathology perform differently from the normal-hearing population on threshold temporal integration tasks (Miskolczy-Fodor, 1953; Wright, 1968). The threshold temporal integration function exhibited by patients with cochlear pathology has a reduced slope and critical duration when compared with that observed in the normal-hearing population.

On the basis of the foregoing information, it appears that the suprathreshold temporal integration function of normal-hearing subjects may be similar to the threshold temporal integration functions of patients with cochlear pathology. A finding of this nature would be consistent with Zwislocki's contention that the critical duration is reduced at moderate and high presentation levels. It would also imply that the shape of the temporal integration function is related to the level of the signal reaching the cochlea, provided the more central aspects of the auditory system are intact.

It is hypothesized, therefore, that the slope and critical duration of the threshold temporal integration function differ from those of the suprathreshold temporal integration functions when the same subjects and similar experimental procedures are used in the investigation. It is further hypothesized that the transition from the threshold function to the highest level suprathreshold function will be a gradual one with a reduction of both the slope and critical duration appearing as the presentation level of the signals is increased.

Because differences among the temporal integration functions at ten (one threshold and nine suprathreshold) presentation levels were to be investigated, it appeared necessary to have an objective means of describing each function. It was decided that a regression analysis would provide the necessary description. The suprathreshold data were analyzed by the method of Analysis of Variance, factorial design, in order to determine if these functions differ from one another.

A discussion of the experimental work related to the investigation of temporal integration at threshold and suprathreshold levels is presented in the following review of the literature.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

It is generally true that as the duration of an acoustic, visual, or tactile signal is decreased, within certain limits, the intensity of that signal must be increased in order to maintain a threshold response. The investigation of the effects of the duration of an acoustic signal on threshold sensitivity had its beginnings in 1928, when Kucharski reported the relationship between signal duration and auditory sensitivity. Likewise, it has been known for a number of years that the loudness of an acoustic signal is dependent upon its duration. The early work of Bekesy (1960), first reported in 1929, demonstrated that as the duration of an acoustic signal is increased within certain limits the loudness of the signal also increased. The increase in sensation which results from increased signal duration is known as temporal integration.

The two important parameters which define the temporal integration function are its slope and critical duration. The temporal integration function is generally plotted with decade increments of signal duration expressed in milliseconds on the abscissa. The amplitude of the signals in decibels is denoted on the ordinate. The parameter plotted may be absolute thresholds, relative changes in threshold, or intensities which yield equivalent loudness for signals with different durations. Lines are fit between decade changes of signal duration. It is generally found that the slope of the threshold temporal integration function is slightly less than 10 dB per decade change in the duration of the signal. The slope of the loudness summation function is generally found to be 8 dB per decade change in signal duration.

The "critical duration" was defined by Harris, Haines, and Meyers (1958) as the location on the abscissa through which a straight line defining the most linear sloping portion of the temporal integration function passes. These investigators used no statistical procedure to evaluate the line. Sanders and Honig (1967) defined the critical duration as that duration beyond which no further improvement in threshold sensitivity occurs. There is a considerable amount of literature to suggest that the former of these two definitions is the more appropriate. It has been questioned whether there is a critical duration as defined by Sanders and Honig. Counter and Tobin (1969) suggest that threshold sensitivity may continue to improve over a considerable range of signal durations, especially if the psychophysical procedure employed is precise enough to detect small differences in threshold. The literature reveals a range of values for the critical duration at threshold from 100 msec to 375 msec. Threshold sensitivity of normal-hearing subjects continues to improve as signal duration increases beyond 2000 msec (Green, Birdsall, and Tanner, 1957). The critical duration for loudness summation ranges from 25 msec in one experiment to greater than one second in other experiments. These differences are the result of several factors including the psychophysical procedures employed, the method of specifying signal duration, and the instructions to the subjects.

Theory of Temporal Integration

Many theories and mathematical models have been proposed to explain the phenomena of threshold and suprathreshold temporal integration. Early theories included a statistical probability concept (Garner and Miller, 1947), the ear as a Fourier Analyzer (Garner, 1947), a middle ear muscle reflex mediation theory (Miller, 1948), mathematical models and electrical analogues of the auditory system. The most prominent current theory is one of neural summation. Zwislocki (1969) comments:

> Temporal summation in hearing does not have to mean a direct integration of acoustic energy. . . . The lack of long latencies and of a slow buildup of neural activity in the peripheral auditory system are incompatible with it. . . . We have no choice but to conclude that the psychoacoustically evident temporal summation has its locus in the central nervous system (p. 431).

Zwislocki (1960) also stated that integration takes place above the level of the first order neurons and probably central to the second order neurons.

Through a series of psychophysical experiments, incorporation of physiological data and mathematical manipulations, Zwislocki (1960) arrives at a mathematical theory of temporal integration at threshold. The theory is based on the assumption of an exponential decay of neural excitation with a time constant or critical duration of approximately 200 msec. Briefly, he suggests that an excitable tissue with a graded and long lasting response (probably at synaptic junctions) is excited by incoming "quanta" of energy. A specified amount of excitation is produced by each quantum and the excitation decays with time. With periodic stimulation the tissue potential displays a characteristic step function. When the quanta are of equal magnitude, the steps are also of approximately equal magnitude. The rate of decay of excitation, however, appears to be proportional to the excitation already present. Excitation of the tissue, therefore, reaches an asymptote after a sufficiently long stimulation.

At suprathreshold levels Zwislocki's theory (1969) is more complex and is based on the following three assumptions:

(1) The existence of a linear temporal integrator with a time constant of 200 msec within the central nervous system

(2) A nonlinear transformer that parallels the loudness function and precedes the temporal summation

(3) A temporal decay of neural activity at the input of the integrator. (p. 439)

Zwislocki maintains that at threshold levels the second and third assumptions are not necessary because the nonlinearity and the temporal decay disappear, ". . . and the psychoacoustic functions reveal directly the character of the integration process." All three of the assumptions are derived from empirical evidence obtained from psychoacoustic or physiologic experiments. The theory, according to Zwislocki, predicts the observed shortening of the time constant or critical duration to 100 msec at moderate suprathreshold levels. When reasonable numerical assumptions regarding the temporal decay of neural firing rate are made, the theory also is claimed to predict correctly loudness level as a function of signal duration at suprathreshold levels. However, Zwislocki also presents recent data which fail to support his theory.

Zwislocki and Sokolich (1972) report critical durations for loudness summation of either 25 msec or in excess of 500 msec depending on whether the listener is instructed to evaluate the total loudness of the signal or only the loudness at its termination. Several other experiments (Dallos and Olsen, 1964; Olsen and Carhart, 1966; Dallos and Johnson, 1966; Wright, 1968) provide only limited support for Zwislocki's theories and this support is generally restricted to the threshold rather than the loudness integration theory.

Physical Characteristics of Short Duration Signals

Before discussing the experimental literature on temporal integration, it is necessary to consider the physical characteristics of an acoustic signal as its duration is progressively shortened. Sonn (1969) defines a pure tone as a ". . . sound wave, the instantaneous sound pressure of which is a simple sinusoidal function of time." In the simplest form a pure tone is an auditory signal which contains a single frequency component. It is true, however, that any pure tone which is reduced in time is no longer pure. As the duration of an acoustic signal is decreased in time, its spectral content becomes more complex. By the process of Fourier Analysis the spectral composition of a tone may be obtained. Using this procedure, Garner (1947_a) demonstrated that two physical changes occur as the duration of the signal is decreased. The bandwidth of the signal is increased and the total energy of the signal is reduced. The inverse relationship between duration and bandwidth is approximated by the formula

$$BW = 1/d$$

where bandwidth, BW, is measured at the half-power points and d is the duration of the signal in seconds. The increase in bandwidth and the decrease in total energy are not independent. As the bandwidth increases, the total energy of the signal is spread to frequencies remote from the fundamental. The total energy of the signal decreases at the rate of 10 dB for each logarithmic decrement in duration (Garner, 1947_a; Doughty and Garner, 1947).

The above discussion has assumed an instantaneous rise-decay time to the signal. Whenever a pure tone is turned on and off abruptly, frequencies other than the fundamental are produced. Auditorily, these extraneous or transient frequencies are perceived as a click. It is for this reason that in most experiments, tones are switched on and off gradually with some measurable rise and decay time. The specification of the duration of such signals is more complicated than that of signals with instantaneous onsets and terminations. The duration of a signal with a gradual rise and decay time may be reported in a variety of ways. For example, an investigator may report the duration of such a tone from its onset to its termination, from the half-power points, from the 6 dB down points, or during the full-on portion of the signal.

Dallos and Olsen (1964) proposed the term "equivalent duration" in an attempt to simplify the specification of the duration of short tones with gradual rise-decay times. The equivalent duration of such a tone is expressed mathematically by the formula:

$$E = 2r/3 + P,$$

where r is the rise-decay time and P is the duration of the signal at peak amplitude. The term equates the energy content of shaped signals to rectangular signals of the same duration. That is to say, a signal with an equivalent duration of 50 msec, regardless of its rise-decay time and peak duration, has the same energy as a signal with a rectangular envelope and a duration of 50 msec. Dallos and Olsen (1964), Olsen and Carhart (1966), and Dallos and Johnson (1966) have experimentally verified that signals with the same equivalent durations yield the same thresholds regardless of the rise-decay time and peak duration combinations. The slope of the temporal integration function for their data is approximately 8 dB per decade change in equivalent duration. Their conclusion is that threshold sensitivity is determined solely by the total energy of the signal. Dallos and Olsen (1964) have also recomputed signal durations employed by other investigators (Harris, 1957; Goldstein and Kramer, 1962) using the equivalent duration formula, and they have plotted the data obtained. The results generally reveal that straight lines fit the data better when signal duration is expressed as equivalent duration than when the duration is expressed as designated by Harris (1957) and Goldstein and Kramer (1962). The slopes of the functions also approximate more closely the 10 dB per decade change in duration that is anticipated by theory.

Threshold Temporal Integration

As discussed previously, numerous investigators have studied temporal integration using a variety of signals and psychophysical procedures. Of particular importance to the present investigation are those studies in which a 1000 Hz tone was employed as a test frequency.

Garner (1947_b) used an ascending method of adjustment to obtain thresholds for a variety of signals with durations ranging from 1 msec to 100 msec. The results obtained for an unfiltered 1000 Hz tone show a difference in threshold sensitivity of 10 dB between signal durations of 8 msec and 100 msec. Between signal durations of 1 msec and 8 msec a 13 dB difference in sensitivity was noted for the same signal. The temporal integration function for a bandpass filtered 1000 Hz tone showed an 8 dB difference in sensitivity between 15 msec and 100 msec. Between signal durations of one msec and 15 msec more than 17 dB difference in sensitivity was observed.

Using an unspecified technique, Miskolczy-Fodor (1959) investigated temporal integration with a 1000 Hz signal and found a 9.0 dB slope between 100 msec and 10 msec. Harris, Haines, and Meyers (1958) concluded from their clinical study of temporal integration that the critical duration could range from 100 msec to 300 msec in "perfectly normal" ears. They found that the slopes of the functions ranged from 4.5 dB to 12.0 dB per decade change in the duration of 1000 Hz signals. In another clinical study, Sanders and Honig (1967) found a critical duration by their definition of 168 msec for 1000 Hz signals. The mean slope of the temporal integration functions was 10.7 dB per decade change in signal duration.

Goldstein and Kramer (1962) in a study designed to investigate the factors which affect threshold temporal integration, employed a method of constant-stimulus-differences to obtain thresholds for a 1000 Hz signal. Signal durations ranged from 20 msec to 2000 msec. The slope of the temporal integration function obtained between 200 msec and 20 msec was approximately 9.0 dB. The investigators reported significant improvement in threshold sensitivity at progressively greater signal durations throughout the range used in the experiment. The temporal integration function in their study had not reached a "parallel or even an asymptotic" relationship to the abscissa at the longest signal duration employed.

A Block-Up-and-Down Yes-No (BUDYEN) technique was used by Counter and Tobin (1969) to investigate the slope and critical duration of the temporal integration function for 1000 Hz signals ranging from 1000 msec to 10 msec in duration. A 9.5 dB slope was obtained between 100 msec and 10 msec. Improvement in threshold sensitivity amounting to 5.0 dB between 300 msec and 1000 msec was also observed. Although the authors concluded,

> ". . . that there obviously exists a point along the integration continuum at which no further 'log unit' threshold shifts occur with changes in duration. This point may be 200-300 msec,"

the data from their study suggest that the critical duration was not reached and that the function is best defined by a single straight line with a slope of approximately 9.0 dB between 10 msec and 1000 msec. Campbell and Counter (1969), using the same procedure, found a temporal integration slope of 10 dB per decade for 1000 Hz signals with durations between 400 msec and 4 msec. Changing the psychophysical procedure to a Bekesy tracking procedure produced only a minor increase in the slope of the function.

Olsen and Carhart (1966) used a Bekesy tracking procedure and found an 8.6 dB per decade slope for 1000 Hz signals. Significant differences in threshold sensitivity occurred between signals with durations of 200 msec and 500 msec but not between signal durations of 500 msec and 1000 msec. Hattler and Northern (1970) employed the same procedure in a clinical study of temporal integration. They obtained thresholds for signals with durations ranging between 300 msec and 10 msec. The mean threshold change for the 1000 Hz signals between 100 msec and 10 msec was 7.8 dB. Martin and Wofford (1970) determined thresholds for 1000 Hz signals of 500 msec and 20 msec duration, using a Bekesy tracking procedure. The mean difference between the thresholds for signals with these durations was 7.5 dB.

Zwicker and Wright (1963), using a bracketing procedure found the threshold in quiet for signals with durations from 500 msec to 10 msec. The results at 1000 Hz showed an approximate 7.0 dB difference in thresholds between signals of 100 msec and 10 msec duration. The threshold difference between 300 msec and 100 msec signals at 1000 Hz was approximately 3 dB.

Temporal integration functions, obtained in the presence of a background of noise appear to have the same slope as those obtained in quiet (Garner and Miller, 1947; Green, Birdsall, and Tanner, 1957; Plomp and Bouman, 1959; Creelman, 1963; Sheeley and Bilger, 1964). Although Green, Birdsall, and Tanner (1957) report a critical duration for a 1000 Hz signal of approximately 140 msec where Plomp and Bouman (1959) found it to be 325 msec, both sets of investigators observed continued improvement in threshold sensitivity with successive increases in signal duration beyond the critical duration.

Numerous investigators (Miskolczy-Fodor, 1953, 1960; Eisenberg, 1956; Harris, Haines, and Meyers, 1958; Elliott, 1963; Sanders and Honig, 1967; Wright, 1968; Watson and Gengel, 1969; Hattler and Northern, 1970; Martin and Wofford, 1970, Gengel and Watson, 1971) have shown that the ability to summate energy over time is altered in patients with cochlear pathology. That is to say, patients with cochlear pathology fail to exhibit normal temporal integration functions. The slope and critical duration of the function are reduced in these patients. While the slope of the normal temporal integration function is 10 dB per decade change in signal duration, the slope may be reduced to approximately 3 dB in patients with cochlear impairment. The critical duration is also reduced from 200 msec in the normal population to about 50 msec in these patients. As in the normal population, considerable variability in the slope and critical duration are noted in the pathologic group. Several investigators (Eisenberg, 1956; Harris, Haines, and Meyers, 1958; Sanders and Honig, 1967) have found that not all patients with presumed cochlear pathology show abnormal threshold temporal integration functions. Wright (1968) proposed that excessive threshold adaptation related to hair cell pathology is responsible for the inefficient temporal summation displayed by these patients. He suggests that the neural output from the cochlea is reduced as a function of time. Therefore, there is less neural energy to be summated at a later stage of the auditory system when pathologic threshold adaptation exists. It is this phenomenon which is responsible for the reduction in the slope and critical duration of the temporal integration function in patients with cochlear pathology according to Wright's hypothesis.

It is apparent from the above review of the literature on threshold temporal integration in normal-hearing subjects that it is difficult to make direct comparisons of the results obtained from the individual investigators. Some of the discrepancies noted in the reported results may be due to differences in methods of specifying signal duration and differences in psychophysical procedures employed. Confounding the problem are differences in methods of reporting the slope and critical duration of the data obtained in these investigations. It will be noted that the method of specifying signal duration employed by Dallos and Olsen (1964), Dallos and Johnson (1966), Olsen and Carhart (1966), and Wright (1968) are essentially the same. The results of these four investigations are also very similar. For these reasons the signal durations employed in the current experiment were calculated using the equivalent duration formula and were compared with the results obtained by the above mentioned researchers.

Loudness Summation

Loudness is defined by the ANSI (1960) as, ". . . the intensive attribute of an auditory sensation, in terms of which sounds may be ordered on a scale extending from soft to loud." Although the loudness of a given signal is primarily dependent upon its sound pressure level, factors such as frequency, waveform, and duration of the signal also affect its loudness. Attempts to determine the exact relationship between the physical magnitude of the signal and the resulting sensory experience date back to the 19th Century and the works of Weber and Fechner. Since that time, investigations of the loudness of a signal as a function of these parameters have consumed a major portion of the auditory researcher's attention. Of particular concern to the present study is the effect that the duration of a signal has on its loudness.

Bekesy (1960), in a study first reported in 1929, used the method of limits to investigate loudness as a function of signal duration. He found that the loudness of an 800 Hz signal presented at 80 dB

SPL decreased as the duration of the signal was decreased below 180 msec.

Garner (1949) investigated the growth of loudness for a 1000 Hz signal as a function of duration. The method of adjustment was used and the subjects were instructed to balance the loudness of a 500 msec signal to that of a signal with a variable duration which was presented at a fixed intensity level. The signal of variable duration was presented at levels of 40 and 80 dB SPL as the first member of the signal pair. For half of the six subjects, loudness at both presentation levels changed as a function of the duration of the comparison signal. At 80 dB, this group acknowledged loudness equality with an average intensity difference of 8.5 dB between the 500 msec reference signal and a 10 msec comparison signal. At the 40 dB level, equal loudness was achieved for signals of these durations with only a 6.0 dB difference in signal intensity. The other three subjects showed essentially no change in loudness as a function of duration at either presentation level.

In 1947, Munson employed the method of limits to investigate loudness summation of pure-tone signals. The test frequencies were 125, 1000, and 5650 Hz. The reference signal was always 1000 msec in duration. The comparison signals varied in duration from 5 msec to 200 msec and were presented as the first member of the signal pair. Three loudness judgments were made by each observer at nine levels of the reference signal covering a range of 32 dB. Full loudness at 1000 Hz was not achieved even with the 200 msec duration comparison signal when the presentation level was 70 dB. Equivalent loudness was achieved with a difference of approximately 30 dB at all frequencies between the reference and the 5 msec comparison signals. In the data presented in Munson's Table I, there appears to be a difference in the growth of loudness at all test frequencies as a function of level. Greater loudness differences are observed with equivalent intensity changes for the higher level signals than for the lower level signals.

Another method for determining the growth of loudness as a function of signal duration is magnitude estimation. Ekman, Berglund, and Berglund (1966) employed this technique to determine the growth of loudness as a function of signal durations ranging from 500 msec to 50 msec at 1000 Hz. It appears from the graphs of the data that the slope of the functions becomes greater as the level is increased. In a follow-up study, Berglund and Berglund (1967) used a scaling technique to obtain loudness estimates of a 1000 Hz signal with durations ranging from 2000 msec to 30 msec. The signals were presented at levels ranging from 56 to 100 dB SPL. The authors separated the data into three groups by presentation level. The three lowest presentation levels constituted the first group, the three highest levels the second, and the combination of all five levels made up the third group. The plot of these data shows the critical duration to be 600 msec for the lower group of levels and 1100 msec for the higher group of levels. The critical duration for all of the levels combined is 800 msec. At the three lowest signal levels the average slope is 7.6 dB per decade change in signal duration while it is 11.6 dB per decade at the three highest levels. When all five presentation levels are averaged the slope is 9.0 dB per decade change in signal duration. It appears that the critical duration and slope of the temporal integration functions are greater as the levels of the signal are increased.

A more recent and somewhat different approach to loudness summation investigations is a report by Zwislocki and Sokolich (1972). These investigators contend that the differences in the data obtained by magnitude estimation and by loudness balance or matching procedures is of a fundamental nature and originates because the two procedures sample two different aspects of loudness. Magnitude estimation procedures generally yield estimates of total loudness while loudness balancing procedures sample the loudness at some instant in time. This latter sample may be denoted as instantaneous loudness. Zwislocki and Sokolich assert that it is necessary to specify stringently to the subject which aspect of loudness he is to judge. An experiment was designed by these investigators to determine if the loudness at the termination of the signal, i.e., instantaneous loudness, differs from the total loudness of the signal. A loudness balance procedure with the method of adjustment was used to determine both aspects of loudness. The signal frequency was 1000 Hz. The test signal was presented at 40 dB SL and was varied in duration from 20 msec to 500 msec. A 10 msec comparison signal followed the test signal after an interstimulus interval of 500 msec. During one segment of the experiment, the subjects were instructed to adjust the level of the comparison signal to be equal in loudness to the termination of the test signal. In the other part of the experiment, they were instructed to adjust the level of the comparison signal to equal the total loudness of the test signal. Different results occurred with the two sets of instructions. Under the first set of instructions the loudness of the test signal increased with the test signal duration only up to 25 msec and then remained constant as the duration was increased further. When total loudness was the criterion, loudness increased with signal duration up to at least 500 msec. Some of the less sophisticated listeners had difficulty changing their criterion for the loudness matches. The authors concluded,

> ". . . loudness of tone bursts can be judged according to two criteria, instantaneous loudness and total loudness. The instantaneous loudness varies little, if at all, with tone duration, the total loudness increases monotonically at least up to 500 msec."

They also indicated, however, that the two sets of data differ from each other only "moderately" because of the limited ability of "most" of the subjects to switch criteria. At durations less than 50 msec the difference between the two sets of data appears to be, at most, 2 dB. The difference between the two sets of data is greatest at longer durations and approaches 10 dB at 500 msec. There is considerable overlap in the interquartile ranges for the two sets of data. When relating these results to those obtained under magnitude estimation and loudness balance procedures, it was concluded by the authors that the data obtained by magnitude estimation are consistent with those obtained using the total loudness criterion. The data obtained with the loudness balance procedures are consistent with those obtained using the instantaneous loudness criterion. According to Zwislocki and Sokolich, if both sets of data are averaged together they most nearly coincide with the loudness matching data reported in the literature. The authors contend that the instructions given to the subjects, regardless of the psychophysical procedure employed, should be explicit. They suggest that this may eliminate some of the discrepancies currently observed in the literature. It must be pointed out that the results of this study are inconsistent with Zwislocki's (1969) theory of loudness summation. The theory predicts the critical duration to be approximately 100 msec at moderate intensity levels. Neither of the critical durations reported in this latest study conforms to this prediction. The critical duration of 25 msec reported by Zwislocki and Sokolich is not consistent with any of the previously reported findings from experiments involving pure-tone signals.

It is perhaps even more difficult to make direct comparisons between the results of the suprathreshold temporal integration investigations than it was between the investigations of threshold temporal integration. The reasons for the difficulty are essentially the same as indicated at threshold, but they are perhaps more exaggerated at suprathreshold levels. For example, the differences in psychophysical procedures are greater at suprathreshold levels as well as the methods of specifying signal duration. Zwislocki and Sokolich (1972) indicate that even the instructions given to the subjects can make a significant difference in the results obtained at suprathreshold levels.

In an attempt to establish some unity in the current experiment, the signal durations employed in the suprathreshold portion of the experiment were calculated using the equivalent duration formula, just as in the threshold portion of the study. The psychophysical technique employed, a transformed up-and-down procedure, was also the same for the threshold and suprathreshold portions of the experiment.

In view of the variety of findings obtained at threshold and suprathreshold levels as well as the apparent discrepancies between the threshold and suprathreshold functions, and between observation and theory, the present study was initiated. The intent of the current investigation was to evaluate the relationship between threshold and suprathreshold temporal integration functions using the same experimental population. A transformed up-and-down psychophysical method (Levitt, 1971) was used to obtain the threshold and loudness balance data. The study was designed to determine if the temporal integration function for a 1000 Hz pure-tone signal is altered as the presentation level of the signals is increased from threshold to 90 dB SL. The questions to be answered were: (1) whether there is a difference between threshold and suprathreshold temporal integration functions; (2) whether the suprathreshold function changes with presentation level; and (3) how the slope and critical duration of the temporal integration functions are related to presentation level.

CHAPTER III

INSTRUMENTATION AND PROCEDURES

Introduction

The present experiment was designed to investigate systematically threshold and suprathreshold temporal integration in the same sample of a normal-hearing population. The literature suggests that the temporal integration function at threshold differs from that at suprathreshold levels in both slope and critical duration. It is yet to be determined if there is a gradual transition in the slope and/or the critical duration between threshold and suprathreshold temporal integration functions or if there exists an intensity level below which the threshold temporal integration function characteristics are evident and above which the characteristics of the moderate to high level suprathreshold functions are more apparent. An experiment was designed to determine the effect of presentation level on the temporal integration function obtained in a selected experimental sample. The threshold data and the loudness balance data used to construct the threshold and suprathreshold temporal integration functions were obtained with a transformed up-and-down psychophysical procedure.

The experiment was designed to make comparisons of the slope and critical duration among nine suprathreshold temporal integration functions and between these and the threshold temporal integration function. Signal durations from 10 to 500 msec were used to investigate the threshold and suprathreshold temporal integration functions. A reference signal duration of 500 msec was used for the loudness balance sessions. The reference signal was presented at nine suprathreshold levels ranging from 10 to 90 dB SL.

The instrumentation, methods and procedures used in this experiment are discussed in the remaining portions of this chapter.

Subjects

The experimental sample consisted of nine normal-hearing male subjects between 20 and 35 years of age. Normal hearing was defined as threshold sensitivity no poorer than 15 dB hearing level (ANSI, 1969) in each ear for pure tones with frequencies at octave intervals between 250 and 8000 Hz. Further requirements for inclusion in the study were a negative history of otologic pathology and successful completion of a practice regimen which included a representative sample of the experimental listening tasks. The subjects were paid for their participation in the study at the rate of $2.00 per hour.

Signal Parameters

Each subject was presented with the complete set of experimental conditions. The order of presentation of the experimental conditions was counterbalanced among subjects and/or was randomly assigned as discussed in the procedures section of this chapter.

The frequency of the test signal was 1000 Hz in all of the experimental conditions. During the threshold portion of the experiment, sensitivity was determined for signals with equivalent durations (Dallos and Olsen, 1964) of 10, 20, 50, 100, 200, and 500 msec. The rise-decay time of the signals specified between the 10 and 90 per cent points, was 10 msec. The signal duration at peak amplitude and the total duration of the signals were calculated from the formula for equivalent duration. The temporal parameters of the signals employed are reported in Table 1.

TABLE 1

TEMPORAL PARAMETERS OF THE EXPERIMENTAL SIGNALS (IN MSEC)

	Equivalent Duration					
	10	20	50	100	200	500
Rise-Decay Time	10	10	10	10	10	10
Duration at Peak Amplitude	3.5	13.5	43.5	93.5	193.5	493.5
Total Duration	23.5	33.5	63.5	113.5	213.5	513.5

During the suprathreshold portion of the experiment, a monaural loudness balance procedure was employed. Comparison signals with equivalent durations of 10, 20, 50, 100, 200, and 500 msec were used. The comparison signal was followed by a 500 msec reference signal after a fixed interstimulus interval of 500 msec. Signal pairs were presented once every 3.5 seconds. Within any session the reference signal intensity level was fixed at 10, 20, 30, 40, 50, 60, 70, 80, or 90 dB SL. The subjects were instructed to evaluate the loudness of the comparison signal relative to that of the reference signal and report whether the former signal was louder or softer.

Apparatus

Acoustic Environment

This experiment was conducted at the facilities of the Audiology and Speech Pathology Service, Veterans Administration Hospital, Oklahoma City, Oklahoma. During the practice and experimental sessions, subjects were seated in an audiometric test room (Industrial Acoustics Co., Model 400). The ambient noise in this room was measured with a sound level meter (General Radio Co., Type 1551-C) and an octave band analyzer (General Radio Co., Type 1558-AP). The measurements were made with the equipment situated at the approximate location of the subject's head. The octave band levels were found to be below those which would cause masking at zero decibels hearing level (ANSI, 1969) for pure tones with frequencies ranging from 250 to 4000 Hz presented through TDH39 earphones set in MX-41/AR cushions and mounted on a standard headband. The only portions of the experimental apparatus located within the test room were the earphones, response box, and the listen and respond lights.

Instrumentation

A simplified block diagram of the instrumentation is shown in Figure 1. The instrumentation was identical for the practice and experimental sessions. An audio oscillator (Hewlett-Packard, Model 200 ABR) generated the 1000 Hz test signal. The output of the oscillator was split in a resistive network and led to two electronic switches, ESW_1 and ESW_2 (Grason-Stadler, Model 829-C). The switches were

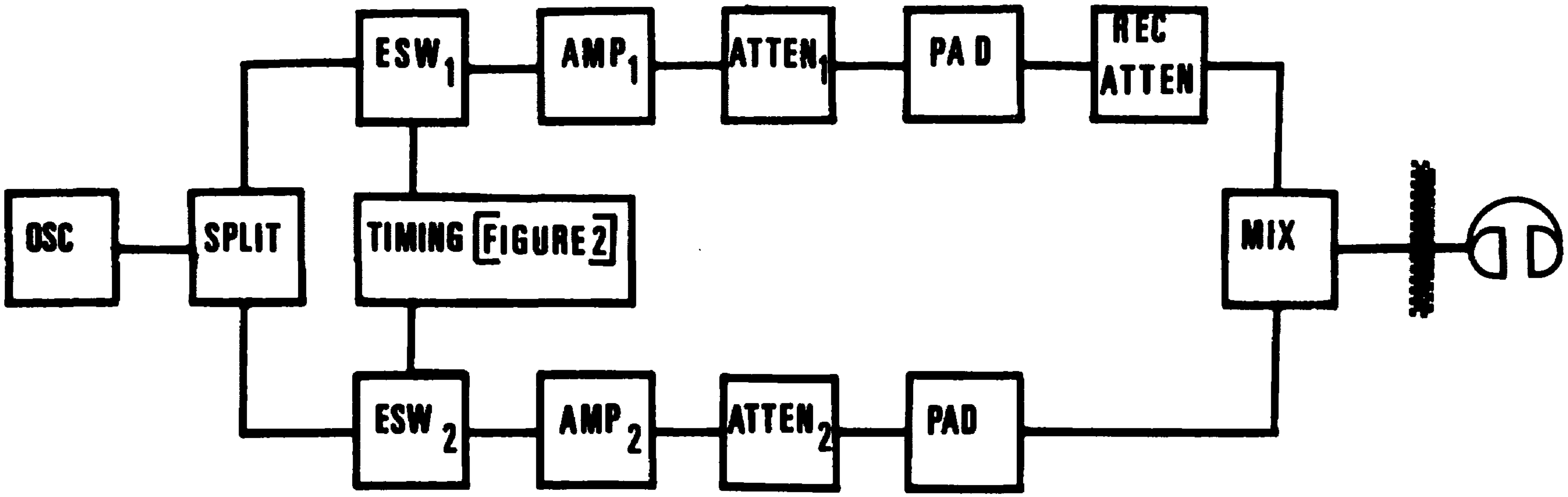

Fig. 1--A Simplified Block Diagram of Instrumentation Employed to Present the Signals for the Threshold and Suprathreshold Portions of the Experiment.

triggered on and off externally by the timing apparatus to be discussed in a subsequent paragraph of this chapter.

The signals used for threshold determination and for comparison signals during the suprathreshold portion of the experiment passed from ESW_1 to a line amplifier, Amp_1 (Altec, Model 436C). The output of the electronic switch was loaded with a 600 ohm resistor. The output of the line amplifier was led to the input of a step attenuator, $ATTEN_1$ (Hewlett-Packard, Model 350D). The signal was then led to a 500-to-10 ohm resistance matching pad. The output of the matching pad was directed to a recording attenuator, REC ATTEN (Grason-Stadler, Model E326A), which was set to operate in the stepped mode. The recording attenuator provided greater or lesser attenuation of the signal depending on the input received from the relay logic system to be described later in this chapter. After passing through a 10 ohm resistive mixing network, the signal from the recording attenuator was terminated in a single TDH39, 10 ohm earphone.

The reference signal for the loudness balance conditions passed through a second electronic switch, ESW_2 (Grason-Stadler, Model 829-C), and on to a second line amplifier, Amp_2 (Altec, Model 436C). The output of the electronic switch was loaded with a 600 ohm resistor. The output of the line amplifier was led to a step attenuator, $ATTEN_2$ (Hewlett-Packard, Model 350D). The output of $ATTEN_2$ was led first to a 500-to-10 ohm resistive matching pad and then on to the 10 ohm mixing network. From the output of the mixer, the reference signal was led to the subjects' earphone. A dummy earphone and cushion were mounted opposite the test earphone on a standard headband.

The timing apparatus is illustrated in Figure 2. It consisted of three waveform generators (Tektronix, Type 162) and seven pulse generators (Tektronix, Type 161). Two power supplies (Tektronix, Type 160A) provided the operating power for the timing system.

The first waveform generator, W_1, regulated the repetition rate of the signals. It was set to the recurrent mode of operation at the beginning of each session and generated successive sawtooth waveforms of 3.5 seconds duration. All other pulse and waveform generators were triggered either directly or indirectly from W_1 and were fired only once during each 3.5 second period.

Pulse generator P_1 served to trigger waveform generator W_2 400 msec after the initiation of the sawtooth waveform from W_1. Waveform generator W_2 generated a 550 msec sawtooth waveform from which pulse generators P_2 and P_3 were triggered. Pulses from P_2 and P_3 regulated the durations of the signals used for the threshold determinations and for the comparison signals employed during the loudness balance conditions. A pulse from P_2 was led to the "A-on" input of ESW_1 500 msec after the initiation of the waveform from W_1. A pulse from P_3 was led to the "B-on" input of ESW_1, thereby terminating the signal. The pulse from P_3 was adjusted in relation to the initiating pulse from P_2 in order to vary the duration of the signal being presented according to a predetermined and fixed schedule. Pulse generator P_3 had been altered in such a way that the output potentiometer was replaced by six independently variable potentiometers and a selector switch. Prior to the practice runs, each of the variable potentiometers was set so that a different signal duration was selected by changing the position of the

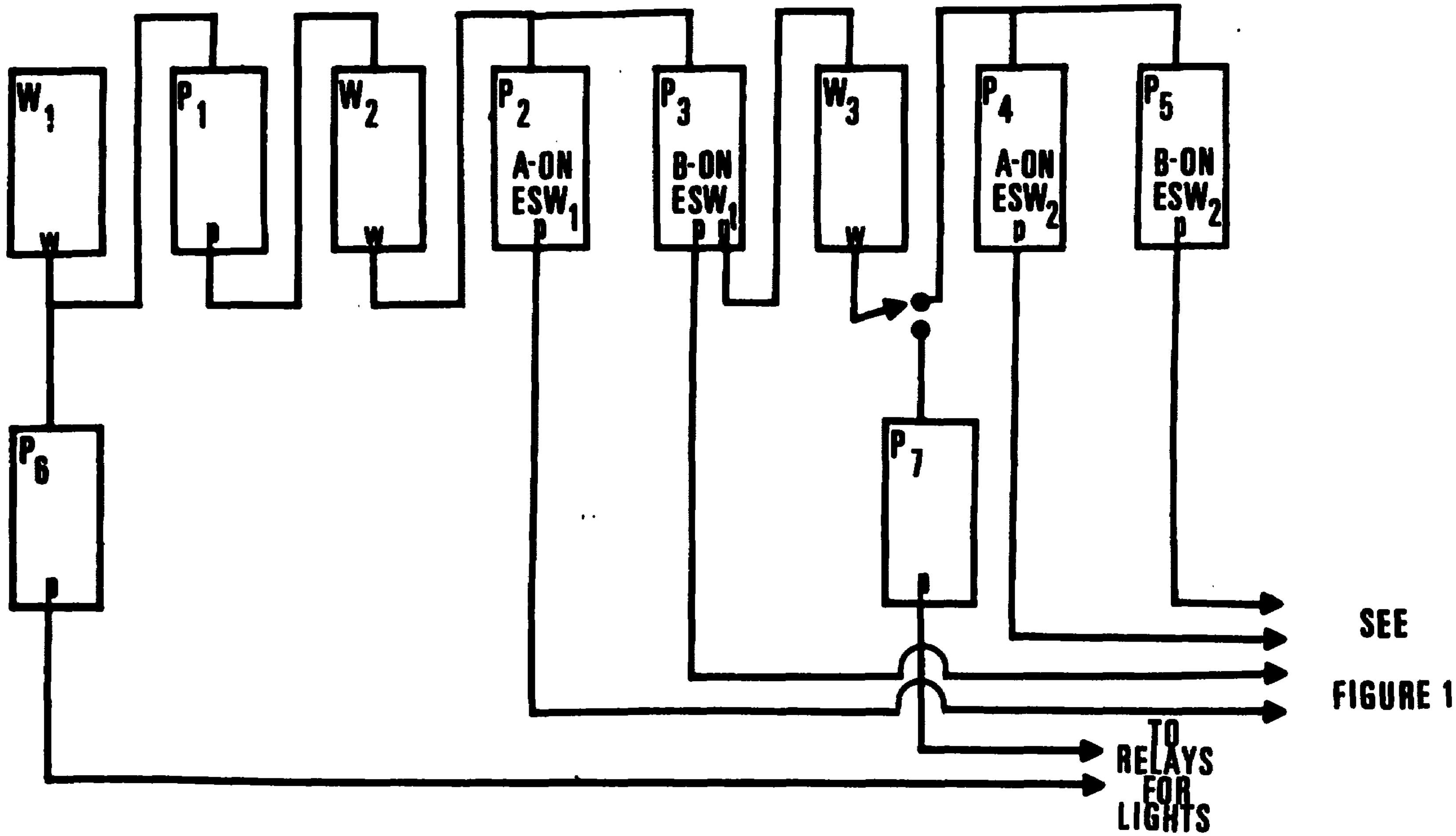

Fig. 2--A Simplified Block Diagram of Timing Apparatus Employed to Trigger the Electronic Switches and the Relays for the Listen and Respond Lights.

selector switch. This allowed the examiner to select the appropriate signal duration with the manipulation of only one selector switch.

The gate output of P_3 was utilized to trigger waveform generator W_3 which regulated the interstimulus interval and the duration of the reference signal for the loudness balance conditions. Waveform generator W_3 was operated in the triggered mode and generated a single sawtooth waveform of 1100 msec duration each time it received a gate from P_3. Pulse generators P_4 and P_5 determined the duration of the reference signal for the loudness balance conditions. A pulse from P_4 triggered "A-on" of ESW_2 500 msec after the termination of the comparison signal and thereby initiated the reference signal. After 503 msec, a pulse from P_5 triggered "B-on" of ESW_2, thus termination the reference signal.

For the threshold measurements, two lights were employed to mark the observation interval. Pulses from P_6 and P_7 controlled the timing relationship for the lights. A pulse from P_6 was initiated from each sawtooth waveform of W_1 500 msec prior to the presentation of the signal. This pulse activated a relay causing a momentary completion of a 6V a/c circuit which illuminated a yellow light in the test room. This light was the subject warning or "listen" light which indicated the beginning of an observation interval. The green "respond" light was illuminated 500 msec after the termination of the signal. This was accomplished by switching the output of waveform generator W_3 from pulse generator P_4 to pulse generator P_7. The pulse from P_7activated a relay causing a momentary completion of a 6V a/c circuit which illuminated the "respond" light in the test room.

The lights, as described above, were inactive during the loudness balance sessions. The green "respond" light was deactivated by switching the output of waveform generator W_3 from pulse generator P_7 to pulse generator P_4, providing the appropriate triggering necessary to establish the interstimulus interval and reference signal duration for the loudness balance conditions as described previously. The yellow "listen" light flashed only at the beginning of each new run of the loudness balance sessions to indicate to the subject that a run was beginning. The input from waveform generator W_1 to pulse generator P_6 was disconnected after the first pair of signals was presented to the subject for each loudness balance run.

Figures 3 and 4 illustrate the signal sequence during the threshold and suprathreshold portions of the experiment, respectively. During the threshold portion of the experiment (Figure 3), the listen light flashed 500 msec before the signal was presented. The respond light flashed momentarily 500 msec after the signal was presented. A variable-response-interval followed the respond light. The duration of the response interval was dependent upon the duration of the signal being presented in such a way that the sequence was repeated once every 3.5 seconds. During the suprathreshold portion of the experiment (Figure 4) the listen light flashed only once at the beginning of each loudness balance condition. The comparison signal followed the listen light after 500 msec. A 500 msec silent interstimulus interval preceded the 500 msec reference signal. Prior to the presentation of the next comparison signal, a variable-response-interval occurred. The sequence of comparison signal, silent interstimulus interval, reference

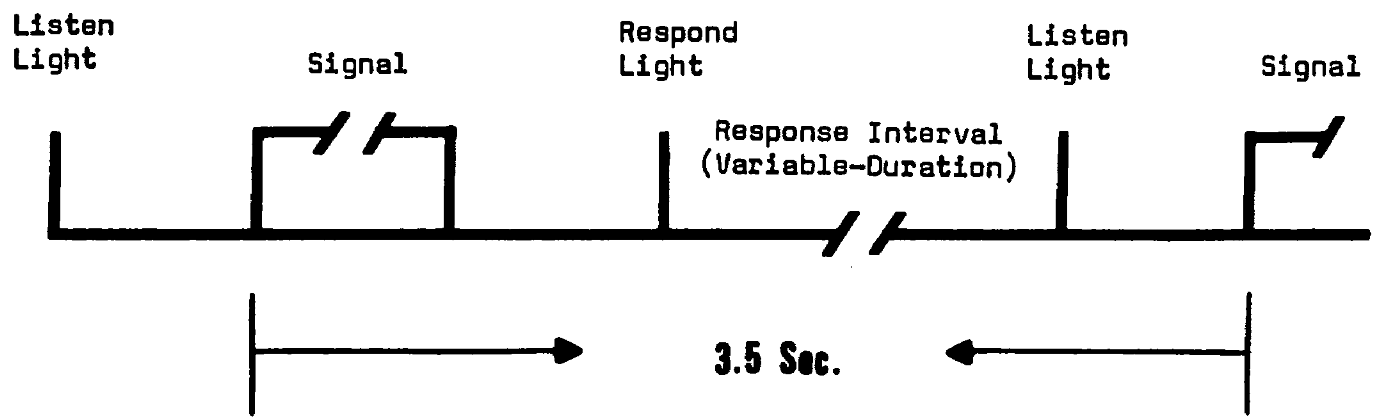

Fig. 3—Illustration of the Temporal Sequence of Events during the Threshold Portion of the Experiment.

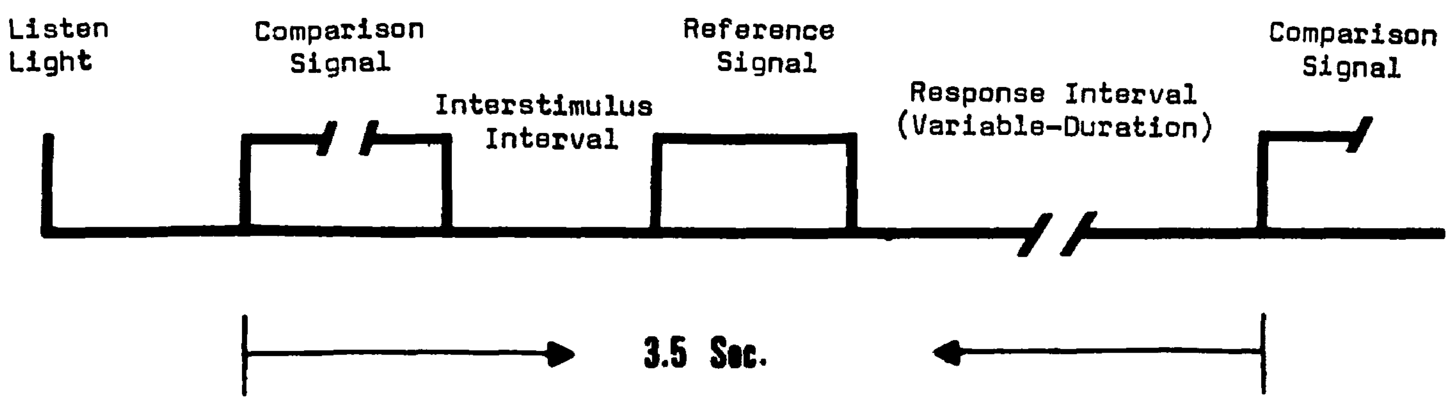

Fig. 4--Illustration of the Temporal Sequence of Events during the Suprathreshold Portion of the Experiment.

signal, and response interval was repeated every 3.5 seconds.

The subject response and relay logic circuit is illustrated in Figure 5. A transformed up-and-down psychophysical method (Levitt, 1971) was used in this experiment for both the threshold and loudness balance determinations. This procedure required that attenuation of the threshold signals or the comparison signals during the loudness balance sessions be increased if the subject responded "yes" (the signal was heard) or "louder" (the comparison signal was louder) during two successive observation intervals and that attenuation be decreased if the subject responded either "yes/louder"--"no/softer" during two successive observation intervals, or "no/softer" in the first interval. The relay logic system was designed so that, if any of the above criteria was met, the recording attenuator was adjusted by a 1 dB step in the appropriate direction. The system was reset upon completion of any of the three response sequences.

The subjects were in possession of a response box which contained a double-throw spring-loaded switch. If the switch was thrown one way, a "yes/louder" response was indicated. When the switch was thrown in the other direction, a "no/softer" response was indicated.

A "yes/louder" response during the first observation interval caused momentary completion of a 6V a/c circuit that tripped a relay, R_1, that advanced the Stepping Relay one position. A second consecutive "yes/louder" response caused the Stepping Relay to advance one step further. Upon reaching this step, relay R_3 was tripped momentarily causing brief completion of a circuit from the recording attenuator that resulted in a 1 dB increase in attenuation. It also briefly completed

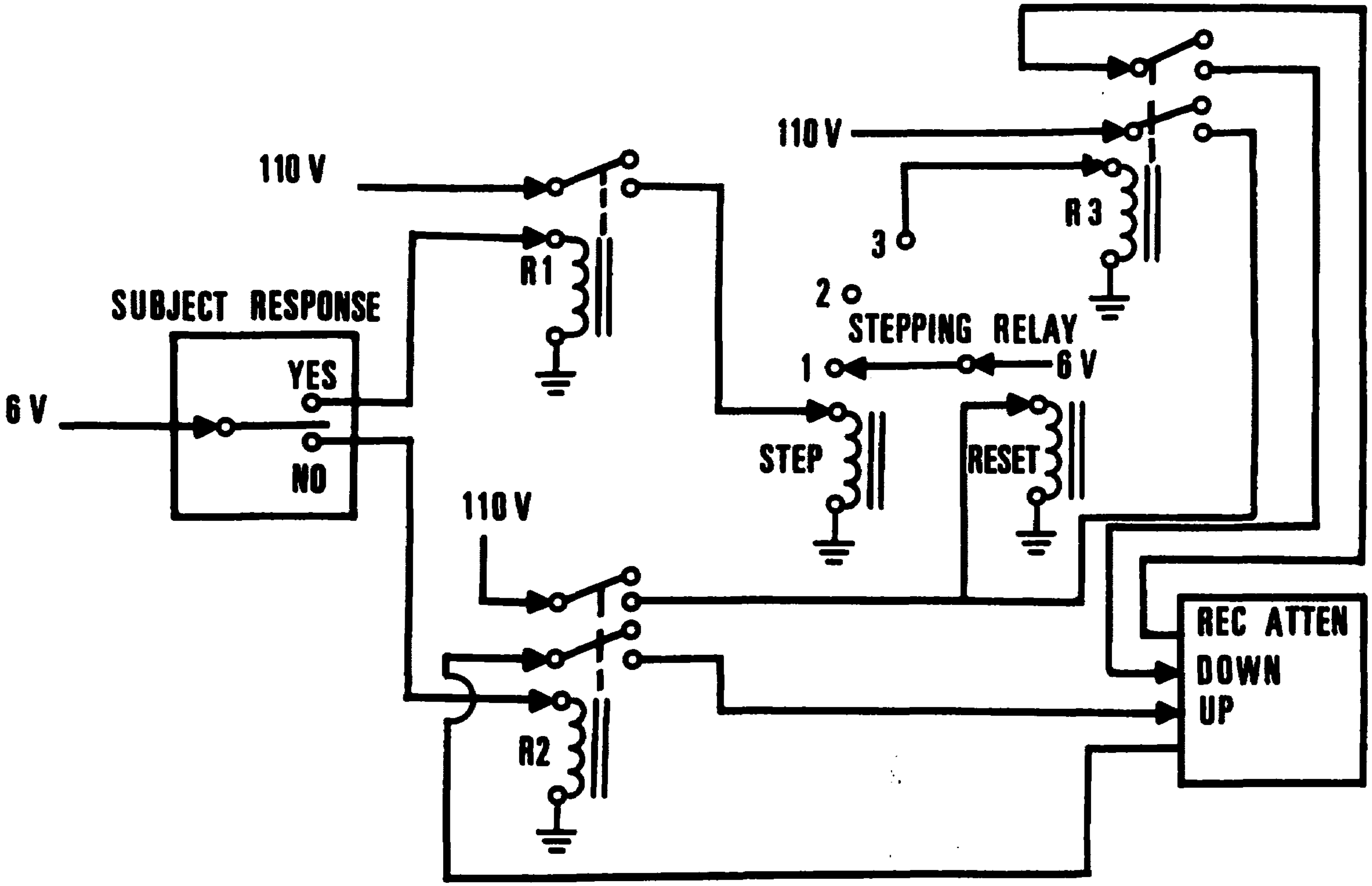

Fig. 5--Schematic of the Circuit Used to Implement the Subject Response and Relay Logic.

the circuit that reset the Stepping Relay in preparation for the next series of signals.

A "no/softer" response during the first observation interval resulted in momentary completion of a 6V a/c circuit that tripped relay R_2, causing brief completion of the circuit that reset the Stepping Relay. It also completed a circuit from the recording attenuator that resulted in a 1 dB decrease in attenuation. In the event a "yes/louder" response was followed by a "no/softer" response, the Stepping Relay was first advanced one step (the first step of the Stepping Relay is holding logic only) and, upon receiving the "no/softer" response, the Stepping Relay was reset and the recording attenuator subsequently decreased attenuation by 1 dB. This procedure resulted in a series of attenuator reversals that were recorded on the chart paper of the recording attenuator. The recorded levels corresponding to the attenuator reversals were used to calculate the thresholds and points of equal loudness for the signal durations employed to plot the temporal integration functions.

The experimenter was in control of an auxiliary switch (not shown on the diagram) with which the recording attenuator could be stepped in either direction independently of the subject's responses. The purpose of this switch was to effect attenuation changes greater than 1 dB between signal presentations. This was done only at the beginning of each run in order to approximate the eventual threshold level or equal loudness level more quickly than could have been done with single 1 dB steps.

Calibration Procedures and Evaluation of the Instrumentation

Complete evaluation of the experimental apparatus was conducted before and after performing the experiment. Routine evaluation and calibration of portions of the experimental apparatus were conducted at regular intervals during the course of the experiment.

The linearity of the system was evaluated from the earphone by use of a condenser microphone (Western Electric, Model 640 AA), a 6 cc coupler (Grason-Stadler, Type 9A), a pre-amplifier and microphone complement (Western Electro-Acoustic Laboratory, Type E and Type 100 D/E, respectively), and a wave analyzer (Hewlett-Packard, Model 3590 A). A 1000 Hz pure-tone signal was used for the evaluation. The attenuators $ATTEN_1$ and $ATTEN_2$ were found to be sufficiently linear throughout the range used in this experiment. Successive 10 dB changes of the attenuator setting resulted in measured attenuation changes of 10 dB $\pm$ 0.1 dB. Successive 2 dB changes in attenuation setting resulted in measured attenuation changes of 2 dB $\pm$ 0.2 dB. The linearity through the recording attenuator was not as good as through attenuators $ATTEN_1$ and $ATTEN_2$. Cumulative 10 dB changes of the recording attenuator setting over the range employed in this experiment resulted in measured attenuation changes of 10 dB $\pm$ 0.7 dB and cumulative 2 dB changes resulted in measured attenuation changes of 2 dB $\pm$ 0.6 dB. Most of the deviations with the recording attenuator were on the order of 0.5 dB or less. Isolation of the attenuators, $ATTEN_1$ and $ATTEN_2$, was checked by using the same equipment described above. The test signal was led to attenuator $ATTEN_1$ and the level of the signal at the earphone was monitored while varying the setting of attenuator $ATTEN_2$. With the test signal delivered to attenuator $ATTEN_2$, the level of the signal at the earphone was monitored while varying the settings of attenuator $ATTEN_1$ and the recording attenuator. The attenuators $ATTEN_1$ and $ATTEN_2$ were considered sufficiently isolated from one another because the output level from any of the attenuators did not vary with changes in the settings of the other attenuators.

Harmonic distortion components were evaluated with the same apparatus described above. An uninterrupted 1000 Hz tone at a sound pressure level of 100 dB was generated at the earphone. Table 2 shows

TABLE 2

RELATIVE STRENGTH OF THE HARMONICS OF THE TEST SIGNAL

Frequency	Strength of the Harmonics in dB Relative to the Fundamental
2000 Hz	- 42
3000 Hz	- 48
4000 Hz	- 69

the relative harmonic content of the signal. The signal was found to be sufficiently free from harmonic distortion to be used in this experiment.

An oscilloscope (Tektronix, Model 561A) was used to monitor and adjust the signals at the outputs of the electronic switches. The vertical (voltage) and horizontal (time) bases of the oscilloscope were calibrated weekly throughout the experiment and were found to remain stable during that time. Vertical calibration was obtained by using the internal voltage source of the oscilloscope. Horizontal calibration was obtained by use of the frequency-time standard generated by a counter-timer (Transistor-Specialities, Inc., Model 361).

Both electronic switches were balanced weekly and were found to possess characteristics within manufacturer's specifications. The rise-decay times of the electronic switches were calibrated on a daily basis using the calibrated oscilloscope. Rise-decay times for this purpose were measured from the 10 to 90 per cent points of the maximum amplitude of the envelope of the waveform. Before adjustments, the rise and decay times of ESW_1 and ESW_2 ranged from 9.5 to 10.5 msec throughout the experimental period. Generally, the day-to-day variation was smaller for the rise time than for the decay time. Daily adjustments of the electronic switches were made to achieve the 10 msec rise-decay times.

At the beginning of each experimental day, the gain control of the audio oscillator was adjusted to provide 1V into the electronic switches. The electronic switches were then adjusted to yield 1V at their outputs as measured with a true RMS voltmeter (Ballantine Laboratories, Inc., Model 323). In addition, the gain of each amplifier was adjusted to produce an output of 100 dB SPL at the earphone through each channel. Attenuator $ATTEN_1$ was set to zero dB attenuation and the recording attenuator was set to provide 10 dB of attenuation when the signal level from Amp_1 was adjusted. Attenuator $ATTEN_2$ was set for zero dB attenuation when the signal from Amp_2 was adjusted. These adjustments never exceeded 0.5 dB from day to day. The frequency of the test signal was checked and adjusted daily using the counter-timer.

At the beginning of each experimental session, the timing apparatus was calibrated using the counter-timer. As experimental requirements changed within the session, the timing network was adjusted. During the threshold session, the signal durations were continuously monitored with the counter-timer. Only the comparison signal durations were monitored during the loudness balance portions of the experiment. The reference signal duration was checked prior to each session using the counter-timer.

The signals were monitored on the oscilloscope from the output lugs of ESW_1 and ESW_2. The rise-decay time, peak amplitude, and total duration of the signals were adjusted with the aid of the oscilloscope at the beginning of each session.

Experimental Procedures

All subjects completed a series of threshold and loudness balance judgments designed to give them practice with a representative sample of the experimental conditions. Following the completion of the practice sessions, subjects began the experimental phase of the research. It is the purpose of this section to describe the methods and procedures utilized for both the practice and experimental sessions.

Practice Sessions

Practice sessions served to familiarize the subjects with the various listening tasks which were required of them during the experimental phase of this study. They also allowed the subjects to gain experience in making threshold and loudness balance judgments utilizing the transformed up-and-down psychophysical procedure.

All stimuli were presented to the subject's right ear during the practice and experimental sessions. The left ear was covered with a dummy TDH39 earphone set in an MX-41/AR cushion. During the practice sessions, the subjects made threshold judgments for a 1000 Hz pure tone at each of the specified durations. Loudness balance determinations were made at three representative levels: 10, 50, and 90 dB SL. Threshold determinations were made prior to the loudness balance measurements. The loudness balance measurements were ordered from high intensity to low intensity because pilot data together with a substantial body of literature indicated that higher level balances are easier for subjects to perform. The order of presentation for the practice sessions is presented in Appendix A, Table 7.

The instructions to the subjects during the practice sessions were similar to those employed during the experimental sessions. Prior to each session, the subjects were instructed with respect to the "listen" and "respond" lights and the use of the subject-response switch. Prior to each run, the subjects were informed as to the nature of the task, i.e., threshold determinations, or loudness balance measurements at high, low, or moderate intensity levels. The subjects were allowed to ask questions and/or make comments about the experimental procedure at any time during the practice sessions. Subjects were instructed to "guess" if detection of the signals or equality of the comparison and reference signal were in doubt during any of the observation intervals. The experimenter repeated trials in which the subjects gave erratic responses or exhibited confused bahavior.

Experimental Sessions

Upon completion of the practice sessions, the subjects began the experimental phase of the research. Each subject participated in ten experimental sessions. Only two sessions each day were completed for a given subject. These sessions were separated by at least one-half hour in order to reduce the effects of general fatigue and/or temporary threshold shift. Each session required no longer than thirty minutes for completion.

The order of presentation of the experimental conditions and their assignment to the subjects is reported in Appendix A, Table 8. The first experimental session for all subjects consisted of the threshold portion of the experiment. The other nine sessions were for the determination of the temporal integration functions at the suprathreshold levels utilizing the loudness balance procedure. The order of presentation of the nine intensity levels comprising the loudness balance conditions was counterbalanced among subjects. The order in which the various signal durations were presented in both the threshold and loudness balance conditions was randomized by sampling without replacement from a random numbers table.

The threshold for the 500 msec comparison signal was obtained at the start of each loudness balance session. The only difference between the reference signal and the 500 msec comparison signal was that the latter was routed through the recording attenuator and its level was manipulated by the subject. The intensity of the reference signal was adjustable only by the examiner. After the threshold had been obtained, the appropriate value was set on attenuator $ATTEN_2$.

The following instructions were read to the subjects prior to the threshold determination session:

> During this session, you will hear a tone in your right ear. The duration of this tone will vary, sometimes being relatively short, at other times being relatively long. Each tone will be presented during an interval defined by the two lights in front of you. The tone will be presented shortly after the yellow "listen" light flashes. Your task is to listen for the tone and to respond after the green "respond" light flashes. Respond either "yes" or "no" depending on whether-or-not you detected the tone. In the event that you are not sure if you heard the tone, you are to respond according to whether-or-not you think you heard the signal. Do not be afraid to guess. Please do not remove the earphones during this session. There will be short pauses between threshold determinations for the different signals; just wait until the "listen" light indicates the beginning of a new run. I will open the door and inform you when the session is finished.

The following instructions were read to the subjects prior to each loudness balance condition:

> During this session you will hear several pair of tones in your right ear. The first tone of each pair will vary in duration from run to run within this session. The second tone of each pair will remain constant in duration and intensity throughout this session. Your task is to listen to each pair of tones and judge which of the tones is louder. Make your response as quickly as possible after the termination of the second tone. If the first tone is louder than the second tone, respond "louder"; if the first tone is softer than the second tone, respond "softer". In the event that you are not sure whether the first tone was louder or softer than the second tone, you are to respond according to what you think was the case. Do not be afraid to guess. There will be short pauses between the loudness balance determinations; just relax and wait for the next run to begin. The lights will be inactive during these sessions except that the yellow "listen" light will flash once at the beginning of each new run to indicate that you are to start to listen again. I will open the door and inform you when the session is finished.

During the first several signal presentations of the threshold and suprathreshold conditions, the level of the signal to be controlled by the subject was set on attenuator $ATTEN_2$ so that the subject would track in the middle range of the recording attenuator chart paper. This setting of $ATTEN_2$ was not changed throughout the session. When the session involved threshold determinations, the intensity of the signal was set to a level above the expected threshold so that it was clearly audible. During the loudness balance sessions, the level of the comparison signal was set above that of the reference tone in order for it to be clearly louder than the reference signal.

After these initial settings had been made, the following procedure was used for both the threshold and loudness balance determinations in order to arrive at the proximity of the expected threshold or the level of equal loudness. The first descending run was presented in 3 dB steps (the experimenter controlled the override switch to activate the recording attenuator in additional 1 dB steps). The first ascending run was also performed in 3 dB steps. The second and third descending runs and the second ascending run were performed in 2 dB steps. All runs thereafter were performed in 1 dB steps and the use of the override switch was discontinued. The presentation of signals continued until fourteen consecutive reversals of the recording attenuator pen had been made in 1 dB steps by the subjects. Only the intensity levels at which the last twelve reversals occurred were averaged to calculate the subject's threshold level and equal loudness levels for the signal durations employed. Group means were calculated from the individual subject means.

A least squares method was used to fit lines to the mean data points as a function of the logarithm to the base ten of the signal durations at each presentation level. This procedure was used to describe each of the temporal integration functions in an attempt to facilitate comparisons of the data. The suprathreshold data were analyzed as a two factor design with each subject appearing under each treatment combination (Winer, 1962). This procedure provided a method for a comparison among the suprathreshold temporal integration functions.

CHAPTER IV

RESULTS AND DISCUSSION

Results

The results of this study are presented in the following three sections. The threshold temporal integration data are described in the first section while the loudness summation data are presented in the second section. The third section includes a comparison of the threshold and suprathreshold temporal integration data.

Threshold Temporal Integration

Thresholds were obtained with a transformed up-and-down psychophysical procedure. The data for the individual subjects are reported in Appendix B, Table 9. Individual means for each signal duration were calculated by averaging the sound pressure levels indicated by twelve consecutive reversals of the recording attenuator pen. The mean individual thresholds for the 500 msec signal range from -1.7 to 15.3 dB SPL. Individual thresholds tend to be greater for each succeeding decrease in signal duration. Only three exceptions to this were noted and two of these occurred between durations of 200 msec and 100 msec. The difference between the thresholds for signals of these two durations is less than 0.5 dB for each of the subjects involved. That is to say, the thresholds of two subjects for the 100 msec signal are better than the thresholds for the 200 msec signal, but this difference does not exceed 0.5 dB for either of the subjects. The third exception occurred between signal durations of 50 msec and 20 msec. Here, the threshold of one subject for the 20 msec signal is 1.3 dB better than that for the 50 msec signal.

The range of standard deviations for the threshold of the 500 msec signal is from 0.8 dB to 1.9 dB for the nine subjects. Standard deviations did not vary greatly as signal duration was changed. The largest standard deviation for any condition is 2.7 dB which occurred for S #8 at 100 msec. The smallest standard deviation was 0.8 dB which occurred for S #3 at 500 msec and S #4 at 200 msec. These rather small standard deviations suggest that each subject tracked his thresholds with little variability.

The group means for each signal duration were calculated from the individual mean values. These are reported in Table 3 along with

TABLE 3

MEAN THRESHOLDS AND STANDARD ERRORS OF THE MEANS FOR SIGNALS WITH DURATIONS RANGING FROM 500 MSEC TO 10 MSEC. THRESHOLD VALUES ARE EXPRESSED IN dB SPL AND REPRESENT THE AVERAGE RESULTS OF NINE SUBJECTS. STANDARD ERRORS OF THE MEANS ARE EXPRESSED IN dB.

	Signal Duration (in MSEC)					
	500	200	100	50	20	10
Mean Threshold	5.8	7.9	9.2	10.9	12.8	16.2
Standard Error	5.3	4.3	4.2	3.7	4.1	3.9

the associated standard errors of the means. The mean threshold for the 500 msec signal is 5.8 dB SPL. This is 1.2 dB less than the ANSI (1969) standard threshold SPL for a 1000 Hz pure-tone signal. The standard error of the mean at 500 msec is 5.3 dB. The standard errors of the means at the other signal durations are less than that at 500 msec. The smallest standard error is 3.7 dB for the 50 msec signal.

An additional threshold for the 500 msec signal was obtained at the start of each of the nine loudness balance sessions. The overall mean of these values is 7.1 dB SPL with a range from 0.9 dB SL to 18.0 dB SPL. The mean is only 1.3 dB greater than the mean threshold for the 500 msec signal obtained in the threshold portion of the experiment and, therefore, is within one standard error of that mean. It is concluded that these measures of threshold sensitivity are reliable and show little variability.

The difference in decibels between the mean thresholds for the 10 msec and the 100 msec signals is 7.0 dB. The difference is 4.9 dB between the 20 msec and 200 msec signals and 5.1 dB between the 50 msec and 500 msec signals. Table 4 compares the current findings with the results obtained by several investigators who used either the same or a similar method for specifying signal duration. The greatest difference between the results of the current investigation and the average of the other studies is 1.6 dB. This value is associated with the threshold differences noted between signals of 20 msec and 200 msec duration. The deviations of the current findings from those of the other investigators are considered small and indicate that the present findings are in good agreement with previous results when signal durations are

TABLE 4

COMPARISON OF THE MEAN RESULTS OF THE CURRENT EXPERIMENT WITH THE MEAN RESULTS OBTAINED BY OTHER INVESTIGATORS WHO SPECIFIED SIGNAL DURATION IN ESSENTIALLY THE SAME MANNER

Investigator	Method	Rise-Decay Time (in Msec)	Equivalent Duration	Decibel Differences in Threshold Sensitivity or Equal Loudness Between the Indicated Signal Duration			
				10 - 100	20 - 200	50 - 500	200 - 500
Dallos and Olsen (1964)	Limits	5 to 50 variable	8.3 to 83.3	7.6*	**	**	**
Olsen and Carhart (1966)	Tracking	7.5	10 to 10,000	8.6	7.5	5.6	1.8
Dallos and Johnson (1966)	Limits	7.5	10 to 500	7.4	5.5	5.1	1.9
Wright (1968)	Bekesy	10***	10 to 500****	7.5	*****	*****	*****
Dague (Threshold Results)	Transformed up-and-down	10	10 to 500	7.0	6.5	5.1	2.1
Dague (Mean Suprathreshold Results Averaged Across Subjects and Presentation Levels)	Transformed up-and-down	10	10 to 500	7.3	6.5	5.2	1.4

* Results indicate the decibel differences between signals with equivalent durations of 8.3 msec and 83.3 msec.

** No data available for signals with these durations.

*** The rise-decay time specified between the 10 and 90 per cent points.

**** Signal duration specified at 0.707 of maximum amplitude. According to Wright this specification is in terms of "effective sound pressure." Wright also indicates that there is little difference in signal duration when calculated in this manner compared with signal durations calculated by the equivalent duration formula.

***** Could not interpolate these values accurately from graphed data.

specified in essentially the same manner. This agreement is also shown in Figure 6 where the data from the investigations of Olsen and Carhart (1966) and Dallos and Johnson (1966) are presented along with the current findings. Although, the present results show better thresholds at all signal durations, except 200 msec, agreement in the slope of the functions is evident.

A larger discrepancy would be anticipated between the present results and those obtained in previous investigations in which signal durations were calculated by methods other than equivalent duration. A review of these studies reveals that the present findings are within 2 dB of the results of other studies for signal durations from 10 msec to 100 msec regardless of the method used to specify signal duration. It must be concluded that for the threshold portion of the experiment the results are consistent with previous literature especially when signal durations are specified in a similar manner.

A least squares method was used to fit a line to the data. The mean threshold values served as the dependent variables and the logarithms of the associated signal durations as the independent variables. The results are reported in Appendix, C, Table 19 and plotted in Figure 7. A single straight line with a slope of 5.8 dB per decade change in signal duration was found to provide an adequate description of the data throughout the range of signal durations used in the experiment. The correlation coefficient, r, associated with the line is 0.99. The correlation coefficient is a summary statement which assesses the degree of the linear relationship between two characteristics. In this case the characteristics are the intensity required for threshold and

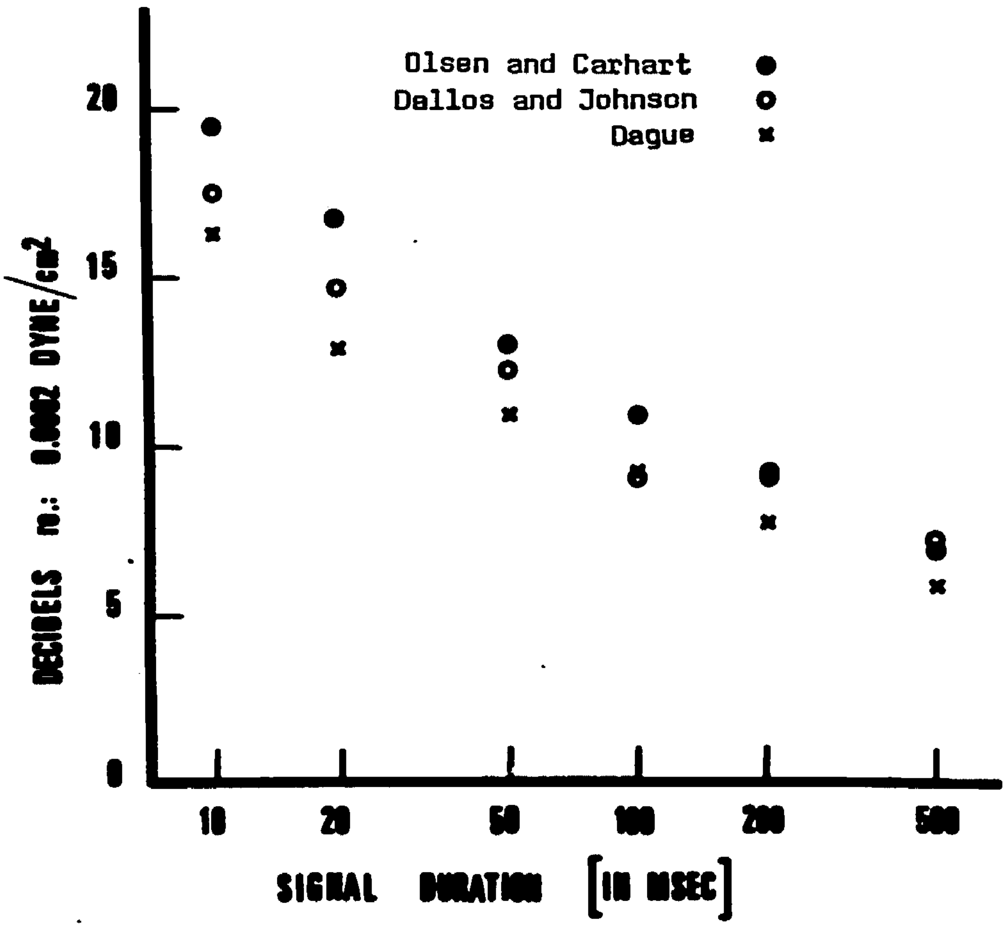

Fig. 6—Comparison of the Mean Threshold Results (in dB SPL) Obtained by Olsen and Carhart (1966) and Dallos and Johnson (1966) with the Mean Results Obtained in the Current Experiment.

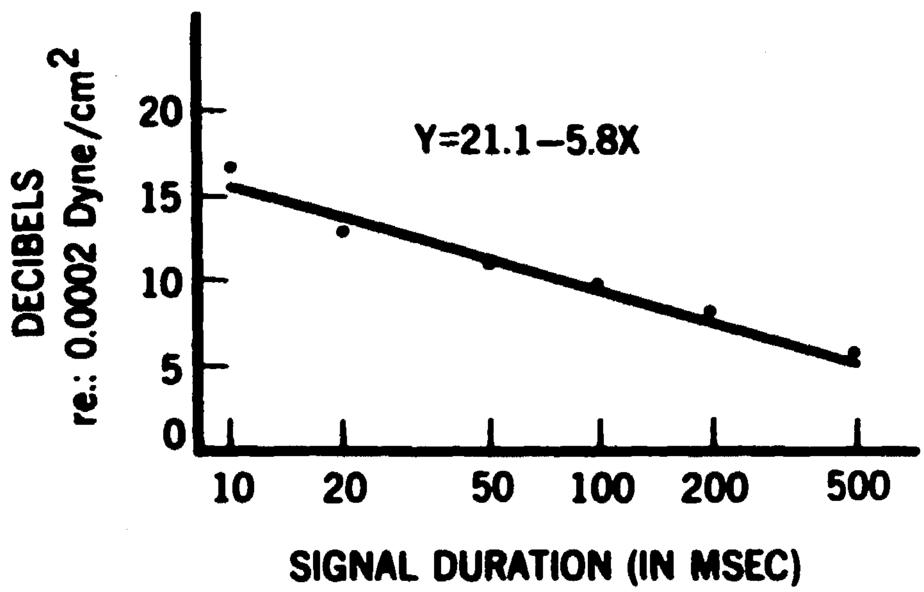

Fig. 7—Mean Thresholds as a Function of Signal Duration. The Solid Line is the Least Squares Fit of the Mean Data Points.

the logarithms to the base ten of the signal durations. A 0.99 correlation coefficient indicates that there is a high degree of linear association between the intensity of the signal required to obtain threshold and the logarithm to the base ten of the signal duration. Squaring the correlation coefficient, r^2, defines the proportion of the variance in the dependent variable (threshold) predictable from, or attributable to, variation in the independent variable (log duration). That is to say, r^2, in the present situation, indicates that approximately 98 per cent of the variability in the mean threshold values is predictable from, or attributable to, variation in the logarithm to the base ten of the signal duration. Only 2 per cent of the variability associated with the mean threshold values is associated with factors other than the duration of the signal. In summary, it appears that a single straight line with a slope of 5.8 dB per decade is a close approximation of the response curve between 500 msec and 10 msec.

The linear nature of the function as described by the regression analysis makes it impossible to define a critical duration with the data obtained in this investigation. It appears that a critical duration as defined by either Harris, Haines, and Meyers (1958) or Sanders and Honig (1962) was not reached in this study. That is not to say, however, that the critical duration lies beyond 500 msec. It is projected that the inclusion of additional longer signal durations in the experiment would have aided in the definition of a critical duration by providing a function composed of two intersecting lines, one being similar to the slope of the line described above and the other being essentially parallel to the abscissa. An alternative fit of such data might be a curvilinear function, but a substantially greater number of data points would be needed to provide adequate definition of the curve.

Several other investigators of temporal integration have described their data simply as decibel changes in threshold per decade change in signal duration. Dallos and Olsen (1964), Dallos and Johnson (1966), and Olsen and Carhart (1966) do not identify an average slope or a critical duration. Their data, however, at least through the range of durations used in the current study, displays a great similarity to the data reported herein.

Loudness Summation

The suprathreshold temporal integration data were obtained by a loudness balance procedure performed with the transformed up-and-down psychophysical method. These data are described in this section. Even though the psychophysical procedure was the same for the threshold and suprathreshold conditions, it was necessary to evaluate the data separately because the tasks required of the subjects were different, i.e., determination of the presence or absence of a signal in contrast to a loudness judgment.

The individual mean equal-loudness values for each signal duration and presentation level were determined by averaging the SPL associated with twelve consecutive reversals of the recording attenuator pen. These individual means and standard deviations are reported in Appendix B, Tables 10 through 18. The values reported in the Appendix represent the mean SPL to which the comparison signals of each duration were raised in order to be equal in loudness to the reference signal at each presentation level. There is a general trend indicating that subjects required more intensity for equal loudness at each presentation level as the comparison signal became shorter in duration. Not every subject performed in this manner at all presentation levels.

The 500-msec to 500-msec loudness balance condition at each presentation level was included as a check of the subjects' ability to judge loudness equality. In this condition these two signals are identical in all respects, and the level to which the subjects set the comparison signal should approximate the level at which the reference signal was presented. It was assumed that the time-order error (Postman, 1946) would be minimal with the inclusion of a 500-msec silent interstimulus interval (Stokinger, Cooper, and Lankford, 1969). Sonn (1969) defines the time-order error as, ". . . an error in judgment between some dimension of two sound stimuli that occurs as a function of the time separation between the stimuli." The error is termed positive when it enhances the first stimulus and negative when it enhances the second stimulus. In order to determine if a time-order error was evident in the data, the points of physical equality were subtracted from the mean loudness balance levels for every subject at each presentation level. Three subjects showed negative time-order errors at all presentation levels while three additional subjects showed negative time-order errors at five or more of the nine presentation levels. Only three subjects showed more positive time-order errors than negative errors. The mean difference (averaged across all subjects and levels) between the point of physical equality and the point of equal loudness is 2.4 dB. That is to say, the subjects on the average required 2.4 dB greater intensity for the first or comparison signal than for the second or reference signal when the two signals sounded equal in loudness. The largest difference occurred during the 60 dB SL session where subjects, on the average, showed a negative time-order error of 3.4 dB. The smallest difference occurred in the 90 dB SL session where only a 1.5 dB negative time-order error was evident.

Individual standard deviations (Appendix B, Tables 10 through 18) for the loudness balance values across all presentation levels and signal durations ranged from 0.6 dB to 2.5 dB. There does not appear to be a trend relating the individual standard deviations to either signal duration or presentation level. These small standard deviations suggest that the individual subjects showed little within-session variability in tracking equal loudness levels.

The group means for equal loudness were calculated from the individual mean values. These are reported in Table 5. The group means at each signal duration increase as the presentation level of the reference signal increases. Within each presentation level, the group means increase as the signal duration decreases.

The decibel differences required for equal loudness between decade changes in signal duration are reported in Table 6 for each reference signal presentation level. The decibel difference between the 10 msec and 100 msec signals is greatest at the 20 dB SL condition (9.2 dB) and least (4.4 dB) at the 90 dB SL condition. The range of difference scores between the 20 msec and 200 msec signals is from 3.3 dB at 90 dB SL to 8.3 dB at 40 dB SL. All of the differences between the 20 msec and 200 msec signals are smaller than those between the 10 msec and 100 msec signals except at 40 dB SL. The decibel difference

TABLE 5

MEAN SOUND PRESSURE LEVELS OF THE COMPARISON SIGNALS WITH DURATIONS FROM 500 MSEC TO 10 MSEC REQUIRED FOR LOUDNESS EQUAL TO THE LOUDNESS OF THE 500 MSEC REFERENCE SIGNALS MEASURED AT EACH OF NINE REFERENCE SIGNAL PRESENTATION LEVELS FROM 10 dB SL TO 90 dB SL. VALUES EXPRESSED REPRESENT THE AVERAGE RESULTS OF NINE SUBJECTS

Presentation Level (dB SL)	Signal Duration (In MSEC) 500	200	100	50	20	10
10	20.3	21.5	22.9	26.0	27.3	31.6
20	30.9	32.2	33.5	37.0	39.7	42.7
30	40.2	42.8	44.4	45.6	50.4	53.4
40	50.2	50.4	54.4	55.3	58.7	60.4
50	60.9	62.8	64.0	66.1	70.3	72.1
60	71.7	73.8	76.3	76.5	79.8	83.2
70	81.8	82.1	85.1	86.9	88.7	92.5
80	88.9	90.8	91.9	94.6	96.0	98.8
90	99.8	101.3	102.2	103.4	104.6	106.6

TABLE 6

MEAN DECIBEL DIFFERENCES FOR DECADE CHANGES IN COMPARISON SIGNAL DURATION WHICH ARE REQUIRED FOR JUDGMENTS OF EQUAL LOUDNESS AT EACH REFERENCE SIGNAL PRESENTATION LEVEL RANGING FROM 10 dB SL TO 90 dB SL. VALUES ARE EXPRESSED IN dB AND REPRESENT THE AVERAGE RESULTS OF NINE SUBJECTS

Presentation Level (dB SL)	Signal Durations (In MSEC)		
	50/100	20/200	10/100
10	5.8	5.8	8.6
20	6.2	7.6	9.2
30	5.4	7.6	9.1
40	5.1	8.3	6.0
50	5.2	7.5	7.5
60	4.8	6.0	6.8
70	5.2	6.7	7.3
80	5.7	5.3	6.8
90	3.6	3.3	4.4

between the 50 msec and 500 msec signals ranged from 3.6 dB at 90 dB SL to 6.2 dB at 20 dB SL. All of these differences, except at 80 and 90 dB SL, are smaller than the 20-msec to 200-msec differences. Averaged over all presentation levels, the difference between the 50-msec and 500-msec signals is 5.2 dB. For the 20-msec to 200-msec signals the average difference is 6.5 dB and for the 10-msec to 100-msec signals the average difference is 7.3 dB. These average values are reported in Table 4 (page 52) for convenience in comparing them with threshold differences.

For statistical purposes, the loudness balance data were analyzed as a two-factor experiment with each subject assigned to each treatment combination (Winer, 1962). The treatments were reference-signal presentation level and comparison-signal duration while subjects were considered as a random factor. The summary of the Analysis of Variance (AOV) is reported in Appendix C, Table 21. The error term used in the AOV was obtained by pooling the variances from all sources involving interactions with subjects. The results of the AOV indicate that the intensity and the duration of the signals had significant effects on loudness ($P < 0.001$). The duration-by-intensity interaction was not significant ($P > 0.05$). It was anticipated that the signal duration would have a significant effect on the loudness of the signals. That is to say, it was expected that loudness would decrease in a systematic manner as the duration of the signal was decreased at each presentation level. The significant intensity effect was also anticipated because the absolute values of equal loudness were used in the analysis. The non-significant interaction between intensity and duration suggests that the slope of the suprathreshold temporal integration functions did not change as presentation level varied. The results of the AOV also show that the differences among subjects were significant ($p < 0.001$). That is to say, even though the subjects were trained prior to the experimental sessions, they tended to perform differently from one another on the task.

In summary, the results of the statistical analysis show the following:

1) Signal duration has a significant effect on loudness.

2) Signal intensity has a significant effect on loudness.

3) The interaction between intensity and duration was nonsignificant suggesting that reference signal intensity and comparison signal duration interacted in an additive manner. That is to say, the increases in the intensity required for equal loudness as the comparison signal duration was reduced were independent of the reference signal presentation level. This resulted in temporal integration functions with similar slopes at all presentation levels.

4) Considerable intersubject variability was noted. This suggests a wide range of "normal" response to the loudness balance task.

Lines were fit to the mean data points at each presentation level by a least squares method with the mean equal loudness values as the dependent variable and the logarithm of the associated signal duration as the independent variable. These results are summarized in Appendix C, Table 20, and plotted in Figure 8. The absolute slopes of the resulting functions between 500 msec and 10 msec range from 3.8 dB per decade change in signal duration at 90 dB SL to 7.7 dB per decade at 30 dB SL. All of the slopes except for the one at 90 dB SL are equal to or greater than 5.7 dB per decade. The correlation coefficients associated with these slopes are equal to or greater than 0.97.

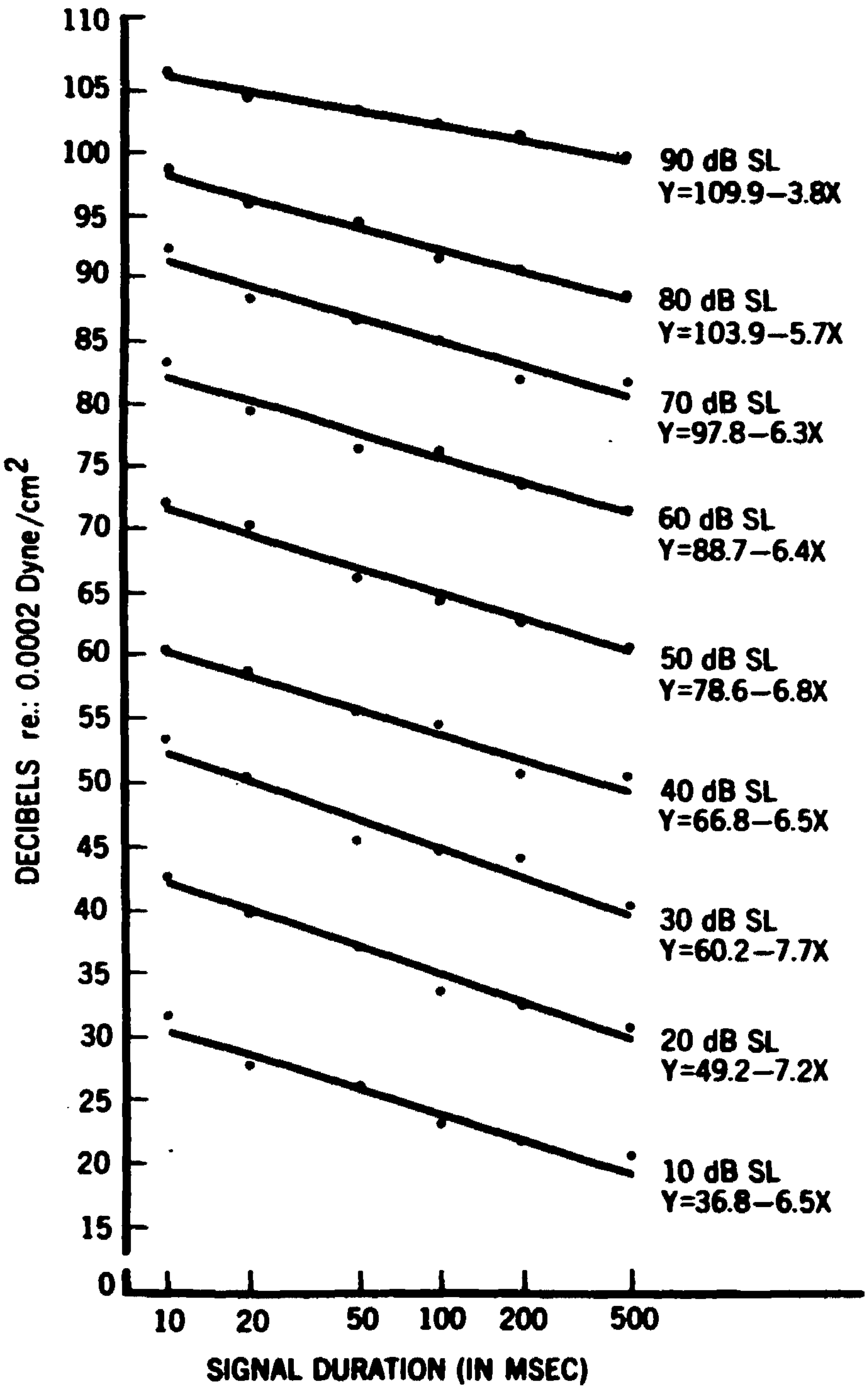

Fig. 8—Mean Points of Equal Loudness as a Function of Comparison Signal Duration and Reference Signal Presentation Level. The Solid Lines Are the Least Squares Fit of the Mean Data Points.

These high correlation coefficients suggest that there is a high degree of association between the mean loudness values and the logarithm of the signal durations. With a correlation coefficient of 0.97 only about six per cent of the variability associated with the mean loudness values is associated with factors other than the duration of the signal. These values suggest that a straight line is a close approximation of the temporal integration function at each presentation level between signal durations of 500 msec and 10 msec. As with the threshold function, had additional data for longer duration signals been gathered, the functions may have consisted of two intersecting lines, thereby yielding a critical duration. In the absence of such data, however, a critical duration cannot be defined.

It is difficult to compare the results of this portion of the experiment with previous investigations of loudness summation because of a lack of consistency in specifying signal durations and because different psychophysical procedures have been employed. It will be remembered that considerable ranges of values have been reported for the slope and critical duration of the suprathreshold temporal integration function (Munson, 1947; Zwislocki and Sokolich, 1972; Berglund and Berglund, 1967). The range of values observed in the current study, however, does appear to be consistent with the reports by Garner (1949) and Bekesy (1960) for similar signal durations although the durations were calculated in a different manner. For example, Garner found an 8.5 dB difference in intensity required for equal loudness between signal durations of 500 msec and 10 msec at 80 dB SPL. In the current study the difference is 9.9 dB under similar conditions. At 60 dB SPL Garner found a

6.0 dB difference between the same signal durations. The difference observed in the current study under similar conditions was 11.5 dB. Bekesy (1960) reported that a 6 dB increase in intensity was required for equal loudness between a comparison signal with a duration of approximately 10 msec and an 80 dB SPL reference signal with a duration of 180 msec. In the current study a difference of 8.0 dB is found between signals of 10 msec and 200 msec duration at a similar presentation level.

Discrepancies are noted between the present findings and those reported by Ekman, Berglund, and Berglund (1966) and Berglund and Berglund (1967) who used a magnitude estimation procedure to obtain their data. These discrepancies may be related to the differences in psychophysical procedures employed as well as differences in the method of specifying signal durations used by these investigators. The present findings are inconsistent with both sets of results reported by Zwislocki and Sokolich (1972).

Comparison of the Threshold and Suprathreshold Temporal Integration Functions

A comparison of the differences in threshold sensitivity between decade changes in signal duration and the average (across all presentation levels) decibel differences required for equal loudness between the same decade changes in signal duration reveals only small differences, as seen in Table 4 (page 52). At threshold the change in sensitivity between signals of 50 msec and 500 msec duration is 5.1 dB. The average intensity difference between signals of these two durations at the suprathreshold levels is 5.2 dB. Only a 0.1 dB difference exists between the threshold and the average suprathreshold values. The threshold difference between signals with durations of 20 msec and 200 msec is 4.9 dB and the average of the suprathreshold values between these two signal durations is 6.5 dB. This shows a 1.6 dB difference between the threshold value and the suprathreshold value. The threshold difference between signals with durations of 10 msec and 100 msec is 7.0 dB while at the suprathreshold levels the average difference is 7.3 dB for signals of the same durations. Only a 0.3 dB difference exists between the threshold value and the average suprathreshold value. Throughout the range of durations from 10 msec to 500 msec, threshold differed by only 10.4 dB. Suprathreshold intensity differences range from 6.8 dB at a reference level of 90 dB SL to 13.2 dB at a reference level of 30 dB SL. The average suprathreshold difference is 10.7 dB which is only 0.3 dB greater than the threshold difference. From these values, it is apparent that the difference between the threshold and the suprathreshold temporal integration functions is minimal.

The absolute slope of the temporal integration function at threshold as determined by a least squares fit of the mean data points is 5.8 dB per decade change in signal duration between 500 msec and 10 msec. The range of absolute slopes for the suprathreshold temporal integration functions between these durations and obtained by the same procedure, is from 3.8 dB to 7.7 dB per decade change in duration.

The critical duration was not observed under either the threshold or the suprathreshold conditions. The temporal integration functions appear to be linear and have similar slopes between 500 msec and 10 msec at all presentation levels explored in this experiment.

Discussion

One of the motivating forces behind the current study was the knowledge that patients with hearing loss of cochlear origin perform differently from the normal population on certain tasks presented at threshold or low sensation levels. However, these same patients perform in a manner similar to normal-hearing subjects when the task is presented at a relatively high hearing level. The return to "normal-loudness" evidenced by complete recruitment on the ABLB test and the comparison of the scores obtained when the SISI is presented at low or moderate hearing levels to that obtained when the same task is presented at a higher hearing level are two examples of this behavior.

It is also documented in the literature that patients with cochlear pathology perform differently from the normal population on threshold temporal integration tasks (Miskolczy-Fodor, 1953, 1960; Harris, Haines, and Meyers, 1958; Elliott, 1963; Northern, 1970; Martin and Wofford, 1960; Gengel and Watson, 1971; Sanders and Honig, 1967; Wright, 1968; Watson and Gengel, 1969). These subjects show temporal integration functions with reduced slopes and critical durations when compared with those exhibited by the normal-hearing population. As was discussed in Chapter II, conflicting and confusing reports are found in the literature concerning the performance of normal-hearing subjects on temporal integration tasks at threshold and suprathreshold levels. There is virtually no information available regarding the performance of subjects with cochlear pathology at suprathreshold levels on similar tasks.

The present study was designed to investigate systematically the temporal integration function at a variety of presentation levels in a group of normal-hearing subjects. It was expected that the suprathreshold temporal integration functions of these normal-hearing listeners would resemble the threshold functions of patients with cochlear hearing loss. A finding of this nature would parallel that noted in SISI test results. Such a finding would imply that the shape of the temporal integration function is related to the level of energy reaching the cochlea provided there is integrity of the VIII nerve and central auditory pathways. It may then be further hypothesized that subjects with cochlear hearing impairments would perform in a manner similar to the normal-hearing population at high suprathreshold levels even though the threshold temporal integration functions obtained by these subjects differ from the normal. It is necessary to establish as accurately as possible how the normal-hearing population functions over a wide range of intensities before investigating the suprathreshold temporal integration function in a pathological population.

A second reason for initiating the study was to test Zwislocki's theories of threshold and suprathreshold temporal integration. As discussed in Chapter II, the empirical evidence, including some of Zwislocki's own findings, is not in agreement with the theory of temporal integration, especially at suprathreshold levels. It will be recalled that the theories propose that the critical duration at threshold is approximately 200 msec and that at moderate suprathreshold levels it becomes 100 msec. This study was designed to determine if changes in the critical duration and slope of the temporal integration functions can be observed as presentation level is increased systematically in 10 dB steps from threshold to 90 dB SL.

It was also hypothesized that activiation of the acoustic reflex at high suprathreshold levels (80 to 90 dB SL) might result in changes in loudness which would be reflected by alterations of the temporal integration functions obtained at these levels. Acoustic stimulation at these high levels is followed by bilateral changes in the acoustic impedance of the middle ear. Numerous investigators (Metz, 1946; Jepsen, 1955; Klockhoff, 1961; Møller, 1962; Djupesland, 1965) have shown that the impedance changes which occur during stimulation with high intensity signals are brought about by the reflex contraction of the stapedius muscle. Reger (1960) and Loeb and Riopelle (1960) concluded from their experiments using a loudness balancing procedure that the action of the acoustic reflex is nonlinear in that attenuation of intense signals is greater than the attenuation of fainter ones. Recently, Djupesland and Zwislocki (1971) have shown that the duration of an acoustic signal has a significant effect on the level at which the reflex is elicited. For example, when the signal is 10 msec in duration, the reflex threshold is raised by approximately 35 dB relative to its normal level of 85 dB SL obtained with a 1000 msec signal. However, when the signal duration is 500 msec, the threshold for the reflex is rasied only about 2.5 dB relative to its normal level.

Pilot data on a small group of subjects suggested that loudness summation at high signal levels may differ from loudness summation at lower levels. Only three presentation levels were investigated (threshold, 10 dB SL, and 80 dB SL) in the preliminary study. The results showed that the threshold and 10 dB SL conditions produced temporal integration functions which were similar to one another. The 80 dB SL condition yielded a somewhat reduced slope which may have been due to the action of the reflex.

In the experimental conditions of the current study, subjects were asked to assess the loudness of a comparison signal which varied in duration from 500 msec (in one session) to 10 msec (in another session) with respect to the loudness of a 500 msec reference signal. Under these conditions, the interaction of the two effects discussed above might be expected to produce a reduction in the slope of the temporal integration function at the higher presentation levels. That is to say, the reference signal is expected to be of sufficient duration to activate the reflex at 80 or 90 dB SL and thereby produce a reduction of its loudness. However, the shorter duration comparison signals fail to reach an intensity level sufficient to activate the reflex until their loudness exceeds that of the reference signal. At a loudness equal to that of the reference signal, the short comparison signals do not elicit a reflex and are, therefore, unaffected by it. The over-all effect then would be that less intensity difference is required to obtain equal loudness between the shorter duration comparison signals and the reference signal thereby producing a reduction in the temporal integration function at the higher presentation levels.

The results of the suprathreshold temporal integration portion of the present experiment are inconsistent with Zwislocki's (1969) theory of loudness summation. Zwislocki suggests that the critical duration for signals presented at moderate and high suprathreshold levels is approximately 100 msec. He makes no comment regarding changes in the slope of the function as signal level is increased. The results of the current study fail to identify a critical duration and therefore can show no change in critical duration with changing presentation level. Decade changes in signal duration resulted in similar dB changes at all of the suprathreshold functions. All of the changes were less than the 10 dB per decade expected by the threshold theory. The decibel changes associated with decade increments in signal duration are in fair agreement with the results of Garner (1949) and Bekesy (1960) for a similar range of signal durations although durations were specified in a different manner.

Straight lines were fit to the data by a least squares method. The slopes of the functions as defined by this procedure range from 3.8 dB per decade change in signal duration to 7.7 dB per decade change in signal duration throughout the range of durations investigated. There is no evidence of a change in the slopes of the functions in either the 100 msec or the 200 msec regions. The slopes of the functions remain approximately the same at all presentation levels.

Comparison of the slope and critical duration of the threshold temporal integration function with those obtained at the suprathreshold levels shows no real differences in either parameter. The present data are fairly consistent with previously reported values for signals with durations between 500 msec and 10 msec.

The results of the current study are not consistent with the theories of threshold and suprathreshold temporal integration proposed by Zwislocki (1960, 1969). At threshold the slope of the function is 5.8 dB per decade change in signal duration. The function appears to be linear throughout the range of signal durations investigated, 500 msec to 10 msec. This is considerably different from the value suggested by the theory. However, the differences between the thresholds for decade changes in signal durations from 500 msec to 10 msec observed in the current study are consistent with those reported by Dallos and Olsen (1964), Olsen and Carhart (1966), Dallos and Johnson (1966), and Wright (1968). In the current study, threshold sensitivity continued to improve substantially as the signal duration was increased to 500 msec. Again, this finding is inconsistent with Zwislocki's theory, but similar findings are reported by Dallos and Johnson (1966) and Olsen and Carhart (1966), as well as by investigators who specify signal duration in a different manner (Watson and Gengel, 1969; Counter and Tobin, 1969).

The results of the present study fail to support the hypothesis that the suprathreshold temporal integration functions are different from that exhibited at threshold in the same sample of the normal-hearing population. It does not appear that the shape of the temporal integration function is dependent upon the level of the signal reaching the cochlea. The reduced slope and critical duration of the temporal integration function exhibited in other studies by patients with cochlear pathology must therefore be explained on the basis of some other factor. The existence of excessive threshold adaptation related to hair cell pathology may account for the reduction in the slope and critical duration of the temporal integration function exhibited by these patients as has been suggested by Wright (1968).

The acoustic reflex appears to have had an effect on the shape of the temporal integration function only at the highest presentation level. This difference, however, is not statistically significant. The fact that a high proportion of the signals presented in this experiment were below the reflex threshold level may have reduced the impact of the supra-reflex data and contributed to the lack of statistical significance associated with the 90 dB SL data. Had additional supra-reflex levels been employed, a greater proportion of the data could have been affected by the activation of the reflex and a significant effect may have occurred. It might be anticipated that a single straight line would not have provided an adequate description of the threshold or suprathreshold temporal integration functions had additional longer signal durations been employed. It might also be projected that expanding the range of signal durations employed would have assisted in the identification of a critical duration in both sets of data. Under these conditions, two intersecting lines or a curvilinear function might better describe the temporal integration functions.

CHAPTER V

SUMMARY AND CONCLUSIONS

Introduction

The literature contains conflicting reports regarding the slope and critical duration of the temporal integration function at threshold and suprathreshold levels in the normal-hearing population. On the basis of several independent investigations, it appears that the threshold temporal integration function differs from the suprathreshold functions in normal-hearing subjects. It remains to be determined in a single sample of normal-hearing subjects, in what manner the slope and critical duration of the temporal integration function are related to the presentation level of the signals.

The current study was designed to investigate systematically threshold and suprathreshold temporal integration in a selected sample of the normal-hearing population. It was hypothesized that the threshold temporal integration function would differ from the suprathreshold functions when the same subjects and similar experimental procedures were used. It was further hypothesized that the transition from the threshold function to the highest suprathreshold function would be a gradual one where a reduction of both the slope and critical duration would occur as the presentation level of the signals was increased.

Summary

A transformed up-and-down psychophysical technique was used to obtain the threshold data and the suprathreshold loudness balance data upon which the temporal integration functions were based. The test frequency for all practice and experimental conditions was 1000 Hz. The rise-decay time for all of the signals was 10 msec. Signals with equivalent durations of 500, 200, 100, 50, 20, and 10 msec were employed for the threshold measurements. In the loudness balance portion of the experiment, the comparison signal was presented as the first member of the signal pair. The durations of the comparison signals were 500, 200, 100, 50, 20, and 10 msec. The 500 msec reference signal followed the comparison signal after a silent interstimulus interval of 500 msec. The reference signal was presented in each session at one of nine suprathreshold levels ranging from 10 to 90 dB SL. Nine normal-hearing adult male subjects comprised the experimental sample.

After completing the practice sessions, the first experimental session for each subject consisted of the determination of the thresholds for the experimental signals. Loudness balance data was collected during the subsequent nine experimental sessions. The order of presentation of the sensation levels for the loudness balance conditions was counterbalanced among subjects. The order of presentation of the signal durations for the threshold and suprathreshold sessions was randomized.

During the threshold portion of the experiment, the subjects were instructed to report "yes" or "no" by means of a response box indicating whether-or-not they detected the presence of a signal in each observation interval. During the suprathreshold portion of the experi-

ment, the subjects were instructed to report whether the comparison signal was "louder" or "softer" than the reference signal. According to the pattern of the subjects' responses, the level of the signal was either increased or decreased by means of a relay logic system and a recording attenuator. Individual mean thresholds and points of equal loudness for each signal duration were calculated by averaging the SPL associated with twelve consecutive reversals of the recording attenuator pen. The group means were then calculated from the individual mean data. A least squares method was used to fit lines to the mean data points at each presentation level as a function of the logarithms to the base ten of the signal durations. The data obtained from the suprathreshold portion of the experiment were subjected to an analysis of variance, factorial design.

Results

The results of the threshold portion of the experiment show thresholds ranging from 5.8 dB for the 500 msec signal to 16.2 dB for the 10 msec signal. A difference in threshold sensitivity of 7.0 dB is observed between signal durations of 10 msec and 100 msec. A 4.8 dB difference in threshold sensitivity was observed between the 20 msec and 200 msec signals, and a 5.0 dB difference was observed between signals with durations of 50 msec and 500 msec. These results are similar to those reported by Dallos and Olsen (1964), Olsen and Carhart (1966), Dallos and Johnson (1966), and Wright (1968) for signals specified in essentially the same manner. The slope of the function as defined by a least squares fit of the mean data points is 5.8 dB per decade change in signal duration throughout the range of durations employed. This is slightly less than that generally reported in the literature and considerably less than that predicted by theory for normal-hearing subjects. The correlation coefficient associated with the line is 0.99. There was no significant deviation from the straight line fit in the area of 200 msec, the expected critical duration.

The results of the suprathreshold portion of the experiment reveal decibel changes required for equal loudness between decade increments of signal duration which are very similar to those obtained at threshold. These results are also in fair agreement with those reported by Garner (1949) and Bekesy (1960) although the signal durations were specified in a different manner. The current findings are inconsistent with the results obtained from the magnitude estimation studies (Ekman, Berglund, and Berglund, 1966; Berglund and Berglund, 1967). The inconsistencies may result from procedural differences and methods of specifying signal duration. The current findings are also inconsistent with the results reported by Zwislocki and Sokolich (1972).

Lines were fit to the suprathreshold data obtained at each presentation level by a least squares method. The average slopes of the temporal integration functions range from 3.8 dB per decade at 90 dB SL to 7.7 dB per decade at 30 dB SL. All of the slopes except the one associated with the 90 dB SL condition are equal to or greater than 5.7 dB per decade throughout the range of signal durations employed. The correlation coefficients associated with the slopes are equal to or greater than 0.97. High correlation coefficients such as these suggest that a straight line provides an adequate description of the data obtained at each level in the suprathreshold portion of the experiment.

No significant deviations from the straight line fits were noted in either the area of 100 msec, the critical duration predicted by Zwislocki's theory of loudness summation, or 200 msec the critical duration generally associated with the threshold temporal integration function in normals.

The results of the statistical analysis of the suprathreshold temporal integration portion of the experiment reveal that the duration of the comparison signal and the presentation level of the reference signal had significant effects on loudness. However, the interaction between the intensity and duration factors was non-significant suggesting that the effect of signal duration was similar at all reference signal presentation levels. This resulted in temporal integration functions with similar slopes. The slope of the 90 dB SL condition, while smaller than the others, is not statistically different from them.

Throughout the range of signal durations from 500 msec to 10 msec, threshold sensitivity differed by only 10.4 dB (500 msec = 5.8 dB; 10 msec = 16.2). Suprathreshold intensity differences ranged from 6.8 dB at a reference signal presentation level of 90 dB SL to 13.2 dB at a reference signal presentation level of 30 dB SL. The average suprathreshold difference between these signal durations is 10.7 dB which is only 0.3 dB greater than the threshold difference.

The average slope of the temporal integration function obtained at threshold is 5.8 dB per decade throughout the range of signal durations employed. The range of the average slopes for the suprathreshold functions is from 3.8 dB per decade to 7.7 dB per decade. From these values, there does not appear to be a significant difference between the slopes of the threshold and suprathreshold temporal integration functions. Further, it does not appear that the critical duration of these functions was observed under either the threshold or suprathreshold conditions. The temporal integration functions are demonstrated to approximate linearity between signal durations of 500 msec and 10 msec at all presentation levels.

Conclusions

The results of the threshold portion of this experiment are similar to the findings reported by other investigators who define signal duration in essentially the same manner. The average slope of the function as defined by a least squares fit of the mean data points, 5.8 dB per decade, is slightly smaller than generally reported in the literature and considerably smaller than predicted by theory for normal-hearing subjects. A single straight line does, however, appear to be an adequate description of these data. Straight lines also appear to be adequate descriptions of the suprathreshold data obtained in this experiment. The statistical analysis of the suprathreshold functions indicates that they do not differ significantly from one another. Comparing the suprathreshold data with the threshold data suggests that temporal integration is similar at all of the levels studied and that the slope of the temporal integration function does not change significantly as presentation level is increased. No critical duration was observed for any of the temporal integration functions obtained in the current investigation.

The results of this study are inconsistent with Zwislocki's theories of threshold and suprathreshold temporal integration. The slope of the threshold and suprathreshold temporal integration functions is less than the 10 dB per decade change in signal duration predicted by Zwislocki. At threshold, Zwislocki suggests that the critical duration is 200 msec and at moderate and high suprathreshold levels it is reduced to 100 msec. Because the temporal integration functions obtained in the current experiment have been shown to approximate linearity throughout the range of signal durations investigated, no change in the critical duration was observed as a function of increasing the presentation level of the signals.

It was hypothesized that the shape of the temporal integration function was related to the level of energy reaching the cochlea. The results of the investigation do not support this hypothesis because the slopes of the temporal integration functions were similar at all intensity levels investigated from threshold to 90 dB SL. Therefore, the clinical results of brief tone audiometry on patients with cochlear hearing impairments probably result from some other factor, such as the pathological condition present. Wright (1968) suggests that excessive peripheral adaptation related to hair cell pathology is responsible for the failure of these subjects to exhibit normal threshold temporal integration functions. It will be remembered that Zwislocki's (1960) theory of threshold temporal integration assumes that adaptation is absent or negligible at threshold. However, if adaptation is present at threshold, the normal relation between signal duration and auditory sensitivity would be altered. According to Wright, the neural output of the cochlea would be decreased with time under these conditions and there would be fewer neural events to be summated over time at a higher level of the auditory system. Therefore, adaptation at the level of the cochlea and not an abnormality in the physiological summation process at a higher level of the auditory system is suggested as being responsible for the reduction in the slope and critical duration exhibited by patients with cochlear pathology.

Although the slope of the temporal integration function at 90 dB SL is smaller than the other suprathreshold functions, it is not statistically different from them. Because the results at 90 dB SL in this experiment do not differ significantly from the results at the lower presentation levels, it appears that the activation of the middle ear muscle reflex had little or no effect on the shape of the suprathreshold temporal integration functions. However, the lack of such a finding may be due to the fact that only one or perhaps two of the nine levels employed were sufficiently intense to elicit the reflex, thereby reducing the impact of the supra-reflex data on the over-all analysis. If the range of reference signal presentation levels had included several conditions above the reflex threshold, as well as several below it, alterations in the suprathreshold temporal integration functions might have been more evident.

It may also be projected that the inclusion of additional longer signal durations would have aided in the identification of the critical durations. It may also have shown a single straight line to be an inadequate description of the temporal integration functions at all presentation levels. An alternative description of the data under these conditions might then have been two intersecting lines. One with a slope similar to those obtained in the current investigation and one parallel to the abscissa. Another possibility is a curvilinear fit of the data. Both of these alternatives would require additional longer signal durations for definition of the functions.

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APPENDIX A

Order of Signal Presentations

TABLE 7

ORDER OF PRESENTATION OF COMPARISON SIGNAL DURATION AND REFERENCE SIGNAL PRESENTATION LEVEL CONDITIONS FOR EACH SUBJECT DURING THE PRACTICE SESSIONS

Subject Number	Presentation Level	Equivalent Duration					
1	Threshold	50	500	100	10	200	20
	90 dB SL	500	20	100	50	200	10
	50 dB SL	200	500	100	20	10	50
	10 dB SL	50	200	10	500	20	100
2	Threshold	500	20	100	200	50	10
	90 dB SL	10	500	50	20	200	100
	50 dB SL	50	200	10	20	500	100
	10 dB SL	200	20	10	100	50	500
3	Threshold	50	20	500	10	200	100
	90 dB SL	100	200	20	500	10	50
	50 dB SL	10	100	500	200	20	50
	10 dB SL	500	20	200	50	100	10
4	Threshold	10	50	500	100	20	200
	90 dB SL	20	50	10	500	100	200
	50 dB SL	50	20	200	100	500	10
	10 dB SL	200	500	50	10	20	100
5	Threshold	500	100	50	200	10	20
	90 dB SL	20	10	200	100	50	500
	50 dB SL	50	20	10	500	100	200
	10 dB SL	200	10	50	20	500	100
6	Threshold	50	100	10	200	20	500
	90 dB SL	100	200	50	10	500	20
	50 dB SL	10	500	20	100	50	200
	10 dB SL	20	500	10	50	200	100
7	Threshold	200	50	100	500	20	10
	90 dB SL	500	100	10	50	200	20
	50 dB SL	20	100	200	10	50	500
	10 dB SL	10	50	100	500	20	200
8	Threshold	500	10	20	50	200	100
	90 dB SL	20	500	50	10	100	200
	50 dB SL	10	200	100	500	50	20
	10 dB SL	10	500	200	50	20	100
9	Threshold	100	200	10	500	20	50
	90 dB SL	200	50	100	20	10	500
	50 dB SL	20	200	500	10	100	50
	10 dB SL	50	100	10	20	200	500

TABLE 8

ORDER OF PRESENTATION OF COMPARISON SIGNAL DURATION AND REFERENCE SIGNAL PRESENTATION LEVEL CONDITIONS FOR EACH SUBJECT DURING THE EXPERIMENTAL SESSIONS

Subject Number	Presentation Level	Equivalent Duration					
1	Threshold	500	20	100	50	200	10
	10 dB SL	20	10	200	50	100	500
	20	50	20	500	100	10	200
	30	10	50	200	20	100	500
	70	20	100	50	10	500	200
	90	10	200	500	50	100	20
	80	100	20	10	200	500	50
	40	200	10	500	100	50	20
	60	10	100	50	20	500	200
	50	20	50	200	10	500	100
2	Threshold	50	500	200	100	20	10
	40	10	100	200	50	500	20
	60	100	200	500	50	20	10
	50	50	20	200	100	500	10
	10	200	100	500	10	20	50
	20	500	20	200	50	10	100
	30	20	50	10	100	500	200
	70	500	100	20	50	10	200
	90	200	20	50	100	10	500
	80	10	100	200	500	50	20
3	Threshold	500	50	20	200	100	10
	70	200	50	10	500	100	20
	90	500	10	50	100	200	20
	80	50	100	500	10	20	200
	40	10	20	200	500	100	50
	60	50	10	100	500	200	20
	50	50	200	500	100	10	20
	10	500	200	20	10	50	100
	20	200	500	20	50	100	10
	30	10	20	200	50	500	10
4	Threshold	200	500	100	50	20	10
	20	20	100	200	10	50	500
	30	500	10	200	100	20	50
	10	500	100	20	50	10	200
	80	50	20	500	200	10	100
	70	10	100	500	50	200	20
	90	200	100	20	50	500	10
	50	500	50	10	200	20	100
	40	20	500	50	200	100	10
	60	500	50	200	20	10	100

TABLE 8—Continued

Subject Number	Presentation Level	Equivalent Duration					
5	Threshold	500	100	50	200	20	10
	50	100	10	200	500	20	50
	40	200	10	100	500	50	20
	60	10	500	20	100	50	200
	20	200	100	20	50	10	500
	30	50	200	10	500	100	20
	10	200	20	50	500	100	10
	80	100	500	200	10	50	20
	70	500	20	50	200	100	10
	90	10	500	100	200	50	20
6	Threshold	200	100	50	500	10	20
	80	200	500	20	100	10	50
	70	200	10	50	20	500	100
	90	20	500	10	50	100	200
	50	10	100	200	500	50	20
	40	500	200	10	50	20	100
	60	50	100	10	500	20	200
	20	10	500	100	200	50	20
	30	100	50	20	10	200	500
	10	100	10	500	20	200	50
7	Threshold	50	20	100	10	200	500
	30	100	500	10	200	50	20
	10	10	50	500	20	200	100
	20	50	500	10	200	100	20
	90	200	10	500	100	50	20
	80	20	50	200	500	100	10
	70	200	10	100	500	20	50
	60	200	50	10	100	500	20
	50	10	500	50	200	20	100
	40	10	50	100	20	200	500
8	Threshold	500	50	10	20	100	200
	90	20	100	500	10	200	50
	80	100	10	200	50	20	500
	70	200	100	10	50	500	20
	60	20	500	100	50	200	10
	50	50	10	50	200	20	100
	40	200	10	500	50	100	20
	30	500	50	200	10	100	20
	10	500	50	20	100	10	200
	20	100	200	500	50	10	20

TABLE 8—Continued

Subject Number	Presentation Level						
9	Threshold	100	50	10	500	200	20
	60	200	50	100	20	10	50
	50	50	100	500	20	200	10
	40	500	100	50	20	10	200
	30	200	20	10	100	500	50
	10	500	100	10	200	50	20
	20	10	500	200	20	50	100
	90	200	500	10	50	100	20
	80	500	200	10	20	50	100
	70	20	500	200	50	100	10

APPENDIX B

Individual Subject Data

TABLE 9

MEAN THRESHOLDS AND STANDARD DEVIATIONS FOR EACH SUBJECT FOR SIGNAL DURATIONS RANGING FROM 500 MSEC TO 10 MSEC. THRESHOLDS ARE EXPRESSED IN dB SPL AND STANDARD DEVIATIONS ARE EXPRESSED IN dB

	Signal Durations											
Subject	500		200		100		50		20		10	
Number	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
1	1.9	1.3	6.2	1.5	6.1	1.2	9.0	1.2	11.4	1.3	15.2	1.6
2	15.3	1.9	17.1	1.2	17.8	1.6	19.8	1.4	22.6	1.4	26.3	1.5
3	13.2	0.8	14.3	1.3	16.1	1.1	17.3	0.9	18.6	0.8	20.7	1.1
4	-1.7	1.4	1.3	0.8	4.3	1.5	4.8	0.9	7.9	1.6	9.7	1.3
5	14.6	1.2	15.5	1.4	16.3	1.2	17.0	0.9	18.8	1.1	21.7	1.5
6	7.2	1.5	8.3	1.4	10.5	1.9	11.2	1.9	14.4	1.6	16.9	1.1
7	0.5	1.6	2.0	1.1	3.6	0.9	5.3	1.3	8.2	0.9	10.5	1.3
8	1.4	1.9	5.3	1.4	5.9	2.7	7.8	1.6	6.5	2.2	15.9	2.1
9	-0.1	1.3	2.1	0.9	1.8	1.7	5.6	1.4	6.6	1.4	8.9	0.9

TABLE 10

MEANS AND STANDARD DEVIATIONS OF THE SOUND PRESSURE LEVELS OF THE COMPARISON SIGNALS WITH DURATIONS RANGING FROM 500 MSEC TO 10 MSEC WHICH ARE EQUAL IN LOUDNESS TO THE 500 MSEC REFERENCE SIGNALS WITH PRESENTATION LEVELS RANGING FROM 10 dB SL TO 90 dB SL. MEAN VALUES ARE EXPRESSED IN dB SPL AND STANDARD DEVIATIONS ARE EXPRESSED IN dB. DATA ARE PRESENTED FOR SUBJECT #1

Presentation Level (in dB SL)	Signal Duration (in msec)											
	500		200		100		50		20		10	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
10	12.7	0.8	15.8	1.1	17.2	1.4	18.5	1.4	20.5	1.5	29.0	2.3
20	28.8	1.9	34.6	1.5	33.9	1.5	42.2	1.2	43.0	2.0	51.7	1.7
30	40.0	1.4	46.3	1.1	46.6	1.2	44.7	0.8	52.6	1.2	61.3	2.3
40	49.6	1.1	47.2	1.5	52.3	1.5	58.1	1.1	63.8	1.2	65.0	1.4
50	59.2	1.7	61.1	0.9	58.0	1.5	65.8	1.1	67.4	0.8	72.0	1.9
60	70.3	1.2	74.3	1.3	74.5	0.8	80.2	1.3	78.8	1.6	83.0	1.6
70	77.8	0.9	79.9	0.8	81.4	1.1	83.4	1.0	84.6	1.3	90.8	1.3
80	87.2	0.9	89.9	0.6	90.1	1.0	96.6	1.3	98.3	1.2	97.8	1.7
90	96.7	1.1	98.8	1.3	99.7	0.7	99.7	1.4	104.0	1.2	103.7	1.2

TABLE 11

MEANS AND STANDARD DEVIATIONS OF THE SOUND PRESSURE LEVELS OF THE COMPARISON SIGNALS WITH DURATIONS RANGING FROM 500 MSEC TO 10 MSEC WHICH ARE EQUAL IN LOUDNESS TO THE 500 MSEC REFERENCE SIGNALS WITH PRESENTATION LEVELS RANGING FROM 10 dB SL TO 90 dB SL. MEAN VALUES ARE EXPRESSED IN dB SPL AND STANDARD DEVIATIONS ARE EXPRESSED IN dB. DATA ARE PRESENTED FOR SUBJECT #2

Presentation Level (in dB SL)	Signal Duration (in msec) 500 M	500 SD	200 M	200 SD	100 M	100 SD	50 M	50 SD	20 M	20 SD	10 M	10 SD
10	29.8	1.2	30.7	1.6	30.3	1.4	32.1	1.6	33.5	2.1	40.0	1.8
20	39.8	0.8	39.8	1.1	41.0	1.1	41.7	1.8	42.8	1.3	49.2	1.7
30	46.7	1.0	47.8	1.0	49.2	1.1	48.9	1.1	51.1	1.1	55.2	1.8
40	54.6	1.2	56.3	1.2	56.3	2.0	56.9	1.6	57.4	1.5	60.9	1.4
50	68.8	1.3	69.3	1.3	70.5	1.3	70.3	1.1	73.1	1.3	74.3	2.1
60	78.0	0.8	78.1	1.1	79.5	1.3	80.9	1.3	82.7	1.3	87.7	1.8
70	84.2	0.9	85.1	0.9	85.9	1.4	87.6	0.8	89.3	1.1	94.1	1.9
80	91.8	0.9	93.7	1.3	95.5	1.2	95.4	1.1	98.3	1.4	102.7	1.4
90	103.6	0.8	104.8	1.1	106.7	0.9	107.6	0.9	109.0	0.8	113.0	1.5

TABLE 12

MEANS AND STANDARD DEVIATIONS OF THE SOUND PRESSURE LEVELS OF THE COMPARISON SIGNALS WITH DURATIONS RANGING FROM 500 MSEC TO 10 MSEC WHICH ARE EQUAL IN LOUDNESS TO THE 500 MSEC REFERENCE SIGNALS WITH PRESENTATION LEVELS RANGING FROM 10 dB SL TO 90 dB SL. MEAN VALUES ARE EXPRESSED IN dB SPL AND STANDARD DEVIATIONS ARE EXPRESSED IN dB. DATA ARE PRESENTED FOR SUBJECT #3

Presentation Level (in dB SL)	Signal Duration (in msec) 500		200		100		50		20		10	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
10	26.8	0.9	26.3	1.3	30.8	0.9	32.9	0.8	29.2	1.5	34.9	1.4
20	39.3	0.8	38.6	0.6	42.3	1.2	44.8	1.1	45.4	0.8	51.9	0.8
30	51.3	1.3	52.2	1.7	56.1	1.7	57.8	0.8	56.5	2.1	59.9	2.3
40	60.1	0.7	60.5	1.5	64.8	0.7	66.8	0.8	66.8	1.1	71.4	2.1
50	68.1	0.9	69.2	1.0	73.6	1.3	75.3	1.3	83.5	2.0	80.3	1.2
60	81.3	0.9	85.3	0.9	85.8	0.8	81.3	1.3	91.7	0.6	88.9	0.9
70	90.3	0.9	86.4	1.6	91.8	1.1	91.8	0.7	97.3	0.6	98.9	0.9
80	95.6	0.9	97.4	0.6	98.5	0.6	102.8	0.7	101.6	0.6	101.1	0.0
90	106.8	0.8	109.2	0.8	107.0	0.8	106.8	0.9	110.8	0.7	111.0	1.3

TABLE 13

MEANS AND STANDARD DEVIATIONS OF THE SOUND PRESSURE LEVELS OF THE COMPARISON SIGNALS WITH DURATIONS RANGING FROM 500 MSEC TO 10 MSEC WHICH ARE EQUAL IN LOUDNESS TO THE 500 MSEC REFERENCE SIGNALS WITH PRESENTATION LEVELS RANGING FROM 10 dB SL TO 90 dB SL. MEAN VALUES ARE EXPRESSED IN dB SPL AND STANDARD DEVIATIONS ARE EXPRESSED IN dB. DATA ARE PRESENTED FOR SUBJECT #4

Presentation Level (in dB SL)	Signal Duration (in msec) 500		200		100		50		20		10	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
10	17.0	1.9	18.7	1.1	23.7	2.4	23.8	1.4	28.8	1.9	26.6	1.7
20	25.7	1.6	28.2	1.2	26.4	1.8	38.4	1.2	40.7	0.8	44.9	1.3
30	34.1	1.9	38.8	0.9	41.7	1.6	42.1	1.6	58.0	1.3	56.8	2.6
40	41.8	0.8	42.3	1.5	49.7	1.9	50.3	1.0	56.6	0.6	54.8	1.2
50	53.0	1.0	57.3	1.6	61.5	1.3	63.3	1.3	68.6	1.3	69.0	1.2
60	62.3	0.8	63.0	1.0	65.7	0.8	71.5	1.0	71.0	1.0	73.2	1.4
70	76.3	1.0	77.3	1.8	82.1	1.1	83.1	2.1	83.7	0.7	86.5	1.3
80	83.7	0.8	86.7	1.3	88.2	1.0	90.1	1.4	93.6	1.6	95.2	1.5
90	94.7	0.8	96.1	0.9	98.1	1.1	99.3	1.3	100.6	1.5	104.5	0.9

TABLE 14

MEANS AND STANDARD DEVIATIONS OF THE SOUND PRESSURE LEVELS OF THE COMPARISON SIGNALS WITH DURATIONS RANGING FROM 500 MSEC TO 10 MSEC WHICH ARE EQUAL IN LOUDNESS TO THE 500 MSEC REFERENCE SIGNALS WITH PRESENTATION LEVELS RANGING FROM 10 dB SL TO 90 dB SL. MEAN VALUES ARE EXPRESSED IN dB SPL AND STANDARD DEVIATIONS ARE EXPRESSED IN dB. DATA ARE PRESENTED FOR SUBJECT #5

Presentation Level (in dB SL)	Signal Duration (in msec) 500 M	SD	200 M	SD	100 M	SD	50 M	SD	20 M	SD	10 M	SD
10	29.5	1.1	27.1	1.1	30.4	0.8	35.9	2.1	31.2	1.2	35.3	1.4
20	37.8	0.9	35.9	1.3	37.3	1.4	42.2	0.9	40.9	1.3	44.6	0.8
30	49.5	1.5	52.3	1.1	51.0	1.8	53.2	1.3	57.0	1.4	59.9	1.6
40	47.3	1.4	47.1	1.8	52.5	1.9	52.4	1.8	56.3	1.7	60.6	1.4
50	68.2	1.2	68.1	1.5	71.3	1.7	71.3	1.6	74.1	1.6	77.3	2.5
60	77.6	0.6	79.6	1.1	84.3	2.2	82.7	1.2	85.3	1.6	87.6	1.6
70	88.0	1.5	89.9	1.3	92.2	1.7	92.4	1.1	95.4	1.3	97.6	1.1
80	96.5	1.0	97.3	0.9	99.3	1.3	100.7	0.7	103.4	1.3	104.4	1.5
90	105.8	0.9	106.1	0.7	107.3	0.9	108.9	1.1	106.7	1.3	112.2	1.3

TABLE 15

MEANS AND STANDARD DEVIATIONS OF THE SOUND PRESSURE LEVELS OF THE COMPARISON SIGNALS WITH DURATIONS RANGING FROM 500 MSEC TO 10 MSEC WHICH ARE EQUAL IN LOUDNESS TO THE 500 MSEC REFERENCE SIGNALS WITH PRESENTATION LEVELS RANGING FROM 10 dB SL TO 90 dB SL. MEAN VALUES ARE EXPRESSED IN dB SPL AND STANDARD DEVIATIONS ARE EXPRESSED IN dB. DATA ARE PRESENTED FOR SUBJECT #6

Presentation Level (in dB SL)	Signal Duration (in msec) 500		200		100		50		20		10	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
10	19.7	1.5	25.1	1.5	24.4	1.2	31.2	1.1	33.0	1.9	39.4	1.3
20	28.8	1.2	30.6	1.9	33.2	1.6	32.4	1.1	36.4	2.2	36.3	1.3
30	29.3	0.9	32.6	1.2	36.1	1.0	40.2	1.8	41.1	0.9	40.9	1.8
40	55.4	1.7	56.2	1.1	61.3	1.5	59.6	1.2	59.9	1.8	68.0	1.4
50	60.0	0.8	65.5	1.6	69.3	1.2	66.0	1.3	70.1	1.3	74.0	0.8
60	72.4	0.9	74.3	1.5	79.8	0.9	77.5	1.4	81.1	1.2	87.3	1.9
70	84.1	1.3	84.4	1.6	87.6	1.1	89.3	1.3	87.8	1.2	91.8	1.2
80	92.1	1.1	93.7	0.9	96.9	1.0	93.5	1.0	96.8	0.9	100.9	2.1
90	100.3	0.9	101.3	0.8	104.1	1.3	106.4	0.9	107.6	0.9	111.4	1.5

TABLE 16

MEANS AND STANDARD DEVIATIONS OF THE SOUND PRESSURE LEVELS OF THE COMPARISON SIGNALS WITH DURATIONS RANGING FROM 500 MSEC TO 10 MSEC WHICH ARE EQUAL IN LOUDNESS TO THE 500 MSEC REFERENCE SIGNALS WITH PRESENTATION LEVELS RANGING FROM 10 dB SL TO 90 dB SL. MEAN VALUES ARE EXPRESSED IN dB SPL AND STANDARD DEVIATIONS ARE EXPRESSED IN dB. DATA ARE PRESENTED FOR SUBJECT #7

Presentation Level (in dB SL)	Signal Duration (in msec) 500		200		100		50		20		10	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
10	12.1	1.7	11.0	1.9	11.8	0.9	12.5	1.1	16.0	1.1	21.5	2.0
20	20.9	1.5	20.5	1.4	22.3	1.9	23.0	1.3	27.1	0.6	27.8	1.6
30	31.0	1.2	31.5	1.6	35.0	1.6	36.2	1.1	35.8	2.1	38.8	0.6
40	41.2	1.4	44.4	1.1	40.7	0.9	43.7	1.4	44.7	1.1	45.3	1.1
50	51.4	0.9	50.8	0.9	50.1	1.6	50.3	1.0	52.3	1.2	53.3	1.7
60	62.0	1.7	61.8	0.8	61.3	1.2	64.3	0.9	71.5	1.0	74.9	0.8
70	71.5	1.2	72.1	1.1	75.9	1.1	77.3	0.9	78.3	1.3	89.7	1.5
80	81.7	0.7	82.3	1.2	83.4	0.8	82.9	0.8	87.1	1.2	88.8	0.9
90	91.0	0.8	92.3	0.9	92.6	0.8	84.5	1.0	94.6	1.1	97.0	1.7

TABLE 17

MEANS AND STANDARD DEVIATIONS OF THE SOUND PRESSURE LEVELS OF THE COMPARISON SIGNALS WITH DURATIONS RANGING FROM 500 MSEC TO 10 MSEC WHICH ARE EQUAL IN LOUDNESS TO THE 500 MSEC REFERENCE SIGNALS WITH PRESENTATION LEVELS RANGING FROM 10 dB SL TO 90 dB SL. MEAN VALUES ARE EXPRESSED IN dB SPL AND STANDARD DEVIATIONS ARE EXPRESSED IN dB. DATA ARE PRESENTED FOR SUBJECT #8

Presentation Level (in dB SL)	Signal Duration (in msec) 500		200		100		50		20		10	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
10	17.3	1.2	18.8	0.9	20.0	1.0	19.6	1.3	20.0	1.7	24.5	0.9
20	30.6	1.4	31.1	2.4	31.6	1.8	32.0	2.0	38.8	1.2	39.8	1.4
30	43.8	1.6	45.3	0.9	46.6	1.8	46.4	1.3	49.5	1.8	49.8	1.6
40	52.8	1.5	53 1	1.1	56.1	1.0	57.7	0.8	64.3	1.3	62.6	2.1
50	59.7	1.9	62.4	0.9	61.8	2.4	65.9	1.2	66.3	1.2	68.1	1.1
60	70.0	1.5	72.7	1.3	73.7	1.2	75.3	1.2	76.1	1.1	74.3	1.2
70	83.5	1.0	85.3	1.5	84.9	1.5	87.4	1.5	87.8	1.3	91.8	2.1
80	82.8	1.4	87.0	1.2	84.5	1.5	91.0	1.1	91.0	1.3	96.0	0.8
90	103.8	0.9	105.4	1.2	105.8	1.1	106.0	1.2	108.5	0.8	108.2	1.5

TABLE 18

MEANS AND STANDARD DEVIATIONS OF THE SOUND PRESSURE LEVELS OF THE COMPARISON SIGNALS WITH DURATIONS RANGING FROM 500 MSEC TO 10 MSEC WHICH ARE EQUAL IN LOUDNESS TO THE 500 MSEC REFERENCE SIGNALS WITH PRESENTATION LEVELS RANGING FROM 10 dB SL TO 90 dB SL. MEAN VALUES ARE EXPRESSED IN dB SPL AND STANDARD DEVIATIONS ARE EXPRESSED IN dB. DATA ARE PRESENTED FOR SUBJECT #9

Presentation Level (in dB SL)	Signal Duration (in msec) 500		200		100		50		20		10	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
10	17.6	1.5	19.6	1.0	18.3	0.9	27.8	1.7	33.8	1.9	37.3	2.5
20	26.3	0.6	30.6	1.3	37.2	1.5	36.8	1.5	42.6	1.2	38.3	1.1
30	36.1	0.9	38.1	1.4	37.1	1.0	40.7	2.1	51.8	1.2	58.1	1.9
40	49.3	1.2	49.3	1.1	55.7	1.2	52.7	1.2	58.3	1.1	54.9	1.2
50	59.4	0.8	61.8	1.3	65.3	2.2	68.4	1.1	76.3	1.3	79.1	2.3
60	71.8	0.8	75.4	2.4	82.5	1.4	74.8	1.0	80.4	2.1	91.7	2.0
70	80.3	0.9	78.0	1.1	84.3	0.9	90.5	1.4	94.6	1.1	91.0	1.3
80	88.8	0.9	88.9	0.9	91.1	1.0	98.7	1.2	94.1	1.2	102.2	2.1
90	95.5	0.9	96.8	0.9	98.8	0.7	100.9	0.8	99.4	0.9	104.2	1.8

APPENDIX C

Statistical Analyses

TABLE 19

SUMMARY TABLE OF THE REGRESSION ANALYSIS OF THE MEAN THRESHOLD DATA. THE EQUATION AND THE CORRELATION COEFFICIENT ASSOCIATED WITH THE RESULTING LINE ARE ALSO INDICATED

Source	df	SS	MS	F
Beta	1	66.19	66.19	149.59 *
Residual	4	1.77	0.44	
$Y = 21.1 - 5.8X$			$r = 0.99$	

* Significant at the 0.001 level of confidence.

TABLE 20

SUMMARY TABLE OF THE REGRESSION ANALYSIS OF THE MEAN LOUDNESS BALANCE DATA. THE EQUATIONS AND THE CORRELATION COEFFICIENTS ASSOCIATED WITH THE RESULTING LINES ARE ALSO INDICATED

	Source	df	SS	MS	F
10 dB SL	Beta	1	83.52	83.52	71.75 *
	Residual	4	4.66	1.16	
	Y = 36.8 - 6.5X			r = 0.97	
20 dB SL	Beta	1	102.61	102.61	111.91 *
	Residual	4	3.67	0.92	
	Y = 49.2 - 2.2X			r = 0.98	
30 dB SL	Beta	1	116.60	116.60	116.60 *
	Residual	4	4.01	1.00	
	Y = 60.2 - 7.7X			r = 0.98	
40 dB SL	Beta	1	83.76	83.76	91.13 *
	Residual	4	3.68	0.92	
	Y = 66.8 - 6.5X			r = 0.98	
50 dB SL	Beta	1	91.92	91.92	193.94 *
	Residual	4	1.89	0.47	
	Y = 78.6 - 6.8X			r = 0.99	
60 dB SL	Beta	1	82.15	82.15	105.29 *
	Residual	4	3.12	0.78	
	Y = 88.7 - 6.4X			r = 0.98	
70 dB SL	Beta	1	79.52	79.52	74.09 *
	Residual	4	4.29	1.07	
	Y = 97.8 - 6.3X			r = 0.97	
80 dB SL	Beta	1	65.33	65.33	211.88 *
	Residual	4	1.23	0.31	
	Y = 103.9 - 5.7X			r = 0.99	
90 dB SL	Beta	1	29.03	29.03	277.69 *
	Residual	4	0.42	0.10	
	Y = 109.9 - 3.8			r = 0.99	

* Significant at the 0.001 level of confidence.

TABLE 21

SUMMARY TABLE OF THE TWO-WAY ANALYSIS OF VARIANCE, FACTORIAL DESIGN PERFORMED ON THE LOUDNESS BALANCE DATA

Source	df	SS	MS	F
Subjects	9	13056.63	1632.07	126.62*
Duration	5	6676.50	1335.30	103.59*
Intensity	8	310304.50	38788.06	3009.22*
D X I	40	264.42	6.61	< 1.00
Residual (Pooled interactions with subjects)	424	5465.22	12.88	

* Significant at the 0.001 level of confidence.