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THE MEASUREMENT OF PERSTIMULATORY LOUDNESS ADAPTATION

CHAPTER I

INTRODUCTION

As with all sensory systems, stimulation of the auditory system results in changes in subject responsiveness which may be noted both during and following sensory stimulation. As early as 1881, Urbantschitsch (99) observed that auditory stimulation results in a reduced sensitivity to subsequent stimuli. Flügel (28), in 1920, noted that localization of a binaurally presented stimulus is altered by the previous exposure of one ear to stimulation. In 1927, Pattie (71) noted that the loudness of a tone was decreased as a result of previous exposure to that tone. Bekesy (4), in 1929, and Wood (108), in 1930, both observed that the loudness of a tone decreases during stimulation.

Since these early investigations, the effects of stimulation have been studied widely with a great proliferation of terminology. Many of these will be discussed in Chapter II.

Of particular interest to this investigation is loudness adaptation. Loudness is defined by Hirsh (43, p. 338) as "the intensive attribute of an auditory sensation in terms of which sounds may be ordered on a scale from soft to loud." Loudness adaptation is a decrease in the apparent magnitude of the auditory sensation which occurs as a result of stimulation of the ear. Loudness adaptation may be observed during stimulation as a decrease in the loudness of the adapting stimulus (perstimulatory), or at some time following the cessation of the adapting tone (poststimulatory).

The measurement of loudness adaptation has presented many problems to experimenters. It is difficult to evaluate the loudness change directly at specific points in time. Therefore, it has been found necessary to compare the loudness in the adapted (test) ear with that in the opposite unadapted (control) ear. Loudness change in the adapted ear is defined as the number of decibels the sound must be increased in the adapted ear or decreased in the unadapted ear in order to achieve an equal loudness balance.

A number of variations in this basic technique have been used by various investigators. In 1950, Hood (46) described a technique known as the simultaneous dichotic loudness balance. In this method, tones of identical frequency and phase are presented to the two ears and the intensity of the tone at the control ear is adjusted to provide a loudness equal to that in the ear to be adapted. The test ear is then exposed to the adapting stimulus. At selected intervals during and after stimulation the balance is repeated and the change in the intensity of the comparison tone necessary to re-establish equality is noted.

A basic difficulty associated with simultaneous balancing is that signals of identical phase and frequency each presented simultaneously at the two ears appear to the subject to fuse into a single "phantom" image usually located within the head. With the proper intensity relation at the two ears the image will appear to be located at the center of the head. Thus, equality at the two ears may be judged on the basis of the location of the phantom image rather than the relative loudness of the tones at the two ears. Egan (22) questioned whether loudness adaptation can be measured by a procedure which gives the subject localization cues. In order to investigate this question Egan compared the results obtained when the tones in the test and control ears are identical in frequency with results obtained when the tones at the two ears differ in frequency. In the latter procedure, the difference in frequency prevents fusion of the two stimuli and, thereby, prevents localization of a phantom image. Egan states that he was unable to demonstrate a difference in the outcomes of these two procedures. Egan's data, however, does reveal a difference between the two procedures of as much as 7.4 dB. Apparently this difference was considered non-significant. More adaptation is measured when the two stimuli are of the same frequency than when the frequencies differ.

The only measure of perstimulatory loudness adaptation which does not involve simultaneous stimulation of the two ears is the method of delayed balance used by Bekesy (4) and Wood (108). The initial loudness of the adapting stimulus is first determined by means of alternate binaural loudness balances. This balance is followed by the adapting period, during which the control ear is rested. At the termination of the adapting period, a single brief comparison tone is presented to the control ear. The subject judges the relative loudness of the comparison and adapting tones and informs the experimenter as to which is louder. A rest period follows in which recovery takes place. The procedure is repeated with the intensity of the comparison stimulus adjusted on each of its presentations until a judgement of equal loudness is made. The intensity of the comparison tone at which this judgement is made is then compared with the comparison tone intensity in the preadapting balance and the difference between them is the amount of adaptation. The method of delayed balance has been used very little, probably because it requires considerable subject and experimenter time to obtain a small amount of data. Use of this method, however, has consistently resulted in smaller amounts of adaptation than those methods in which localization cues may be a factor (46, 52. 92, 111).

Egan and Thwing (23) report a study comparing the simultaneous dichotic loudness balance and the delayed balance. With the latter procedure, only loudness cues are available to the subject while with the simultaneous balance method the subject may make use of localization as well as loudness information. Adaptation was measured in one subject for several durations of the adapting stimulus. It was observed that the use of the simultaneous balance procedure resulted in more adaptation than did the use of the delayed balance method at all durations investigated. The difference in the amounts of adaptation recorded ranged from 3 dB to 4 dB with the greater difference being observed when longer adapting stimuli were used. Durations greater than three minutes were not investigated, but it appeared that an asymptote was being approached more rapidly with the delayed balance method. The two methods, as used by Egan and Thwing (23), are not directly comparable since the comparison tone durations were of one second duration in the delayed balance method and fifteen seconds duration in the simultaneous balance procedure. Because of this difference and the limited sample size, it is difficult to compare the two procedures on the basis of this study.

Wright (111) and Small (91) do not consider the method of delayed balance to be a valid means of measuring perstimulatory adaptation. They base their argument on the fact that the comparison stimulus is presented to the control ear after the adapting tone is turned off. Small (91, p. 291) states, "The delayed balance procedure as well as alternate binaural loudness balance measures post-stimulatory adaptation."

Egan and Thwing (23), however, consider the method to be a valid measure of perstimulatory adaptation. They state:

> This method represents, in our opinion, the most valid means of measuring loudness adaptation in the strict sense of the term. This stand is taken with respect to the latter method because, by its nature, neither a localization judgement nor a re-stimulation of the adapted ear is involved.

The objection of Small (91) to the delayed balance method as a measure of perstimulatory adaptation appears to be based on the definitions of the terms "perstimulatory" and "poststimulatory." As used by Small, these terms refer to the time of the presentation of the comparison tone and not to the time of sampling of the adapted ear. This use of terms, however, seems unjustified because the adaptation being measured is that occurring in the test ear and not the control ear. Therefore, in this paper, loudness adaptation is defined as perstimulatory when that pure-tone segment to be compared with the tone in the control ear is a portion of the adapting tone. It is contended that since the loudness of a segment of the adapting tone itself is being observed that this is a measure of perstimulatory adaptation. Under this definition, it must be agreed along with Small, that the alternate binaural loudness balance following the adapting period is a measure of poststimulatory adaptation. It must be agreed with Egan and Thwing (23) also, however, that the delayed balance procedure measures perstimulatory loudness adaptation.

In addition to those studies already cited, the results of Jerger and Harford (56) on the relation between simultaneous and alternate loudness balances in impaired ears raise substantial doubt that simultaneous stimulation of the two ears can result in a measure of true loudness in one of the ears. The question, however, as to whether simultaneous presentation results in a measure of loudness adaptation has not been satisfactorily answered. Only Egan (22) and Egan and Thwing (23) have studied the question directly and their results must be interpreted only in a limited way for reasons stated earlier.

It is the purpose of this study to investigate two aspects of this question. First, what is the effect of the task the subject is asked to perform in the simultaneous balance?, *i. e.* will the same or different results be obtained when he is instructed to localize the phantom image in the center of the head as opposed to when he is asked to equate the loudness of the stimuli at the two ears? Second, are the same results obtained when the experimental paradigm and instructions are identical with the single exception that the comparison tone immediately follows the adapting tone in one procedure while it overlaps the terminal portion of the adapting tone in the other? This second question also is concerned with whether or not the simultaneous balances may be influenced by some binaural interactive effect.

The subsequent chapters will present a review of the pertinent literature; a detailed description of the procedure, equipment and subjects used; and the results obtained and a discussion of these results.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

The adaptation of sensory systems is a familiar experience. For example, sensitivity to odor and light quickly diminishes over exposure time. Recovery from light adaptation is even more noticeable. In a dark room, the eye quickly adjusts permitting the perception of objects which, only a moment before, were engulfed in darkness. Geldard (31) cites references to adaptation phenomena in all human senses. Only since the advent of sophisticated electronic equipment, have these stimulus effects been explored systematically, providing quantitative as well as qualitative data. These data have provided valuable information on the physiology of sensory systems. The present study is concerned with auditory adaptation.

Early Studies

A number of early experimenters observed that changes in the sensitivity of the auditory system result from exposure of the ear to sound. A variety of methods were used to detect these changes.

Flügel (28), in 1920, studied the effects of a fatiguing tone on the localization of a binaural signal. A single pure-tone source was fed to a dual system of tubing which ended at the two ears of the subject. Initially, the lengths of the tubes were adjusted to provide the subject with a sound image in the median plane. One ear was then fatigued for a given duration while the tubing to the other ear was occluded to prevent contralateral stimulation. At the end of the fatiguing period, the stimulus was again directed to both ears, and the subject adjusted the length of the tubing to again achieve a median plane localization of the sound image. Flügel's major finding was that binaural localization is affected by a preceding monaural stimulus, and that a median plane localization could be regained by lengthening the tubing used to conduct the sound to the unfatigued ear. The adjustment of tubing length corresponds to a phase shift and, possibly, an intensity change, however, quantitative measures of these changes are not available. Flügel's results can be compared with other studies on adaptation or fatigue only on a qualitative basis.

Pattie (71), in 1927, used a procedure to measure auditory fatigue which involved a re-stimulation of the adapted ear. At the termination of the adapting stimulus, pairs of stimuli were presented to the two ears either simultaneously or alternately. The intensity of the comparison tone was adjusted with each presentation until the loudnesses at the two ears were equal. Pattie found that the loudness of a tone is decreased for about 30 seconds following adaptation, but no quantitative measure was made of this decrease. Pattie's procedure permits a degree of recovery to occur before the actual measurement takes place. The condition of the adapted ear at the time of that restimulation which provides the actual measurement cannot be assumed to be the same as that ear's physiological state at the termination of the adapting stimulus. Thus, Pattie's study is of the residual loudness change that remains at some point in time after the adapting stimulus is terminated.

The experiments of Bekesy (4), in 1929, were the first which reported specific intensity levels and durations of the adapting and test stimuli and a specific interval between the two. Bekesy used the method now known as delayed balance which is described in the preceding chapter. The duration of the comparison stimulus used was 200 msec, and it was presented immediately at the termination of the adapting tone. The adapting tone was an 800 Hz sinusoid at intensities of 2, 10 and 50 dynes/cm^2. Bekesy observed that the amount of adaptation increases with increasing intensity of the adapter and with duration increases up to about 2½ minutes. This duration appears to produce maximum adaptation for any given intensity. Adapting tone frequencies from 300 Hz to 8 kHz produced results essentially the same as those from the 800 Hz stimulus. The loudness of tones adjacent in frequency to the adapting tone is also affected. The spread of loudness adaptation was observed to be symmetrical from 300 Hz to 2 kHz following an 800 Hz adapting tone. Recovery from adaptation was also studied. Within fifteen seconds of the termination of the adapting tone, a tone presented to the adapted ear has regained more than 90% of its preadapted loudness value. Bekesy (3, p. 366) relates the "fatigue" function to his theory of "eddies" in the cochlear duct.

> The observations of these eddies made on the cochlear model provide the best representation of the form of the fatigue function. The present view concerning the stimulation of pressure receptors is that pressure produces a change of concentration in the sensory cells by osmosis, which in turn gives an electrical excitation to the nerve fibers. On this hypothesis it is easy to understand why the rapidly alternating positive and negative pressures that constitute a tone would

> not produce as large osmotic changes of concentration as are produced by the steadily acting pressure of the eddy.

Wood (108), in 1930, employed essentially the same procedure as Bekesy (4). He used a comparison tone of $1\frac{1}{2}$ seconds and did not specify the intensities of the adapting stimuli. A somewhat greater initial rate of fatigue is reported than that reported by Bekesy, but the asymptotic values are essentially the same. Wood (108) observed that the amount of adaptation was not increased by increased intensity of the adapting stimulus over the range he studied. Both Bekesy's and Wood's subjects reported perceptual changes in the adapting ear in addition to decreased loudness. Bekesy's (4) subjects observed that the pitch of tones differing in frequency from the adapting tone was shifted away from the pitch of the adapting tone. Wood's (108) subjects reported that the pure-tone adapting stimulus sounded dull with a low, atonal background. Such pitch and quality changes have been reported in more recent studies (22, 92), but they have not been investigated thoroughly.

Differentiation of the Phenomena

Auditory changes resulting from stimulation have been measured in a number of ways. Differentiation among the phenomena is not clear and terms have sometimes been used interchangeably. The terms "adaptation" and "fatigue" in this review of the literature are not used to differentiate the actual physiological processes, but only to indicate the terms used by the various investigators. The phenomena of adaptation and fatigue apparently are not the same, but it is difficult to differentiate between them. Selters (87), Hood (46) and Harbert and Young (34) discuss several of the points of difference. Changes in the threshold for and the magnitude of a stimulus have been observed both during and after stimulation of the ear. These changes are known by a variety of terms. Poststimulatory effects include fast adaptation, also known as short-duration fatigue and residual masking; temporary threshold shift and poststimulatory loudness adaptation. Changes which are observed by sampling the auditory system during the stimulation of the ear are threshold adaptation or tone decay and perstimulatory loudness adaptation. Tone decay can possibly be considered as a special case of loudness adaptation if one considers threshold to be dependent on loudness. Although this paper deals with perstimulatory loudness adaptation, the other effects mentioned will be discussed briefly.

Threshold Shifting Phenomena

Growth. Fast adaptation, as the name implies, occurs very quickly, so its effect is detectable after only a very brief adapting stimulus. The process of fast adaptation occurs during the presentation of the adapting stimulus, but the effect is measured poststimulatorily. The shifted absolute threshold, which is used as the measure of fast adaptation, is present for a very short time. Physiological studies by Derbyshire and Davis (20) and Coats (15, 16) provide confirmation of the rapid adaptation phenomenon observed in the psychophysical studies of Harris and his co-workers (38, 39, 40, 78), Munson and Gardner (66) and Lüscher and Zwislocki (62, 63).

Often differentiation from fast adaptation is temporary threshold shift (TTS), a greater and longer-lasting reduction of sensitivity which results from longer and/or more intense fatiguing stimuli. TTS includes the effects of fast adaptation, but it has not been demonstrated that the two are on the same continuum. Both, however, are effected similarly by changes of the duration, intensity and frequency of the exposure stimulus.

Increasing the duration of the fatiguing stimulus has generally been shown to increase the amount of TTS (15, 17, 36, 44, 57). Holding other factors constant, TTS at 2 minutes post exposure (TTS_2) grows linearly with the logarithm of time (36, 102). Low intensity stimuli, *i. e.*, below about 80-dB SPL, have not been investigated thoroughly with regard to the effects of the exposure duration. Increases in threshold shift with exposure duration have also been observed in the fast adaptation studies of Coats (15) and Zwislocki, Pirodda and Rubin (114). Rawnsley and Harris (78), however, report that there is no change in the amount of adaptation resulting from adapting stimuli whose durations are from 100 to 6000 msec and whose intensities are below about 70-dB SPL. With higher intensities, increasing the duration was found to increase the amount of adaptation. Coats (15) also found that the duration effect was greater at higher intensities.

A number of experimenters have observed that high frequency adapting or fatiguing tones cause more threshold shift than do lower frequencies (17, 30, 38, 53, 77, 96). Kylin (58) has also demonstrated a similar effect using noise bands as the fatiguing stimuli. Equivalent exposures to pure tones and noise bands do not result in the same degree of TTS. Pure tones, especially those of higher frequencies, cause the greater shift presumably because the acoustic reflex is maintained better by noise stimuli than by tones (57, 101), and because the reflex affords the ear greater protection from lower frequency exposures. However, stimuli presumably below the threshold of the acoustic reflex also demonstrate a differential frequency effect. Bell and Fairbanks (6), using fatiguing stimuli of 40 and 60-dB SL, report that the amount of TTS increases as the frequency is increased from 1 kHz through 2 kHz to 4 kHz. Epstein et al. (26) used 20-dB SL fatiguing tones and reported greater threshold shift to result from 4 kHz stimuli than from either 1 kHz or .5 kHz tones. The effects of stimuli above 4 kHz have not been investigated thoroughly and the data are not sufficient to support any trend.

Greater intensities of the adapting or fatiguing stimuli generally result in greater threshold shift. There are two general exceptions to this rule. Selters (87), Munson and Gardner (66), Reger and Lierle (79) and Hirsh and Bilger (44) all report that for a wide range of exposure intensities, from about 20-dB to 60-dB or 80-dB SPL, the amount of adaptation remains constant. Using intensities of about 120-dB SPL, Davis et al. (17), Ward (101), Miller (65) and Trittipoe (98) have found that some subjects demonstrated less TTS than when exposure intensities were at lower levels. It has been hypothesized (17, 101) that this is due to a change in the mode of vibration of the stapes which affords a degree of protection to the inner ear. A number of studies of fast adaptation and TTS have used fatiguing stimuli in the range from 70-dB to about 110-dB SPL (27, 35, 51, 65). These studies have demonstrated that the amount of threshold shift is directly related to the level of the exposure. Hood (46), Selters (87) and Jerger (51) have observed that the growth of the resultant threshold shift increases out of proportion to the increase of the exposure level above exposure levels of 85-

to 90-dB SPL. Selters (87) has proposed that this level corresponds to a change from adaptation to fatigue of the auditory system. Hood (46) labels this change as a change from physiological to pathological fatigue using the term physiological fatigue to mean the same thing as Selters' adaptation. It appears that a function relating threshold shift to exposure level would be quite complex, but it would probably show an overall positive slope.

Other observations and measures of the auditory system have been made subsequent to the presentation of a fatiguing stimulus. Changes in the pitch and quality of tones have been noted by Liebermann and Révész (60), Bekesy (4), Rüedi and Furrer (85) and others (17, 25, 84, 104). Loudness "recruitment" in fatigued ears has been demonstrated by several methods including loudness balancing (3, p. 208; 17; 37) the intensity difference limen (3, p. 210; 24; 81) and threshold variability as measured with a Bekesy audiometer (5, 27, 84).

An asymmetrical spread of the threshold shift to higher frequencies results from high intensity levels of the fatiguing stimulus. Munson and Gardner (66) report that this shift occurs when the exposure level exceeds about 60-dB SL. Epstein and Schubert (27) found that with exposure tones of 70-dB and 80-dB SL, the threshold shift at the exposure frequency is equal to the shift at the frequency one octave above. At higher levels the asymmetry was more extreme with the maximum shift at a frequency one-half octave or more above that of the fatiguing tone. Rawdon-Smith (76, 77), Davis *et al.* (17), and Hirsh and Ward (45) have also noted the spread of TTS to higher frequencies. Using fatiguing stimuli of 40-dB SL and less, Caussé and Chavasse (14) report that TTS is greatest at the exposure frequency. Peyser (74), Huizing (50) and Epstein et al. (26), in the administration of clinical tests, use low intensity level fatiguers to produce TTS at the exposure frequency. Harbert and Young (34) speculate that the exposure level at which the asymmetrical spread of the threshold shift becomes apparent is the level which separates fatigue from adaptation.

Another threshold shifting phenomenon which has been studied primarily from a clinical standpoint is threshold adaptation or tone decay. A tone of threshold intensity or slightly above the intensity at threshold is presented to the patient's ear. The patient responds until the signal is no longer audible. The intensity is then raised by a pre-determined amount and the procedure repeated. The amount of adaptation is the sensation level at which the steady tone remains audible for a duration estiblished by the experimenter - usually one minute or more.

Albrecht (1) was the first to recognize this phenomenon, but credit for the first thorough investigation goes to Schubert (86). Carhart (11), Owens (67, 68) and Sørenson (94) have used the procedure outlined above with minor modifications and have established the value of the "Tone Decay Tests" in a clinical setting.

A further modification makes use of the Bekesy (5) audiometer to record threshold for interrupted and continuous tones. Jerger, Carhart and Lassman (55), Harbert and Young (34) and others (54, 70, 112) have used this technique. In some cochlear and retrochochlear pathologies, the subject's threshold for the continuous tone is poorer than that for the interrupted tone and the difference is reported as the amount of adaptation.

Aside from being influenced by various auditory pathologies, threshold adaptation also depends on the duration and frequency of the stimulation (86). Further references to threshold adaptation will be included in the ensuing discussion of loudness adaptation.

Recovery. Recovery from fast adaptation generally occurs within the first 500 msec after the termination of the adapting stimulus (8, 35, 41, 63, 78). Coats (15), however, reports that recovery can take in excess of one second when the exposure stimulus is as long as three seconds and as intense as 80-dB SPL. Lüscher and Zwislocki (62, 63), Bentzen (8) and Rawnsley and Harris (78) report that recovery is linear with log-time. Coats (15, 16) reports that recovery is dependent not only on the level of the exposure and the amount of threshold shift, but also on the duration of the fatiguing stimulus. Bentzen's (8) results also reveal this dependence on duration.

Recovery from longer and more intense stimuli is somewhat more complex, especially during the first two minutes. After this time, recovery is exponential (linear in log-time) and depends on the amount of threshold shift from which recovery is occurring (103). This has been called the R-2 phase of recovery by Hirsh and Bilger (44). The R-1 phase, occurring in about the first minute, is also exponential, and its duration is about one to one-and-one-half minutes. Following the R-1 recovery phase is a brief period of decreasing sensitivity called the "bounce" (42, 44, 51, 61, 80, 96). The bounce does not occur in all recovery curves and appears to be limited to recovery from exposure levels above 80-dB SPL and below 110-dB SPL (14, 36, 51). The significance of this multiphasic recovery function is not clear, but it may be speculated that more than one "structure" is returning to its prefatigued condition.

Loudness Adaptation

Measurements of loudness adaptation, the change in the loudness of a stimulus over time, have been made both during and after the presentation of the adapting stimulus. These measurements involve a comparison of the loudnesses of stimuli at the adapted ear and the unadapted or control ear. In this discussion when adaptation of the adapted ear is based on the perceived loudness of some segment of the adapting stimulus itself, the resultant loudness change is called perstimulatory loudness adaptation. On the other hand, when the judgement is based on a stimulus presented to the adapted ear after the adapting period, the measurement is one of poststimulatory loudness adaptation. This latter type measurement has been used by Pattie (71) and Hood (46). Since the adapted ear is re-stimulated after the period of adaptation, some recovery does take place, therefore, it appears that less adaptation has occurred. Although these procedures do not provide us with the loudness change of a stimulus during stimulation, they are valuable in the measurement of recovery from adaptation and have been used for this purpose by Bekesy (4), Canahl and Small (10) and others (12, 21, 33, 109).

In the following sections of this chapter, the term adaptation will be used to refer only to perstimulatory adaptation. In addition to the loudness change itself, other perceptual changes are reported. The following paragraphs will deal with these changes as well as the factors affecting the growth of and recovery from loudness adaptation.

Growth. The growth of loudness adaptation resembles that of TTS in that it is generally increased by increases of the intensity, frequency and duration of the stimulus. There appear to be limits to the amount of adaptation produced by any given intensity of signal regardless of increases in the frequency and duration. With regard to duration, the extent of its differential effect seems to depend on the values of the other two parameters. A discussion of the effects of each of these parameters follows.

With the exception of Wood (108) and Palva (69), all experimenters who have studied the effects of different intensities on the amount of adaptation have found that adaptation increases with stimulus intensity (4, 12, 13, 33, 49). Wood (108) used two unspecified intensities of the stimulus and found equal amounts of adaptation resulting from each. Palva (69) also used two levels, but he found less adaptation to the higher intensity adapting tone, though variability was found to be great with both intensities. Bekesy (4), Hood (46) and Hood and co-workers (21, 33, 47, 48, 49) used three levels of the adapter and found adaptation to increase with intensity. Carterette (13), using broad band noise stimuli, reports the function relating adaptation to stimulus intensity to be positively accelerated above 90-dB SPL (the increase in adaptation with stimulus intensity is greater above stimulus intensities of 90-dB SPL). Jerger (52), on the other hand, reports a negative acceleration above a stimulus intensity of 60-dB SPL when using a pure-tone adapter. This latter finding might be explained by the assumption that the control ear will be adapted by cross-conduction when stimulus intensities exceed the 60-dB level, hence, the measured adaptation would be the difference in the amounts of adaptation in the two ears and would theoretically remain the same at even higher stimulus levels. The positive acceleration observed by Carterette (13), and to a certain extent by Hood (46), might be explained by a transition from "adaptation" to "fatigue" as reported in TTS studies by Hood (46) and Selters (87). Neither of these two findings, positive or negative acceleration, are consistently found, possibly because so few experiments have utilized a sufficient range of stimulus intensities.

Experiments in which observations of adaptation were made for different frequencies reveal that greater adaptation results from higher frequencies (46, 52). Bekesy's (4) data is an exception to this as he found that stimuli from 300 Hz to 8 kHz produced the same degree of effect. Jerger's (52) study includes all octave frequencies from 125 Hz to 8 kHz. He reports that adaptation increases with frequency through 1 kHz, then remains nearly constant through the higher frequencies. This relation of stimulus frequency holds true regardless of whether equal SPLs or equal SLs of the stimulus are used. When the stimulus level and adaptation are converted to loudness units (sones) the low frequencies continue to demonstrate less adaptation than the high frequencies, but the difference is not as great as when intensity units are compared. Thus, regardless of the intensity measure used, the differential frequency effect remains. Carterette (13) compared adaptation produced by a pure tone with that produced by bands of noise of the same overall SPL and with a center frequency the same as that of the pure tone. He found the pure tone to produce the most adaptation. The widest band, however, did not produce the least, as might be expected, but produced more than either of the narrower bands. From this, it cannot be concluded that greater spread of the energy along the basilar membrane results in less adaptation. It appears that further studies on the frequency and band width of adapting stimuli might provide more information about the development of loudness adaptation.

The effect of the duration of the adapting tone has customarily been studied as the "time course" of adaptation with measures for different durations being made during the same stimulus exposure. The exceptions to this are the investigations by Bekesy (4) and Wood (108) who used the delayed balance procedure. In all studies of adaptation, it is reported that the loudness decrease is rapid initially, then progressively decelerates, eventually reaching an asymptote. The stimulus duration required for asymptotic adaptation varies with both the intensity and frequency of the tone and with the method of measurement. Hood (46), using the simultaneous dichotic balance, reports that asymptote is reached after 3½ minutes of stimulation with adapting tones of 40-, 60- and 80-dB SL. Jerger (52), using essentially the same method, observed that, for a 90-dB SPL high frequency adapting tone, asymptote is not reached for five to six minutes. For lower intensities and frequencies, such as 125 Hz at 90-dB SPL and 1 kHz at 40-dB SPL, asymptote is reached within two minutes. Bekesy (4) and Wood (108) found that stimulus durations in excess of about two minutes did not result in much greater adaptation than observed within that time. The levels of stimulation used by Bekesy (4) (80-, 94- and 108-dB SPL) both parallel and exceed those used by Jerger (52), thus it seems that the difference is due to the different procedures used. Egan and Thwing (23) compared the two procedures and confirm the observed difference in time required to reach asymptote. Wright (111) used seven minute stimuli to insure that asymptote is reached for the methods of asymptotic localization and the moving phantom, however, the latter technique reveals that maximum adaptation occurs much more quickly. When using adapting and comparison tones of the same intensity, up to 80-dB SPL, the time required for the moving phantom to reach the median plane can be considered to produce the same amount of adaptation in the control ear as that produced in the experimental ear by a stimulus duration exceeding seven minutes. Wright (111) reports this time measurement to be less than two minutes in the majority of cases. Although these studies reveal some discrepancies in the time course of adaptation, they all report that an asymptote is reached, beyond which, increases in the duration of the stimulus have no effect.

Several other factors either are, or may be, involved in influencing the extent of loudness adaptation. The presence of a "central factor," as reported in TTS investigations (7, 29, 82, 105, 106), has not been determined, although a number of other parallels between the phenomena have been noted. A finding which is commonly observed is that individual differences are great, implying that some subjects are more susceptible than others. Another factor which influences results is the method used to make the measurement. This will be discussed in a later section.

In addition to the change in the loudness of the adapting stimulus, other alterations of the auditory system's perception are also noted. Among these are the spread of the effect to other frequencies, changes in the quality of the adapting stimulus and changes in the localization of a binaural signal. The former two are discussed in this section while the latter will be discussed in the section on measurement of loudness adaptation.

To study the frequency spread of the adapting tone, both Bekesy (4) and Thwing (97) employed procedures which actually lead to post-stimulatory observations. Thwing's (97) procedure was a modification of the simultaneous dichotic loudness balance using an adapting tone of 1 kHz except during the balance periods when both ears were stimulated with a tone of another frequency. Bekesy's (4) procedure is a modification of the delayed balance. At the termination of the adapting tone, the experimental ear is stimulated with a 500 msec tone of another frequency. Another tone, varying only in intensity, is then presented to the control ear for a loudness judgement. These measures are post-stimulatory since the auditory system's functional state is observed after the adapting stimulus is terminated. Both of these studies reveal that the loudness of tones adjacent in frequency to the adapting tone is decreased by the adapting stimulus. This loudness decrease is not as great as that observed when both adapting and test frequencies are the same, and becomes less with greater frequency separation of the tones. The effect is nearly symmetrical with both higher and lower tones being affected to a similar extent. No technique has been devised to measure the perstimulatory frequency spread of adaptation.

Changes in the perceived quality of the adapting sound have occasionally been reported in loudness adaptation experiments. Wood (108) reports that his subjects often noted that the tone sounded dull and was accompanied by a low atonal background noise. The subjects used by Small and Minifie (92) were instructed to base their equality judgements on loudness. During about the first minute of a session their loudness judgements were made with the aid of localization cues. After this time, however, a fused sound image could not be localized and the judgements were made on the basis of loudness alone. Further, the adapting tone appeared to them to be dull and noisy and to lack a pitch quality. Egan (22) also reports that his subjects found the balance procedure to become more difficult as the adapting period progresses. It has not been reported that these changes in quality occur with any specific adapting intensity, frequency or duration except in the case of Small and Minifie's study (92), or as the result of any measured amount of adaptation.

Recovery. It is apparent from the literature that studies of recovery are of two types; those which observe the recovery of the loudness of short tones and those which observe recovery of the system's ability to respond normally to subsequent adapting stimuli. The former method, used by Bekesy (4) and by Canahl and Small (10), reveals a much shorter recovery period than does the latter used by Hood (46), Egan (22), Thwing (97), Wright (109) and Carterette (12, 13). In addition to these studies, several investigations have provided indirect indices of recovery.

In the direct studies of recovery the test stimuli are presented simultaneously, but their durations vary from the 200 msec and 300 msec used by Bekesy (4) and by Canahl and Small (10) to the 30 seconds duration used by Hood (46). The recovery of loudness as reported by Bekesy (4) is within 90% of complete in 15 seconds. The complete recovery of the auditory system, however, requires more than one minute and often up to four minutes. It should be noted that recovery is slowed by the restimulations of the adapted ear during the recovery period. While this may lengthen the apparent recovery period, it cannot be avoided as such stimulation is required in order to sample the function of the adapted ear. Until recovery of the system is complete, the simultaneous stimulation of the two ears will result in the occurence of unequal adaptation with the previously adapted ear adapting more quickly or exhibiting a "relapse" as reported by Hood (46). Hood (46) explains the normal or near normal response to the loudness of short tones presented subsequent to the adapting stimulus as being a result of the "on effect" which returns to normal in a very brief time. "On effect" is defined by Hallpike and Hood (33) as " . . . an initial high frequency discharge . . . " in the action potential response. In discussing recovery from loudness adaptation, it is apparent that we need to identify just what is recovering; the "on effect" or the auditory system's ability to respond normally to an adapting tone.

Carterette (12) compared the adaptation produced by an interrupted noise to that produced by a steady noise of the same average SPL. At an interruption rate of 12.5/sec. the amount of adaptation was less than that for the steady noise, however, an extrapolation of the data reveals that at 25 interruptions per second, allowing 20 msec between pulses for recovery, the adaptation would be equal to that produced by a continuous noise. On this basis, Carterette speculates that no effective recovery occurs within 20 msec. Sergeant and Harris (88), using interrupted tones, report that when recovery time is equal to the on-time of the signal (50% duty cycle), no adaptation is measured, except with on-times of one second or less. With these short durations, adaptation apparently occurs more rapidly than recovery. Small and Minifie

(92) also report a finding bearing indirectly on recovery. They observed that recovery from a 75-dB SL tone of up to 30-seconds duration is complete within 20 to 30 seconds. From these studies it appears that some parallel might exist between the courses of adaptation and recovery. Further studies, of the type reported by Small and Minifie (92), might provide the key to this relationship.

Comment

Perstimulatory changes in the perception of an acoustic stimulus have been studied in a variety of ways. Through the use of these techniques experimenters have investigated a number of these changes and the effects of varying the parameters of the stimuli used to produce them. Certain relationships between the stimulus and the resultant degree of adaptation have been established within the limits of the parameters investigated, but other relationships are not clear due to conflicting reports in the literature. The phenomenon of tone decay has received little attention except from a clinical standpoint. Its relation to loudness adaptation is not well defined though the concept of threshold is sometimes considered to be a special case of loudness perception (87). One may consider that when the perception of a continuous stimulus presented at an initial threshold level disappears, the loudness of that stimulus has decreased. Another major problem is seen to be that of the method used to measure loudness adaptation. This aspect will be discussed subsequently.

Since both perstimulatory and poststimulatory changes, and both loudness and absolute sensitivity changes are observed as a result of acoustic stimulation, it appears that some relationship may exist.

Certain parallels are observable among these changes, notably the effects of stimulus intensity, frequency and duration. Others, such as frequency spread of the effects and the possible existence of critical levels of stimulus intensity, are not as apparent, but this seems to be due to insufficient investigation rather than to a demonstrated absence of these parallels. With few exceptions, most notably the recent work of Selters (87), investigators have seemingly ignored the co-existence of those related phenomena not directly under study. Further experimentation on adaptive phenomena and their cause(s) will undoubtedly provide us with the information needed to relate them to one another and with a better knowledge of the physiology of the auditory system.

The Mechanism of Loudness Adaptation

The mechanism of loudness adaptation remains a mystery despite the numerous psychophysical experiments reported and a number of physiological studies of the auditory system. Such physiological studies generally involve the recording of either the cochlear microphonic (CM) response and/or the neural response from some level of the auditory pathway. Eighth nerve action potentials (AP) and the CM can both be recorded by electrodes placed on the round window membrane, making them relatively easier to obtain than potentials from higher neural centers. Since perstimulatory loudness adaptation as well as poststimulatory changes make themselves apparent in recordings of the action potentials (2, 18, 20, 72, 83), it would seem unnecessary to search for the mechanism at any higher level. It should be noted, however, that the possibility of a central factor, perhaps mediating an efferent inhibitory influence as proposed by Wernick and Tobias (106), has not been ruled out.

Barring this possibility, we are left with the choice of a peripheral mechanism situated either in the cochlea or in the VIII nerve.

Hood and his co-workers (21, 33, 46) observed that persons with Meniere's Syndrome evidence a disturbance of the hair cells and exhibit abnormal adaptation or "relapse" though the presence of recruitment reveals an apparent normalcy of the "on-effect." The same investigators also reported that the adapted ear has a normal on-effect and exhibits relapse. From this parallel, they concluded that adaptation is a hair-cell phenomenon.

Since the hair cells are considered to be the generators of the cochlear microphonic, this response should exhibit adaptation if the conclusion of Hood (46) is valid. An investigation of the CM response and of the impedance between the scala media and scala tympani was carried out by Shimizu, Konishi and Nakamura (90). They used stimulations of from 70- to 100-dB SPL for durations up to 20 minutes and report that the CM decreases over time and that its phase also changes. A decrease in the electrical impedance between the endolymph and perilymph was also noted. This required a few minutes of poststimulatory silence to return to normal. From this study, they speculate that an increase of ion diffusion at the hair cell membrane and a consequent decrease of the electrical charge of the membrane are essential factors of auditory adaptation. Because of their placement of the electrodes in scala media and scala tympani, it cannot be assured that injury to the cochlea did not result. Such injury may have resulted in the decrease of the CM response as the authors did not report its recovery. It is also possible that the CM response was contaminated with the AP, thus the reduction of the response may have been due to a decreased AP, not a decreased CM.

Several other investigations of the CM response to continuous stimuli have failed to demonstrate the decrease observed by Shimizu et al. (90). Lawrence (59) was unable to observe adaptation of the CM for stimuli less than 114-dB SPL and even at this level, the CM did not decrease in magnitude until the stimulus duration was $6\frac{1}{2}$ minutes. Gisselsson and Sørensen (32) observed a very slight decrease in the CM response at a stimulus level of 100 dB after 20 seconds of stimulation. No such decrease was noted for lower levels of the stimulus. Rahm, Strother and Gulick (75) observed essentially no change in the microphonic response to a 60-dB SPL stimulus for durations up to 85 hours. These studies all used experimental animals. The results imply that the adaptive mechanism lies central to the hair cells of the organ of corti.

Clinical studies of tone decay (9, 11, 48, 67, 68, 73, 94) reveal that subjects with VIII nerve lesions exhibit considerably more adaptation than do those with either conductive or cochlear hearing losses. Yantis (112) speculates from this that the locus of adaptation is neural. Derbyshire and Davis (20), in recording action potentials from the auditory nerve of the cat, observed a decline in response to sustained stimulation. This "equilibration" of the response reached an asymptotic level in about three minutes. Matthews (64), in 1931, observed essentially the same phenomenon in the stretch receptor of the frog.

There is also a possibility that the adaptive mechanism might lie at the level of the initiation of the action potential. Sørensen (93) states:

> The cause of the depression must be sought either in the mechanism which transmits the impulse from the hair cells to the nerve

> endings or in the neural units themselves . . . . An intermediary link, possibly of a chemical nature, cannot be definitely excluded, and if such a link exists, the observed depression of the nerve activity may be localised to it.

Deatherage, Eldredge and Davis (18) recorded CM and AP responses in the guinea pig and measured latencies and amplitudes of the N_1 response. They found the latency to be inversely related and the magnitude directly related to the strength of the stimulus. After fatiguing an ear, the amplitude of N_1 is decreased and its latency is increased by as much as one msec. Recovery of the amplitude occurs much more quickly than the return of the latency to its pre-fatigued value. Deatherage and Hirsh (19) report that the latency of the AP is dependent primarily on the N_1 response and that this response is due to the synchronous firing of fibers in the basal coil of the cochlea. When this synchronous response is disrupted by a noise of high frequency, the latency of the AP resulting from a low frequency click is determined by later components of the AP which arise from more apical cochlear fibers. The high frequency noise was found to be ineffective in masking the lower frequency clicks, so the latency shift cannot be attributed to a reduction in the loudness of the click stimulus. These studies imply that an adapting or fatiguing stimulus causes an increase in the latency of the AP.

The normal latency of the AP, the time between the CM response and the AP, has been determined by Derbyshire and Davis (20) to be less than one msec. This was found to vary slightly with stimulus intensity varying from approximately 0.8 msec when the intensity is 10-dB SL to about 0.6 msec with stimuli 20-dB SL and higher. Deatherage, Eldredge and Davis (18) observed that this latency was as great as 1.9 msec for 500 Hz tone pips at an SPL of 5 dB above that of the AP "threshold."

It has been speculated that this normal latency is due to a chemical change which may mediate the action potential. Since continued stimulation of the ear by sound has been found to result in chemical changes (100), it seems possible that the adaptive process might be related to a chemical phase in the initiation of the nerve impulse. The latency shift observed by Deatherage and Hirsh (19) might explain the localization changes observed by most investigators of loudness adaptation (12, 13, 21, 22, 23, 28, 33, 46, 52). If this is the case, then at least a part of the adaptation phenomenon can be located at the intermediate step before the initiation of the AP.

Measurement of Loudness Adaptation

All methods used in the measurement of loudness adaptation have employed a comparison signal presented to the control or unadapted ear. These methods assume that the control ear is essentially unaffected by the adapting stimulus and that loudness in the adapted ear is unaffected by the comparison tone. These assumptions are made even when contralateral stimulation by either cross-conduction or the efferent auditory pathway is a possibility. The comparison stimulus and its presentation have been varied in a number of ways, leading to different results. In one procedure, the adapting tone is also changed during some of the observation periods. In general, four modifications have been investigated; changes in the duration, frequency and time of presentation of the comparison tone and changes in the intensity of the adapting tone.

The adapting tone is either presented at the same intensity throughout an experimental period (fixed intensity) (22, 46) or its intensity is altered during some of the balance periods (varied intensity) (22). Each of these procedures can be further modified. With the method of fixed intensity, the comparison stimulus can be adjusted directly to the balance point (22) or the subject can control attenuation, usually with a Bekesy (5) type audiometer, and vary the intensity about the level needed for a balance (tracking) (21, 33, 46). The modified method of varied intensity restricts the alteration of the intensity of the adapting stimulus to the preadapting periods only (12, 13, 23, 97). Both direct adjustment and tracking can be used with varied intensity and its modification as well as with fixed intensity.

The tracking method was first used by Hood (46) who permitted his subject to control directly the attenuation of the comparison tone, the rate of attenuation being limited only by the speed of the subject. Hood reports up to 40 dB of adaptation after $3\frac{1}{2}$ minutes of exposure to an 80-dB SL, 1 kHz tone. Palva (69), using the same stimulus, observed a mean of only 2.2 dB of adaptation in his subjects. He used a recording attenuator with an attenuation rate of 2.3 dB/second. Such divergent results may be due to the rate of attenuation which varied considerably in the two procedures. Small and Minifie (92) used an intermediate rate of 5 dB/second and report an intermediate amount of adaptation though their adapting stimulus differed in both intensity and frequency from that used in the other two studies. The direct adjustment procedure is similar to Hood's (46) tracking method in that adjustment of the attenuator is made quickly. It differs in that the subject simply reports when the two stimuli are equally loud instead of alternately making the comparison tone louder and softer. The method of direct adjustment has yielded results also intermediate between those of Hood (46) and Palva (69). Jerger (52) and Wright (109) have used this method, demonstrating about 20 dB of adaptation to stimuli essentially the same as those used by Hood (46) and Palva (69). In all of these studies the adapting stimulus was maintained at a constant intensity throughout a given experimental run.

Egan (22) felt that the method of fixed intensity might lead the subject to set a loudness standard for the adapting tone. This standard would tend to correspond to the loudness at the initiation of the stimulus and, therefore, bias the results in the direction of less adaptation. To test this hypothesis, the intensity of the adapting stimulus was decreased to a new level during some of the pre and per-stimulatory balance periods in order to disrupt this loudness standard. Egan found more adaptation with this method than with the method of fixed intensity thus supporting his hypothesis. There is a possibility that some recovery may occur during the low intensity balances; however, if this were a factor, it would act in opposition to the increased adaptation observed. This procedure has not been used in any other studies although a modification of it has been employed by Thwing (97), Carterette (12, 13) and Egan and Thwing (23).

Thwing (97), in determining the frequency spread of adaptation, used a modification of the method of varied intensity wherein the intensity of the test stimulus was reduced only in some of the preadapting balancing periods. Thus, during the adapting period, the test stimulus was not altered in intensity. His results demonstrate somewhat more adaptation than observed by Jerger (52) using the method of fixed intensity, but less than Hood (46) observed with the tracking procedure. A direct comparison with Egan's (22) varied intensity method was not made. Carterette (13) also used the modified varied intensity procedure, adapting the ear to bands of noise, and Egan and Thwing (23) used it with one subject to compare several measurement procedures. Neither of these studies report a comparison of the modification with Egan's (22) original method of varied intensity, so it is not possible to determine the effect of the modification from the available data.

The variations thus far described have resulted in some apparent differences in the degree of adaptation measured. However, direct comparisons of the procedures are generally lacking, making it difficult to ascertain the nature of the differences among them. In addition, the results of each of them are affected by the use of a long comparison stimulus duration which influences the obtained results.

The comparison stimulus which is presented to the control ear produces adaptation in that ear, the amount being dependent on the intensity, frequency and duration of the stimulation. In the methods thus far discussed, the duration of this comparison tone has generally been from ten to thirty seconds. That such durations cause considerable adaptation is demonstrated by the early studies of Bekesy (4) and Wood (108) who report that up to 10 dB of adaptation occurs in the first 10 to 15 seconds.

Small and Minifie (92) studied various comparison tone durations of from ten seconds up to a duration equal to that of the adapting tone. They observed that, regardless of the time allowed the control ear to recover between balances, the greatest amount of adaptation was measured with ten second comparison tone presentations. As this duration increased, measured adaptation in the experimental ear decreased.

The effect of comparison tone duration was also studied by Wright (111). With his method of asymptotic localization, this duration is reduced to only one second, essentially preventing the occurrence of any adaptation in the control ear. The adaptation resulting from a 90-dB SPL, 500 Hz exposure of 7 minutes was 50 dB. Jerger (52), using the same adapting stimulus, measured only 20 dB of adaptation when using a comparison tone duration of fifteen seconds. The adaptation measured in these two studies is presumably the difference between the amount occurring in the test ear and that occurring in the control ear. If this is the case, the results imply that with Jerger's (52) method, more adaptation occurs in fifteen seconds in the control ear than is measured as the difference between the two ears. This is possible though not likely in view of the smaller amounts of adaptation reported by Bekesy (4) and by Wood (108) in the same fifteen second period. However, these experimenters used the delayed balance procedure which differs from the methods of Wright (111) and Jerger (52) in that the judgement is one of loudness not localization. From these studies it is apparent that the duration of the comparison tone should be kept at a minimum to avoid adaptation in the control ear. Since this has not been the case in most studies, a re-evaluation of loudness adaptation seems in order. However, the procedure used by Wright (111) requires a median plane localization (MPL) rather than a loudness balance and the relationship of these two has not been adequately explored.

As discussed in Chapter I, the judgement required in the simultaneous dichotic balance method is not necessarily based on loudness alone but may involve the localization of a single fused sound image. Deatherage, Eldredge and Davis (18) and Deatherage and Hirsh (19) suggest that a MPL is based on equal AP latencies at the two ears while loudness is related to AP magnitude and does not depend on latency. Thus, localization changes are not necessarily equivalent to loudness changes though they may be related. Flügel (28) demonstrated that binaural localization is altered when one ear is adapted. He was able to compensate for this by creating a phase lag in the signal presented to the control ear. More recently, experimenters using the simultaneous dichotic balance procedure have compensated for a similar localization change by decreasing the intensity of the tone in the control ear. This intensity change has been presumed to produce a loudness change equivalent to that occurring in the adapted ear. This presumption is in question since the method of delayed balance (4, 23, 108), based on a loudness judgement alone, does not provide the same results as the method of simultaneous dichotic balance (12, 13, 21, 22, 23, 46, 47, 73). Since the MPL appears to be dependent on AP latency, some factor other than loudness, which has an effect on this latency might be operant in the adapted ear. Thus, it seems probable that the localization changes observed are not due to loudness changes alone.

The simultaneous dichotic loudness balance is a convenient means of studying loudness adaptation as the course of the phenomenon can be plotted during a single adapting period. For this reason it has received wide use even though its validity as a means of measuring loudness has been questioned by Egan and Thwing (23), Jerger (52) and Jerger and Harford (56). The basis for the subjects' judgements is not entirely clear as pointed out by Small and Minifie (92) who report that their subjects could perform the localization task during the pre-adapting balances and during the first minute of the adapting period, but after that, were unable to detect the single fused sound image and were forced to base their judgement of equality on the loudness of the stimuli at the two ears. Wright (111) on the other hand, reports that the task is one of localization even after seven minutes of stimulation. Other experimenters (12, 13, 46) also refer to the task as being one of localization and apparently assume its equivalence to a loudness balance.

Egan (22) questioned this assumption and devised the method known as the heterophonic loudness balance. With this method, the adapting and comparison stimuli are separated in frequency enough so that each tone is heard separately at the ear to which it is presented, precluding a localization judgement. Using an adapting tone of 800 Hz at 80-dB SPL, Egan measured 12.5 dB of adaptation when the comparison tone was 805 Hz and only 3.8 dB when the comparison tone was 1 kHz. This comparison was made on only one subject. In an expanded experiment, he compared comparison tones of 800 Hz and 1 kHz in 8 subjects with the adapting tone remaining at 800 Hz. The mean amounts of adaptation were 17.16 dB for the homophonic balance and 9.84 dB for the heterophonic balance. This difference was significant only at the 7% level of confidence. These results were obtained using the method of fixed intensity. With the method of varied intensity the difference was less (27.48 dB for the homophonic balance and 22.54 dB for the heterophonic balance) though in the same direction. Since a significant difference between the two procedures was not observed, Egan concludes that the MPL provides results equivalent to a true loudness balance. Evidence to the contrary is presented by two early experiments, those of Bekesy (4) and Wood (108), and a later one by Egan and Thwing (23) which have used the method of delayed balance. The latter of these studies is the only one other than Egan's (22) study which compares loudness judgements with judgements that may utilize localization cues. Therefore, it is difficult to evaluate the effects of the type of judgement because of the limited evidence.

Results obtained using the delayed balance procedure appear to demonstrate less adaptation than is reported from use of the methods employing the simultaneous dichotic loudness balance. Egan and Thwing (23) speculate that the reason for this difference is that localization may be determined by the location of the maximum rather than by the total area of the excitation pattern on the basilar membrane. It is also apparent from the data of Egan and Thwing that with the delayed balance procedure, asymptote is reached in a shorter time than with the simultaneous balance method. From this study it might be speculated that the loudness change and the localization change are distinctly different entities and may not be specifically related to one another. Egan and Thwing's results, however, are from only one subject, and their simultaneous balance was carried out using a long, 15 second, comparison tone. For these reasons, definite conclusions cannot be reached about the relationship between these two procedures on the basis of this study.

It seems that the results of many loudness adaptation experiments are contaminated by localization changes. It would add considerably to the knowledge of auditory physiology if these two changes could be separated with regard to their extent and their relation to the stimuli that cause them. In order to do this, the method of delayed balance which measures loudness adaptation must be compared with the simultaneous dichotic loudness balance procedure which measures localization-plus-loudness adaptation. These procedures are, unfortunately, time consuming and require precise control of the stimuli. Perhaps it is for these reasons that neither procedure has been utilized to any considerable extent.

CHAPTER III

INSTRUMENTATION AND PROCEDURE

Introduction

This investigation is designed to determine whether experimental procedures in which signals of identical frequency and phase are presented simultaneously to the two ears can yield results similar to those produced by procedures in which the subject must make equality judgements based on loudness cues alone. The purpose is to compare the results of the delayed balance procedure used by Bekesy (4) and by Wood (108) which provides only loudness information to the subject with those obtained by a modification of Hood's (46) simultaneous dichotic loudness balance procedure which presents the subject with both loudness and localization information.

It became apparent in the design of the experiment that instructions to the subject for responding to the simultaneous presentations could take any one of three forms. These instructions can be a vague statement to "equate" the tones in the two ears in any way the subject chooses, or they can be a definite statement to equate on a loudness basis or, finally, to produce a median plane localization. A review of the literature revealed few references to instructions given the subject for the simultaneous balancing task and no attempts to determine the effect of instructions on simultaneous balance results. It was, therefore, felt essential to investigate this variable before proceeding to the primary question.

Subjects

Part I of this study employed ten subjects with normal hearing between the ages of 21 and 35 years. In Part II of the study, five of these ten subjects and one additional subject were used. The subjects were selected from the student body of the Department of Communication Disorders, University of Oklahoma Medical Center, Oklahoma City, Oklahoma. Each had had previous experience as a subject in psychophysical experiments in audition and demonstrated an ability to perform the tasks required by this study. Normal hearing was defined as thresholds not greater than 10 dB (ISO) at any frequency in either ear at the octave interval frequencies from 500 Hz to 2 kHz inclusive. In addition, thresholds of the two ears of each subject for a 1 kHz tone were within 5 dB of each other as determined by the standard clinical procedure modified only by the use of 2-dB rather than 5-dB steps. The participants also reported a negative history of ear pathologies and negative findings upon otologic examination.

The right ear of each subject was designated as the test ear while the left was the control ear. This designation remained unchanged throughout the study.

Apparatus

Acoustic Environment

All screening, practice and experimental tests were conducted in one room of a sound-isolated suite located in the Speech and Hearing Center, University of Oklahoma Medical Center, Oklahoma City, Oklahoma. Visual communication between subject and experimenter was carried out through an acoustically-damped window located in the wall separating the two rooms of the suite. A "talk-back" system permitted the subject to communicate verbally with the experimenter. The subjects' room contained a standard headset with matched earphones, a light signal and a talk-back microphone. All other equipment was located in the experimenter's room.

Ambient noise levels in the experimental chamber were measured by a sound level meter (General Radio, Type 1551-C) combined with an octave band noise analyzer (General Radio, Type 1558-AP). Readings were obtained for octave bands whose center frequencies were at octave intervals from 125 Hz to 8 kHz. Average spectrum levels and levels per critical band (95) for the bands centered at the standard audiometric testing frequencies were calculated. To determine the effective masking level of this noise, the attenuation characteristics of MX-41/AR cushions, used in this study, as determined by Shaw (89) were subtracted from the critical band levels. It was found that these levels are considerably below the threshold levels of normal listeners. The results of the above procedures are recorded in Table 1.

The critical band widths used to determine the levels per critical band are those given by Stevens (95). These are approximately one-half the width of the bands established by Zwicker, Flottorp and Stevens (113). When these greater widths are used, the resulting levels are still well below normal threshold at all standard testing

TABLE 1

NOISE CHARACTERISTICS UNDER EXPERIMENTAL CONDITIONS

Frequency	125	250	500	1000	2000	4000	8000
Noise levels in sound isolated room Octave band level	27.0 dB	26.0 dB	25.0 dB	24.5 dB	22.0 dB	21.0 dB	21.5 dB
Level per critical band	25.5 dB	20.5 dB	17.0 dB	15.0 dB	11.5 dB	11.5 dB	11.5 dB
Average attenuation of earphones	10.0 dB	8.0 dB	8.0 dB	16.0 dB	29.0 dB	35.0 dB	31.0 dB
Average noise level at subject's ears	15.5 dB	12.5 dB	9.0 dB	-1.0 dB	-17.5 dB	-23.5 dB	-19.5 dB

All dB levels are re: .0002 dyne/cm^2

frequencies.

Screening Apparatus

The screening apparatus consisted of a commercially available pure-tone audiometer (Beltone, Model 15 CX) feeding one of a pair of earphones (Telephonic TDH-39 10Z) set in MX-41/AR cushions and mounted on a standard headband. The output of the system was calibrated with an audiometer calibration unit (Western Electric 640AA Condenser Microphone and Condenser Microphone Complement, Western Electro-Acoustical Laboratory, Type 100 D/E).

Practice and Experimental Test Equipment

A pure-tone audio oscillator (Hewlett Packard, Model 201 CR) was used to generate both the adapting and comparison signals. A splitting network divided the signal which was then led to two electronic switches (Grason Stadler, Models 829 C and 829 S 159) which were triggered by an external source to provide the temporal relations required for a given experimental run. A speech audiometer (Grason Stadler, Model 162) provided attenuators to control the intensities of the signals. Two matched earphones (Telephonic TDH-39 10Z) were used to transduce the signals. These were set in MX-41/AR cushions and mounted on a standard headband.

Prior to the start of each experimental session, the intensity of the signals was calibrated with an artificial ear (Allison Labs, Model 300) which had been checked against another of the same model and against the Western Electric unit mentioned above. Attenuator linearity was established with the same unit before the study was begun.

An oscilloscope (Tektronix, Type 532 with a Type CA Plug-in Unit) was used to determine the phase relation of the simultaneously presented signals. The experimental apparatus is diagrammed in Figure 1. The timing apparatus used to trigger the electronic switches which initiate and terminate the signals is shown in Figure 2.

The timing network utilized two waveform generators (Tektronix 162) and three pulse generators (Tektronix 161) powered by a Tektronix 160 A power supply. Four arrangements of these were used for (A) preadapting simultaneous balances, (B) simultaneous balance test runs, (C) preadapting loudness balances, and (D) delayed balance test runs. Part I of the study employed arrangement "A" and a minor modification of "B" whereby the signal from switch #1 was not terminated when that from switch #2 was. These arrangements were all made by modifying the connections among the generators. The pulse delays, which determine the durations of the preadapting and the final balance comparison tones, were calibrated prior to each session with a counter-timer (Transistor Specialties Inc. 361) which was also used to calibrate the frequency of the signals.

The various signal sequences were controlled as follows: For the preadapting balances (see Figure 2-A and C) the waveform generator was set on recurrent to provide a series of waveforms, thereby producing a continuous pattern of signals as shown on Figure 3-A and C. In test runs, waveform generators 1 and 2 were triggered manually by the experimenter, releasing the pulses used to initiate and terminate the adapting signal. In addition, the pulses triggered by waveform generator 2 initiated and terminated the comparison signal. With a delayed balance run,

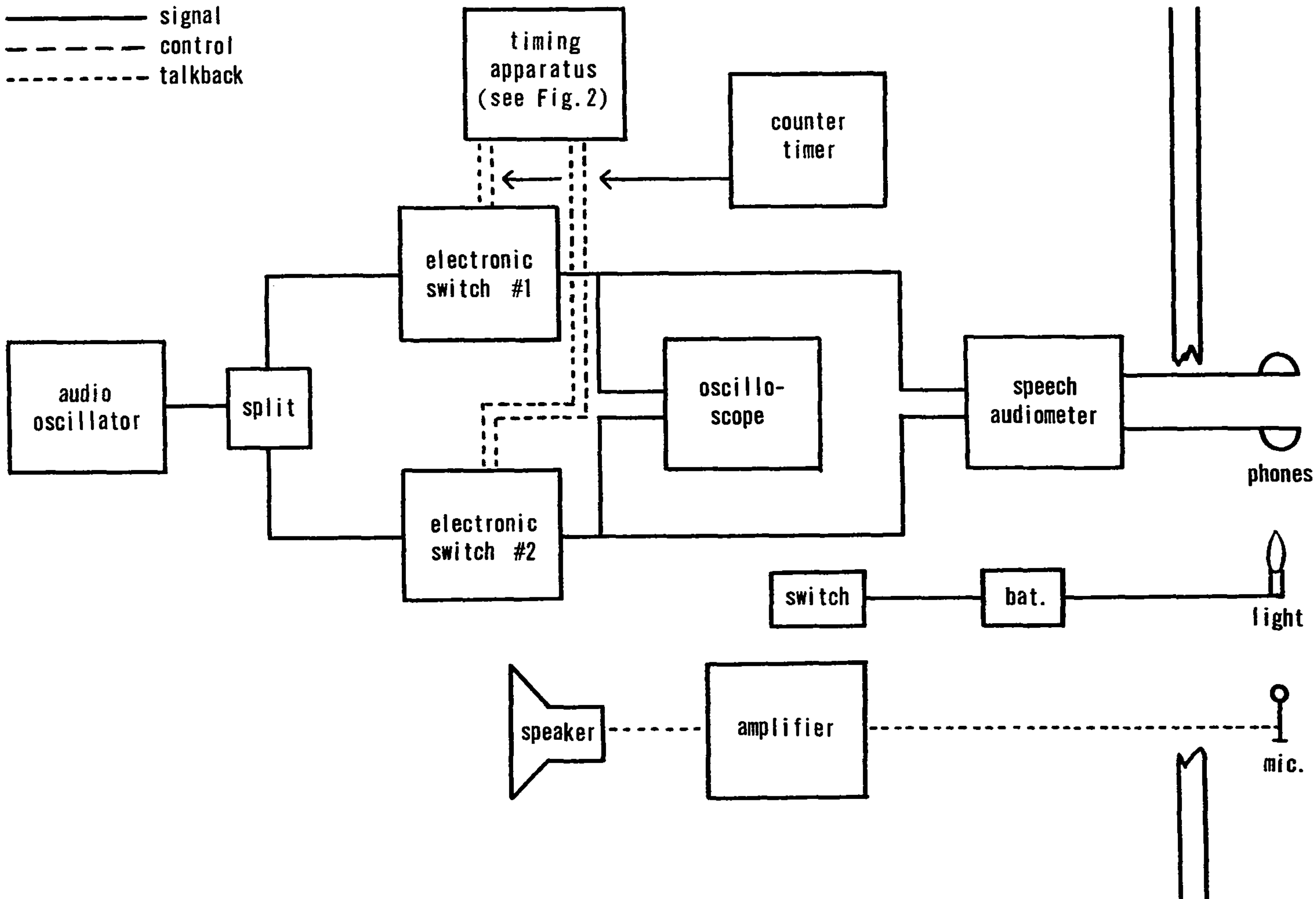

Figure 1. Simplified block diagram of experimental apparatus.

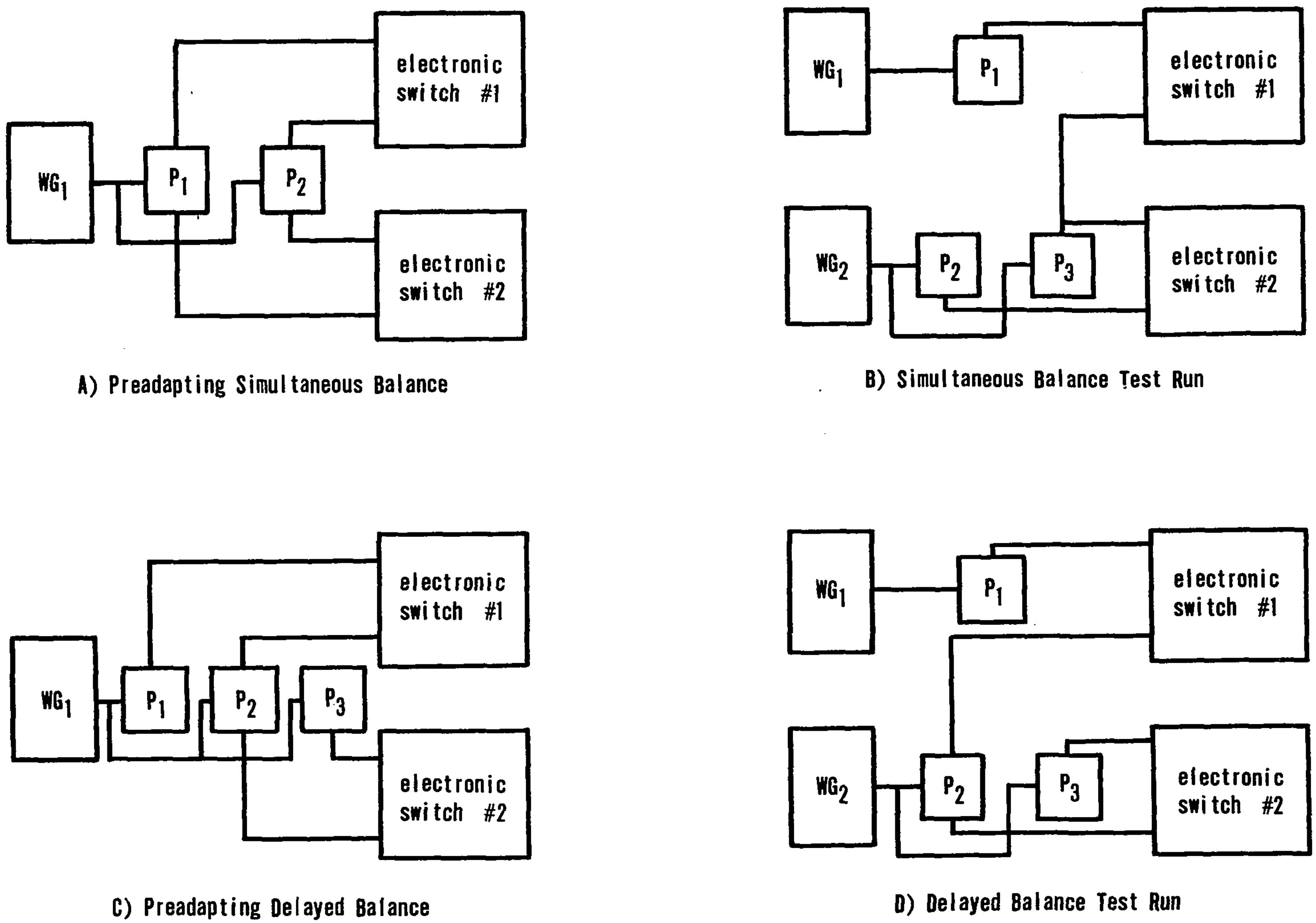

Figure 2. Simplified block diagrams of timing networks.

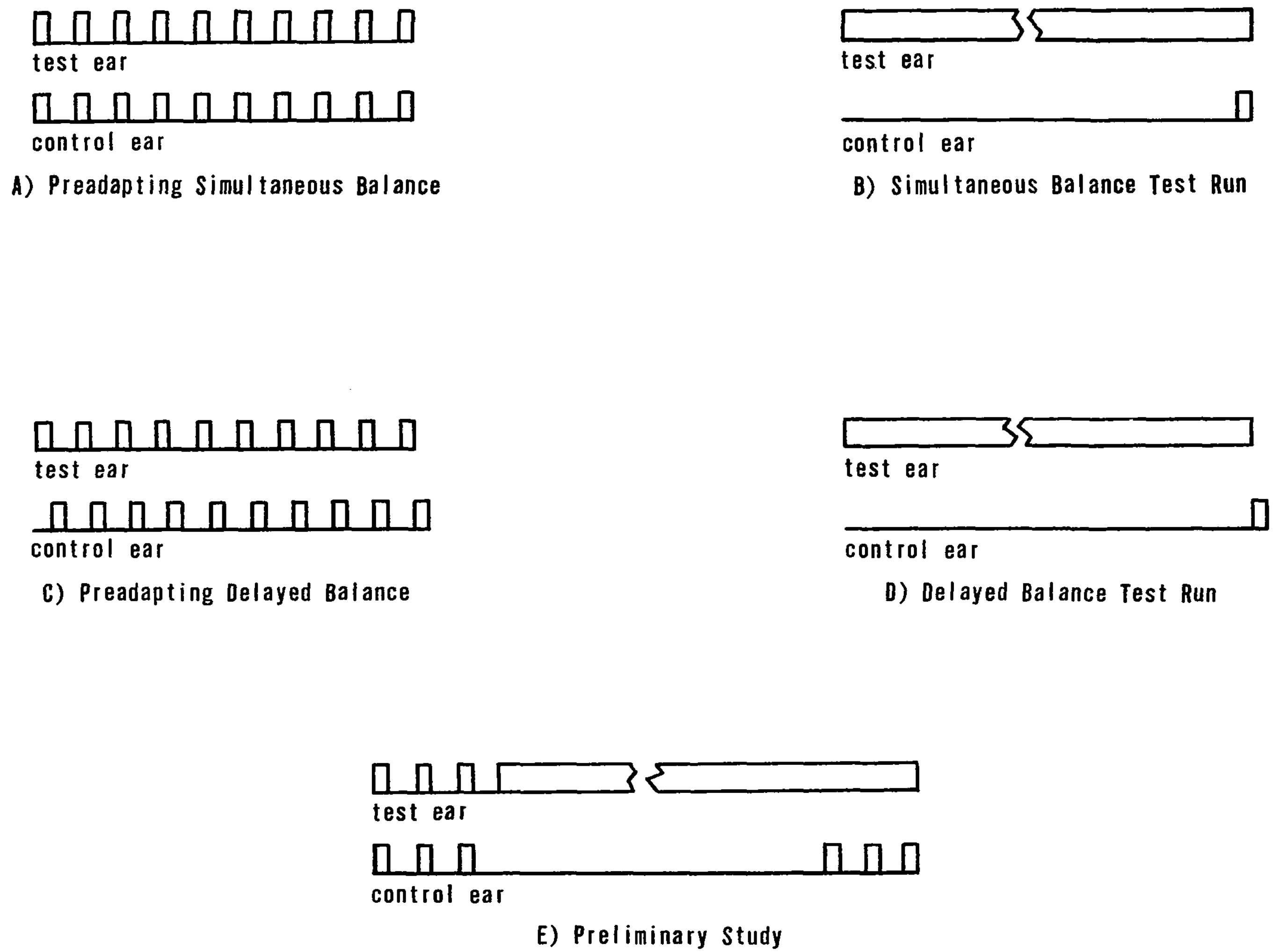

Figure 3. Experimental paradigms.

the comparison signal began when the adapting signal was terminated and then ended one second later. With a simultaneous balance run, the comparison signal started one second before the end of the adapting signal and they both terminated at the same time. The counter-timer was triggered by pulses 1 and 3 (Figure 2B - simultaneous) or by pulses 1 and 2 (Figure 2D - delayed) and the durations of the adapting tones were monitored on the counter-timer by the experimenter. The durations of these adapting stimuli were maintained within $\pm$ .5 second of those prescribed in the study.

In Part I of the study (see Figure 3E) the preadapting balances were presented in the same way as during the preadapting simultaneous balance. To present the adapting period and perstimulatory balances, the arrangement shown in Figure 2B was modified by disconnecting pulse 3 from switch #1 and setting waveform generator 2 for recurrent triggering. The five-minute presentation of the adapting tone prior to the perstimulatory balances was timed by the experimenter with an ordinary wrist watch.

Procedure

Introduction

The measurement of perstimulatory loudness adaptation consists of three phases: the preadapting balance during which stimuli presented to both ears are equated along some sensory experience parameter, the adapting period during which only the test ear is stimulated and a measurement period or periods during which the opposite or control ear is restimulated and the auditory experience at the two ears compared. The stimulus to the comparison ear can be presented one or several times and either during or following the adapting period. Usually, the stimulus to the comparison ear is adjusted either during or between the measurement periods until the subject judges that a balance between the two ears has been re-established. The measure of adaptation is the extent to which the signal at the comparison ear must be modified from the preadapting balance to re-establish a balance in the measurement period.

The present investigation is composed of two parts: the first is designed to investigate the effect of instructions to the subject, and the second is designed to compare a simultaneous with a delayed balance holding all other factors constant including the instructions to the subject. All signals used in the study were 1 kHz pure tones with rise-decay times of 50 msec. According to Wright (110) these rise-decay times are sufficient to prevent audible transients. Prior to the start of the study it was observed that changes in the rise-decay times did not appear to affect the amount of adaptation measured. The signals presented to the test ear were either 50- or 80-dB SPL in all parts of the study. Preadapting-balance tones and comparison tones were all one second in duration, and when more than one was presented to an ear they were separated by a duration of two seconds.

Part I

Each of ten subjects participated in two experimental sessions to determine the effects of the instructions given by the experimenter and, thereby, the task to be performed by the subject. One-half of these subjects were exposed to an adapting tone of 50-dB SPL while the exposure level for the other five subjects was 80-dB SPL. All other factors remained constant throughout the study. Figure 3E shows the signal relationships employed in this part of the study.

Preadapting balances were made by simultaneously presenting one-second 1-kHz tones to the two ears. The subject reported equality of the two stimuli when the tonal image appeared to be in the midline. The subject was instructed to report any deviation from midline while the experimenter adjusted the intensity being presented to the comparison ear. Several midline judgements were made during the preadapting period.

The subject was then informed that he would hear a steady tone in his right ear and that after five minutes, comparison tones (one one-second tone every three seconds) would be re-introduced to his left ear. The subject was told that he was to equate the steady adapting tone with the interrupted comparison tone on a loudness basis and, after each presentation of the comparison tone, report which was louder, or whether they were equal in loudness. After several of these judgements, the experimenter would signal the subject. The subject was instructed to change his task at this signal to one of localization. On each presentation of the comparison tone the subject was to localize the stimulus by placing his finger at that point on his head where the tonal image appeared to be. After several of these judgements and another signal from the experimenter the task reverted to equal loudness judgements followed by another signal from the experimenter and more localization judgements to end the session.

Following these instructions, the session was begun with the presentation of the adapting tone. After five minutes the comparison tones were introduced to the control ear while the adapting tone continued. The experimenter controlled the intensity of the comparison tones in three ascending and three descending series in each measurement period, thereby obtaining six equality judgements per period - a total of twenty-four judgements per subject, twelve loudness and twelve localization. This entire procedure was repeated in a second session during which the order of judgements was reversed to localization-loudness-localization-loudness.

Part II

Practice sessions. Two practice periods were conducted for each of the six subjects used in Part II. In the first of these, the subject was given practice in making judgements of equal loudness and of median plane localization. For the loudness judgements, the experimenter alternately presented 1-kHz pure tones to the subject's two ears and adjusted the intensity of the comparison tone about the level which provided the equality judgement. The median plane localization judgements were made by presenting 1-kHz tones simultaneously to the two ears. Again, the experimenter adjusted the intensity of the comparison tone until the midline judgement was made. Reference tone intensities were 80-dB and 30-dB SPL. When the subject demonstrated proficiency at these tasks, the first session continued, using the delayed-balance technique described in the next section.

The second practice period employed the simultaneous-balance procedure also described in the next section. In these practice periods, the experimenter presented a wide range of comparison tone intensities in an attempt to approximate the intensity which would provide an equality judgement. When two intensities not more than 10 dB apart yielded opposite judgements, i. e., "left louder" and "right louder," the actual final balance level would lie somewhere between. Attainment of this 10-dB range for each procedure and each condition ended the practice sessions.

Experimental sessions. In this part of the study, six experimental sessions were conducted for each of six subjects, two sessions under each of three experimental conditions. The experimental conditions were parameters of the adapting tone; (A) 50-dB SPL for 30 seconds, (B) 80-dB SPL for 30 seconds and (C) 80-dB SPL for 2 minutes. Each session consisted of preadapting balances and several runs of each of two types, delayed balance and simultaneous balance, presented in a balanced order. The order of the six sessions was also balanced among the observers. Figure 3 shows the signal relationships of (A) preadapting simultaneous balances, (B) simultaneous balance test run, (C) preadapting delayed balances and (D) delayed balance test run.

In the preadapting period, the observer was presented a series of one-second 1-kHz tones either alternately or simultaneously to the two ears. The intensity of the tones presented to the test ear was either 50-dB or 80-dB SPL depending on the condition under investigation. In the delayed balance, a one-second tone was presented to the right then to the left ear. This was followed by at least one second of silence in which the loudness judgement was to be made. Each ear was thereby allowed a two-second period for recovery between stimuli. When the tones were presented simultaneously, subsequent stimulations were also separated by a silent interval of two seconds.

The subject was instructed to respond to each pair of stimuli by saying in which ear the tone was louder or when the loudness was equal during the delayed balance. During the simultaneous balances, equality was judged by a median plane localization. Jerger and Harford (56) have reported that alternate binaural loudness balances and simultaneous binaural balances yield equivalent results in normal hearing subjects. The subject was instructed to localize the sound image by pointing to its apparent location in or about his head. During all balances, the experimenter adjusted the comparison tone intensity with a 2-dB step attenuator, three crossings of the balance level being made from each direction. For each of the procedures, the mean of the six judgements was used as the preadapting balance level for a given experimental session.

Following the preadapting balances, the subject was informed that he would hear a steady tone in his right ear for either 30 seconds or 2 minutes, and that just before this tone ends (simultaneous balance) or just as it ends (delayed balance) a brief comparison tone would be presented to the control ear. In both cases, he was instructed to compare the loudness of the comparison tone with that of the final segment of the adapting tone and report to the experimenter which was louder or if they were of equal loudness. The complete written instructions presented to the subject are found in APPENDIX A.

The experimenter then initiated the adapting signal and simultaneously the counter-timer was triggered on. The attenuator controlling the comparison tone intensity was set at some level within the 10-dB range established in the practice sessions. About 5 seconds before the end of the adapting period, the experimenter turned on the light placed before the subject to signal him that the comparison tone was about to be presented. The experimenter then presented the comparison tone in the proper temporal relation for the type of balance required. The counter-timer was triggered off with the adapting tone and the duration of the tone was noted. If this duration was within the limits allowed ($\pm$ .5 sec.), the subject's loudness judgement and the comparison tone intensity level were recorded for that run.

For the final balance judgement, three different responses could be given by the subject: (1) the comparison tone is louder, (2) the adapting tone is louder and (3) the tones are of equal loudness. If the first response was given, the intensity used for the comparison tone in the next identical run was decreased by 4 to 6 dB from that used in the first run. Similarly, if the second response was given, the intensity used in the next run would be increased by 4 to 6 dB. If the third response was given, the comparison tone intensity used in the next run was either increased or decreased by 4 to 6 dB. This was done to determine the appropriateness of the subject's response and to establish the limits of the range of comparison tone intensities throughout which the equal loudness judgement would be maintained. Further modifications of the comparison tone intensity were made in subsequent runs, thereby reducing the possibility of accepting false positive responses and establishing the range of comparison tone intensities which consistently provided the desired equality judgement. Consistency was considered to have been achieved when two out of three balances with a given comparison tone level resulted in the same judgement. When the range of intensities which resulted in equality responses had been determined, the experimental session ended.

Between the runs in an experimental session, the subject rested quietly in the sound isolated room to allow recovery from the effects of the adapting tone. This recovery period was no less than one and one-half minutes following short duration stimulations and no less than three minutes following longer exposures. It has been demonstrated by Small and Minifie (92), Thwing (97) and Sergeant and Harris (88) that these periods are sufficient to allow complete recovery.

CHAPTER IV

RESULTS

Introduction

This investigation is concerned with two of the variables encountered in the measurement of loudness adaptation. The first involves the judgement the subject is asked to make. Reports of previous investigations (12, 13, 23, 46, 52) have not been specific as to the instructions given the subject for the simultaneous balancing procedure. It has not been determined that asking the subject to equate the loudness at the two ears and asking him to attain a midline localization of a fused sound image will yield equivalent results when used to measure loudness adaptation. The first purpose of the present study was to determine whether or not this is true.

The second variable is the time of presentation of the comparison tone; that is, the effect of whether it is presented simultaneous with or subsequent to (delayed) the adapting tone. Although both temporal sequences appear to provide measures of perstimulatory adaptation, no controlled comparison of the procedures has been made. The second purpose of this investigation was to make a comparison of the results obtained by these two methods holding all other parameters of the adapting and comparison tones constant and requesting that judged equality at the two ears be based on loudness in both cases. The results obtained in both parts of this study and a comparison of these results with those of other loudness adaptation studies are reported in this chapter.

Results of the Present Study

The results are divided into two parts. Asymptotic adaptation measured by equal loudness balances and midline localization balances are presented in Part I. The results of the simultaneous and delayed balance techniques are presented in Part II.

Part I

Individual subject data for Part I are reported in Table 2. The analysis of variance and the results of the factorial analysis are reported in Table 3.

Mean amounts of asymptotic loudness adaptation as measured by simultaneous loudness balances are 21.98 dB with a 50-dB SPL tone and 24.15 dB with an 80-dB SPL tone. When the instructions to the subject are to localize a fused sound image at the midline, the amounts of asymptotic adaptation are 31.92 dB with a 50-dB SPL tone and 52.65 dB with an 80-dB SPL tone. The factorial analysis reveals a significant difference ($p < .05$) between the measurements made by loudness and localization balances. The difference in adaptation resulting from signal levels of 50-dB and 80-dB SPL is also significant at the .05 level. The difference between measures determined in the first and second experimental sessions is not significant.

A significant interaction is observed between task (loudness and localization) and level (50- and 80-dB SPL). The analysis of this

TABLE 2

MEAN DATA FROM INDIVIDUAL SUBJECTS IN PART I OF THE PRESENT STUDY

Subject #	Adapting Tone Level	Session I		Session II		Mean	
		Loudness	Localization	Loudness	Localization	Loudness	Localization
1	50	12.67[a]	25.83[a]	14.50[a]	26.33[a]	13.58[b]	26.08[b]
2	50	26.67	34.83	23.50	31.17	25.08	33.00
3	50	24.50	38.67	27.17	37.17	25.83	37.92
4	50	24.00	29.83	20.33	28.50	22.17	29.17
5	50	26.33	37.67	20.17	29.17	23.25	33.42
Mean	50	22.83	33.37	21.13	30.47	21.98	31.92
6	80	27.17	46.33	18.67	53.67	22.92	50.00
7	80	18.33	39.00	23.00	40.17	20.67	39.58
8	80	20.83	65.17	42.50	64.00	31.67	64.58
9	80	38.17	51.83	35.33	46.00	36.75	48.92
10	80	22.50	64.50	16.67	55.83	19.58	60.17
Mean	80	25.40	53.37	27.23	51.93	26.32	52.65
Grand Mean		24.12	43.37	24.18	41.20	24.15	42.28

[a] Average of 12 judgements
[b] Average of 24 judgements

TABLE 3

SUMMARY OF THE ANALYSIS OF VARIANCE OF PART I OF THE PRESENT STUDY

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Between Subjects	9	31 599.97		
Intensity Level (I)	1	18 850.14	18 850.14	11.83[b]
Subjects/I (error I)	8	12 749.83	1 593.73	
Within Subjects	470	59 444.83		
Task (T)	1	39 458.14	39 458.14	49.95[b]
Task x Intensity Level (T x I)	1	8 068.79	8 068.79	10.21[a]
T x Subjects/I (error T)	8	6 319.24	789.91	
Session (S)	1	132.20	132.20	0.38
Session x Intensity Level (S x I)	1	187.50	187.50	0.54
S x Subjects/I (error S)	8	2 784.03	348.00	
Task x Session (T x S)	1	149.63	149.63	0.52
Intensity Level x Task x Session (I x T x S)	1	32.04	32.04	0.11
T x S x Subjects/I	8	2 313.16	289.15	
Within Cell	440	4 020.67	9.14	

[a] Significant at the .05 level of confidence
[b] Significant at the .01 level of confidence

interaction is found in Table 4. The comparisons evaluated are not independent of one another, thus, the confidence levels are only approximate. The loudness balance results obtained with the 50-dB SPL adapting tone do not appear to differ significantly from those obtained with an 80-dB SPL adapting tone. Localization balance results at the two stimulus levels, however, do appear to differ significantly. Loudness and localization results apparently differ significantly both when the adapting tone is 80-dB SPL and when it is 50-dB SPL.

For localization balances, the comparison tone sound pressure levels are approximately the same for adapting tones of 50-dB and 80-dB SPL; that is, the image is centered in the head by a 20- to 30-dB SPL comparison tone whether the adapting tone is 50-dB or 80-dB SPL. On the other hand, when loudness balances are requested of the subject, the comparison tone intensities appear to be directly related to the level of the adapting tone while the apparent shift in the loudness of the adapting tone remains relatively constant across these two levels. Also, the difference between the results of loudness and localization balances increases as the SPL of the adapting tone increases.

Several of the ten subjects who participated in this part of the study volunteered that they had considerable difficulty making the localization judgements. When asked, all subjects expressed that localization judgements were more difficult to make than loudness judgements. A common report was that the adapting tone had lost much of its tonality or clearness by the time the judgements were made. This often was not noticed until the comparison tone was introduced, probably because the change in clarity of the adapting tone took place gradually.

TABLE 4

ANALYSIS OF THE TASK X INTENSITY LEVEL INTERACTION IN PART I

Source of Variation	Reference	Difference	Standard Error
Difference due to:			
Tasks	Intensity Level I (50-dB SPL)	9.94 dB[a]	3.63
Tasks	Intensity Level II (80-dB SPL)	26.33 dB[b]	3.63
Intensity Levels	Task I (Loudness)	4.34 dB	4.46
Intensity Levels	Task II (Localization)	20.73 dB[b]	4.46

[a] Significant at the .05 level of confidence
[b] Significant at the .01 level of confidence

This lack of clarity was described as a "fuzz" accompanying the tone. When the localization judgements were made, the subjects were unable to move the image of the "fuzz" from the adapted ear, and therefore, based their median plane judgements solely on the location of a tonal image which was separated spatially from the noise in the adapted ear. Midline judgements were made by all ten subjects, and it is assumed that contributions from both ears make up the tonal image; the comparison stimulus from the control ear and the tonal component of the adapting stimulus from the test ear. The quality change in the adapted ear will be discussed in more detail in the final chapter.

Part II

Individual subject data for Part II are reported in APPENDIX B, and means are presented in Table 5. The analysis of variance and the results of the factorial analysis are reported in Table 6.

The overall mean amounts of adaptation measured by the delayed and simultaneous balance methods are 5.4 dB and 12.8 dB respectively. Subject #2 demonstrated essentially no difference between the two procedures while the differences observed for the other subjects ranged from 6.5 dB to 13.8 dB, with more adaptation being measured by the simultaneous method than the delayed in all cases. The results of Subject #2 will be discussed in more detail later in this section.

Among the three adapting conditions, both the intensity and the duration of the adapting tones were varied. Mean amounts of adaptation to 30-second tones of 50-dB SPL and 80-dB SPL were 3.7 dB and 7 dB respectively with the delayed balance method and 11.3 dB and 14 dB respectively with the simultaneous balance method. Differences exhibited

TABLE 5

MEAN ADAPTATION IN EACH TASK, TRIAL AND CONDITION
FOR EACH SUBJECT IN PART II

Subject #	Means					Grand Mean
	Trial		Condition			
	I del./sim.	II del./sim.	A del./sim.	B del./sim.	C del./sim.	del./sim.
1	10.67/25.33	10.67/23.67	5.00/22.50	14.50/27.00	12.50/24.00	10.67/24.50
2	-4.00/-3.33	-2.33/-3.33	-4.00/-2.50	-3.00/-2.50	-2.50/-5.00	-3.17/-3.33
3	9.33/18.00	7.33/14.00	8.00/16.50	8.50/14.50	8.50/17.00	8.33/16.00
4	2.00/14.00	1.00/ 7.00	1.50/ 6.00	2.00/14.00	1.00/11.50	1.50/10.50
5	8.00/15.67	4.00/11.00	7.50/13.00	6.00/13.00	4.50/14.00	6.00/13.33
6	11.33/18.00	6.67/13.00	4.00/12.00	14.00/18.00	9.00/16.50	9.00/15.50
Mean	6.22/14.61	4.56/10.89	3.67/11.25	7.00/14.00	5.50/13.00	5.39/12.75

TABLE 6

SUMMARY OF THE ANALYSIS OF VARIANCE AND FACTORIAL ANALYSIS OF PART II OF THE PRESENT STUDY

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Subsamples	72	156.00	2.17	
Task (Ta)	1	1 950.70	1 950.70	15.47[a]
Condition (C)	2	224.39	112.20	0.89
Trial (Tr)	1	261.37	261.37	2.07
Ta x C	2	2.39	1.20	0.01
Ta x Tr	1	38.02	38.02	0.30
C x Tr	2	74.38	37.19	0.29
Ta x C x Tr	2	7.73	3.87	0.03
Error	60	7 566.33	126.11	

[a] Significant at .01 level of confidence

by individual subjects varied, with most of them demonstrating more adaptation with 80-dB tones than with 50-dB tones.

The subjects were all exposed to the 80-dB SPL stimulus for two durations, 30 seconds and 2 minutes. The mean amounts of adaptation with both delayed and simultaneous balance procedures were greater with the shorter stimuli. The delayed balance results were 7 dB and 5.5 dB for the 30-second and 2-minute durations respectively while the simultaneous balance results were 14 dB and 13 dB respectively. Differences exhibited by the individual subjects again varied, with the majority of the subjects demonstrating more adaptation to the shorter stimulus.

Under each of the adapting conditions, measurements of loudness adaptation were replicated in a second trial. Mean amounts of adaptation measured across the three experimental conditions in Trial I were 6.2 dB and 14.6 dB with the delayed and simultaneous balance methods respectively. In Trial II, the amounts of adaptation were 4.6 dB and 10.9 dB respectively with the delayed and simultaneous balance methods. These results reveal less adaptation in the second trial than in the first. Subjects #1 and #2 demonstrate essentially no difference between the trials while the other four subjects differ in the direction of less adaptation in Trial II. Though this difference is not significant at the .05 level of confidence, it may be indicative of either a learning factor or a long-term inhibitory effect.

Of the three factors, task (simultaneous and delayed balances), condition (50 dB for 30 seconds, 80 dB for 30 seconds and 80 dB for 2 minutes) and trial (first and second trials) only the difference due to tasks is significant at the .05 level of confidence. None of the interactions among the three factors is significant.

In addition to the measures of adaptation made in Part II, two additional tabulations were made. In Table 7 are found the numbers of experimental runs required of each subject for each task, under each condition and in each trial. Although no statistical analysis was made on this data, it appears that fewer runs were required for delayed balances than for simultaneous balances.

In most experimental sessions, several intensity levels of the comparison tone yielded judgements of equal loudness. The numbers of such levels per session are reported in Table 8. It is apparent that fewer of these levels were needed with the delayed than with the simultaneous balancing task.

The difference between the simultaneous and delayed balances is clearly observed for all subjects except Subject #2 (see APPENDIX B) whose balance levels were the same for both tasks. This subject demonstrated no adaptation with either procedure. Indeed, he demonstrated negative adaptation in ten of the twelve measurements made. Subject #2 made his judgements with relative ease. This is numerically illustrated first, by the number of experimental runs in a session and, second, by the number of comparison tone levels which yielded consistent equality judgements in a session. Subject #2 required a total of 101 experimental runs throughout Part II of the study, 11 fewer than any of the other subjects and 29 fewer than the mean of the six subjects. Subject #2 also required fewer runs for the simultaneous balances than for the delayed while the other five subjects required more runs for the simultaneous balance task.

TABLE 7

NUMBER OF EXPERIMENTAL RUNS PER SESSION IN PART II

Subject #	Trial I			Trial II			Totals					Grand Total
	Condition			Condition			Trial		Condition			
	A del./sim.	B del./sim.	C del./sim.	A del./sim.	B del./sim.	C del./sim.	I del./sim.	II del./sim.	A del./sim.	B del./sim.	C del./sim.	del./sim.
1	11/14	10/14	13/13	7/8	10/12	12/9	34/41	29/29	18/22	20/26	25/22	63/70
2	10/7	14/12	8/8	6/9	7/8	7/5	32/27	20/22	16/16	21/20	15/13	52/49
3	9/12	8/16	11/13	13/11	9/12	8/12	28/41	30/35	22/23	17/28	19/25	58/76
4	7/18	11/22	9/15	9/12	13/14	10/12	27/55	32/38	16/30	24/36	19/27	59/93
5	11/11	6/9	7/13	9/12	8/12	5/9	24/33	22/33	20/23	14/21	12/22	46/66
6	6/12	14/16	11/12	11/20	8/14	13/11	31/40	32/45	17/32	22/30	24/23	63/85
Totals	54/74	63/89	59/74	55/72	55/72	55/58	176/237	165/202	109/146	118/161	114/132	341/439

TABLE 8

NUMBER OF COMPARISON TONE LEVELS PER SESSION IN PART II
YIELDING CONSISTENT EQUALITY JUDGEMENTS

Subject #	Trial I			Trial II			Totals					Grand Total
	Condition			Condition			Trial		Condition			
	A del./sim.	B del./sim.	C del./sim.	A del./sim.	B del./sim.	C del./sim.	I del./sim.	II del./sim.	A del./sim.	B del./sim.	C del./sim.	del./sim.
1	1/2	1/2	1/3	1/1	2/2	2/1	3/7	5/4	2/3	3/4	3/4	8/11
2	0[a]/0	2/1	1/0	0/1	0/0	0/0	3/1	0/1	0/1	2/1	1/0	3/2
3	2/1	1/3	2/1	2/2	2/2	1/3	5/5	5/7	4/3	3/5	3/4	10/12
4	1/6	2/6	2/3	2/2	2/4	2/2	5/15	6/8	3/8	4/10	4/5	11/23
5	1/2	1/0	1/2	2/2	1/2	0/0	3/4	3/4	3/4	2/2	1/2	6/8
6	0/2	1/2	2/2	0/5	1/2	2/3	3/6	3/10	0/7	2/4	4/5	6/16
Totals	5/13	8/14	9/11	7/13	8/12	7/9	22/38	22/34	12/26	16/26	16/20	44/72

[a] "0" refers to sessions in which two consecutive comparison tone levels consistently yielded judgements to the opposite though appropriate ears. The equality level is interpolated as being midway between these levels.

The numbers of different comparison tone levels (in 2-dB steps) yielding consistent equality judgements give an indication of each subject's variability for both tasks (simultaneous and delayed), under each of the three conditions and for both trials. Subject #2 made equality judgements over a smaller range of levels than others and, in some sessions, he did not make an equality judgement; that is, he reports consistent opposite-ear judgements for comparison tones with intensities only 2 dB apart. Also, more variability is associated with the simultaneous than with the delayed balance task for all subjects except Subject #2.

A key to the reduced variability of Subject #2 is the subjective responses and comments made by this subject. All except Subject #2 reported either a change in the pitch of the adapting tone or a change in its quality or both. The quality change was described by most subjects as a "fuzz" or "noise" accompanying the tone. Subject #2 reported neither change. Thus, he was able to balance two stimuli which appeared to him to be identical in pitch and quality. Loudness balances are more reliable when the pitches of the stimuli are the same, thus the lack of clarity or the change in pitch of the adapting tone noted by all subjects except Subject #2 may have contributed to the larger variability of their responses.

The simultaneous loudness balance procedures of Parts I and II differ primarily in that with the asymptotic adaptation procedure of Part I, a series of one-second comparison tones is used while in Part II only one one-second comparison tone is presented in each experimental run. With this latter procedure, it appears that an asymptote of less than 15 dB is reached within 30 seconds. In Part I, however, the mean amount of asymptotic adaptation is found to be approximately 25 dB for the same stimulus intensity levels. It appears that this difference in measured adaptation is due to either the difference in the procedures used, or the difference in the durations of the adapting tones.

The present study has employed four methods which have been used to measure loudness adaptation. It has been demonstrated by this study that these methods yield different results. The method of asymptotic localization appears to demonstrate more adaptation than either the simultaneous or delayed loudness balances. The simultaneous loudness balance methods yield more apparent adaptation than does the delayed loudness balance method. In addition, the simultaneous loudness balance procedure used in Part I of the study yields more loudness adaptation than the simultaneous procedure used in Part II.

Comparison of Results of Present Study With Those of Other Studies

Asymptotic Localization

The method of asymptotic localization was used by Wright (111) in 1960. Wright stimulated with a 90-dB SPL, 500 Hz tone for a duration in excess of seven minutes and measured 50 dB of adaptation. In the asymptotic localization portion of the present study, using a 1 kHz tone of more than five minutes duration, the amounts of adaptation were 31.92 dB with a 50-dB SPL tone and 52.65 dB with an 80-dB SPL tone. The 80-dB SPL result is in good agreement with that of Wright.

Simultaneous Loudness Balance

Simultaneous loudness balance procedures have been used in prior studies of loudness adaptation, but not under the same stimulus conditions employed in this investigation. Both of these methods differ from those used by other investigators (12, 13, 22, 23, 46, 52, 97) in that comparison tone durations of only one second rather than ten to thirty seconds are used. A second difference should not be overlooked. This is the possibility that midline localization judgements may have either influenced or replaced judgements of equal loudness in the earlier studies.

In spite of the differences between the simultaneous loudness balance methods used in this study and those used by other investigators, a fair amount of agreement is observed. Comparisons made in the following paragraphs involve results obtained by both procedures of the present study.

Hood (46) reports approximately 40 dB of adaptation when stimulating with a 1-kHz adapting tone of 80-dB SPL for $3\frac{1}{2}$ minutes. This is about 15 dB greater than demonstrated for any duration in the present study. Hood's results also disagree with those of Egan (22) and Jerger (52) by about the same amount. Egan measured 27.48 dB of adaptation with the simultaneous dichotic balance using the method of varied intensity. His stimuli were 80-dB SPL, 800 Hz tones and his measures were the average of those obtained at the fourth and seventh minutes of stimulation. With the method of fixed intensity, only 17.16 dB of adaptation was measured. Egan's (22) results with varied intensity are in the same range as those obtained in Part I (26.32 dB) of the present study. Jerger's (52) measurements with a 1-kHz, 80-dB SPL tone at two minutes and five minutes and a 1-kHz 50-dB SPL tone at five minutes were 21 dB, 25 dB and 17 dB respectively. These are also in fair agreement with the results obtained with comparable stimuli in the present study; 13 dB, 26.32 dB and 21.98 dB respectively.

Though a similarity exists between the results of Egan (22) and Jerger (52) and the results of the present study, a difference is noted in the rate of growth of adaptation over time. Under the conditions of Part II of the present study, it is observed that asymptote is reached within the first thirty seconds of stimulation, there being no greater adaptation observed with two-minute stimuli. In a recent study, Wittich (107) has demonstrated that asymptote is reached in sixteen seconds. His study, however, used a midline localization procedure. The studies of Egan (22) and Jerger (52) as well as those of other experimenters (12, 13, 33, 46) report that asymptote is not reached for several minutes. It is possible that this difference is due to the difference in procedure, more specifically to the differences in the duration and the number of presentations of the comparison tone in a given experimental run.

In both parts of the present study, the simultaneous dichotic loudness balance revealed no significant difference in the amounts of adaptation resulting from adapting tones of 50-dB and 80-dB SPL. Hallpike and Hood (33), on the other hand, report the amount of adaptation to increase with increasing levels of exposure. Carterette's (12, 13) studies also reveal this dependency of the amount of adaptation on the SPL of the adapting stimulus. Jerger's (52) results reveal a similar though not as clear a relationship. It is interesting to note that the localization results in Part I of the present study demonstrate a similar relationship, but the loudness balance results do not. The earlier studies (46, 52, 92) did not make explicit to the reader just what judgement, localization or loudness, their subjects were instructed to make. While the reporting and titles of these works imply that loudness judgements were made, the present study suggests that the outcomes may not be based on loudness judgements alone.

Delayed Loudness Balance

In the present study, the method of delayed balance yielded about 7 dB less loudness adaptation than the simultaneous loudness balance method. This finding is in agreement with the results of Egan and Thwing (23) who also compared simultaneous and delayed loudness balance methods, though their simultaneous balances were made with 15-second comparison tones. Egan and Thwing found 9 dB of adaptation with the delayed balance method and 13 dB with the simultaneous balance method when the adapting tones were 2 minutes in duration. The intensity of their adapting tones is not reported. Bekesy (4) measured 8 dB of adaptation with the delayed balance method when the adapting stimulus was an 80-dB SPL, 800-Hz, two-minute tone. The mean of the six subjects in Part II of the present study was 5.5 dB for a similar adapting stimulus. When the results of Subject #2, who did not adapt, are removed from consideration, the mean adaptation for this adapting stimulus becomes 7.1 dB. A comparison of the present study with that of Wood (108) is difficult to make since Wood did not report the intensity levels of his adapting tones. From an interpolation of the graphic representation of Wood's results, it appears that as much as 18 dB of adaptation results from signal durations of one minute or more.

Wood reports that adaptation reaches a maximum with one minute stimuli. Bekesy's (4) data, on the other hand, reveals that an asymptote is approached though not reached within the first 2½ minutes of stimulation. The results of the present study indicate that an asymptote is reached within the first 30 seconds which is in better agreement with Wood's data than with Bekesy's.

The present results reveal that the amount of adaptation, as measured by the delayed balance method, appears to be dependent on the intensity level of the adapting stimulus. Mean data of the present study reveal a difference of 3.13 dB between the adaptation to 80- and 50-dB SPL stimuli, but this difference is not significant. Bekesy (4) also reports more adaptation to result from more intense stimuli though the levels he used are greater than those used in the present study. Wood (108), on the other hand, found the amount of adaptation to be independent of stimulus intensity though he did not report the intensity levels used.

In conclusion, the present study yields data which are relatively consistent with that obtained in other loudness adaptation studies, provided that such comparisons take into consideration the methods used. Several of the earlier experimenters (52, 92, 108) also report that their subjects noted quality changes in the adapting tone similar to those reported in this investigation. The results of this study suggest that the adaptation obtained in a simultaneous presentation procedure is dependent upon whether the subject is asked to equate the tones at the two ears in loudness or to make a median plane localization of a fused sound image. Further, when the subject is asked to make a loudness judgement the outcome is dependent upon whether the comparison tone overlaps the adapting tone in time or whether it is presented after the adapting tone is turned off. A discussion of these results follows in Chapter V.

CHAPTER V

SUMMARY AND CONCLUSIONS

Introduction

The effects of constant stimulation of the auditory system, measured both during and subsequent to the stimulation, have been investigated by a variety of methods for more than half a century. One of these effects, loudness adaptation, has received considerable attention over the past forty years, since it appears that this phenomenon may yield valuable information about auditory physiology.

Of the procedures which purport to measure adaptation, most present the comparison tone to the control ear during stimulation of the adapted ear. Some of these experiments provide a measure of loudness adaptation while others provide a measure of an adaptation based on median plane localization. The reports of these studies do not make the instructions to the subject explicit. Further, no direct comparisons have been made of results obtained with the different instructions. One purpose of this study was to compare the apparent adaptation of the subjects under instructions to make median plane localization judgements with the performance of the same subjects under instructions to make equal loudness judgements.

As assumption underlying the use of simultaneous comparison tones is that the loudness of the comparison tone is unaffected by the presence of the tone in the adapted ear, or, alternatively, that whatever loudness change results from binaural stimulation occurs in both the control ear and the test ear equally. This means that there is no interaction between ears or that the interaction is such that the relationship between ears in unaffected. The second purpose of this study was to determine whether either assumption is valid under the stimulus conditions selected for investigation.

Procedure and Experimental Design

In the first part of the study, adaptation was measured by two simultaneous balance methods which differed only in that the subject in one instance was instructed to equate the adapting and comparison tones on the basis of their loudnesses, while in the other he was to equate them on the basis of a median plane localization of the tonal image. In the second part of the study, loudness adaptation was measured by the delayed balance method and a modification of the simultaneous dichotic balance method. With these two procedures, all parameters of the signals were held constant with the exception that with the delayed balance method, the one-second comparison tone was presented immediately subsequent to the adapting tone while with the simultaneous balance method, the one-second comparison tone was presented simultaneously with the final second of the adapting tone. In both cases the instructions to the subject called for equating the tones on the basis of their loudnesses.

All of the experimental sessions were conducted in a two-room sound-isolated suite. The subject was seated in the test chamber and all experimental apparatus except the earphones, talk-back microphone, and light signal were located in the other room. The experimental apparatus consisted of a pure-tone oscillator, splitting network, two electronic switches, a series of waveform and pulse generators, a two-channel speech audiometer and a pair of earphones. Monitoring and calibrating equipment included an artificial ear, a dual-trace oscilloscope and a counter-timer. The talk-back system consisted of a microphone, amplifier and speaker. All signal parameters were controlled by the experimenter.

Ten normally-hearing young adults, proficient at auditory tasks, were employed in the first part of the study. Two experimental sessions were conducted, each providing twelve judgements of equal loudness and twelve median plane localizations. For half of the subjects, the adapting stimulus was a 50-dB SPL 1-kHz tone while for the other half, the level of the 1-kHz tone was 80-dB SPL. An analysis of variance was applied to the results.

In the second part of the study, six sophisticated subjects with normal hearing performed delayed and simultaneous loudness balances in each of six experimental sessions. Two experimental sessions were devoted to each of the three experimental conditions under study - 1-kHz adapting tones with intensity-duration combinations of 50-dB SPL for 30 seconds, 80-dB SPL for 30 seconds and 80-dB SPL for two minutes. The first and second sessions for each of the conditions were treated respectively as Trial I and Trial II. A three-factor (task x condition x trial) analysis of variance was used to statistically analyze the results.

Results

Part I

The results of Part I of the study reveal that when a series of one-second comparison tones are employed in the measurement of asymptotic adaptation, the amount of adaptation measured is dependent on the type of judgement requested of the subject. When midline localization judgements are called for, more adaptation is measured than when equal loudness judgements are requested. When adaptation is measured on the basis of localization judgements, the amount of adaptation appears to be related to the level of the adapting stimulus. On the other hand, adaptation measured on the basis of loudness judgements does not appear to be dependent on the adapting tone intensity, at least between intensity levels of 50- and 80-dB SPL.

During this portion of the study, all of the subjects reported that the adapting stimulus lost its clarity and sounded as though it was accompanied by a "fuzz" or noise. This quality change made localization judgements particularly difficult for the subjects as their perception of the noise could not be moved away from the adapted ear. Thus, it would appear that only a portion of the adapting stimulus is involved in the localization judgements while the loudness of the total complex is used in making the equal loudness judgements.

Part II

When the simultaneous and delayed loudness balance methods were used, a significantly greater amount of adaptation was measured with the simultaneous method. This difference, approximately 7 dB, was constant across experimental conditions and trials. No significant differences were found among the conditions or between the trials. Neither of the two procedures used in this part of the study yielded as much adaptation as was observed with the methods used in Part I, though modifications of the simultaneous loudness balance were used in both parts. The difference in adaptation measured with these modifications may be due to either the procedural differences or to the longer adapting stimulus durations employed in Part I.

The results obtained on one subject (see Subject #2, APPENDIX B) were considerably different from those of the other subjects. Negative amounts of adaptation were consistently recorded for this subject and no apparent difference was observed between adaptation measured by the simultaneous and delayed loudness balances. In addition, Subject #2 required fewer experimental runs, demonstrated less variability and had less difficulty making judgements than any of the other subjects. An explanation for the deviant results of this subject might lie in the fact that he did not detect pitch or quality changes in the adapting tone.

Comparisons between the results of the present study and those of earlier investigators reveal good agreement when similar procedures are compared. In particular, the asymptotic localization results agree well with those obtained by Wright (<u>111</u>) with a similar method. The delayed balance results of Part II are in good agreement with those obtained by Bekesy (<u>4</u>) and Egan and Thwing (<u>23</u>). Simultaneous loudness results are difficult to compare with earlier studies, since the modifications employed in the present study have not been previously reported. Taking procedural differences into consideration, the results obtained with the present simultaneous loudness balance methods seem to agree well with those obtained in other studies.

Discussion

The results of the present study demonstrate that the measurement of loudness adaptation is dependent on both the procedure used to measure it and the judgement requested of the subject. Median plane localization balances and equal loudness balances have been shown to yield different results when the comparison tones employed are only one second in duration. This does not imply that the same difference occurs when longer comparison stimuli, such as those used by Hood (46), Egan (22) and others (12, 13, 52. 97) are utilized.

The loss of clarity of the adapting tone not only makes it difficult to localize a simple tonal image, but also provides a sufficient spacial separation of the adapting and comparison tones allowing the subject to balance the two with respect to their loudnesses. The subjects who were instructed to perform these tasks reported that two distinct sounds were perceived; a constant sound similar to a narrow band of noise was perceived in the adapted ear while, when the comparison tone was presented, a clear tonal image was perceived in addition to the noise. The location of this tonal image could be shifted from the left (control) ear to the midline and sometimes beyond the midline by attenuating the comparison tone. At no time, however, did the tonal image appear to be at the adapted ear as further attenuation of the comparison tone resulted in a disappearance of the tonal image, leaving only the noise in the adapted ear.

The development of the perceived noise in the adapted ear is felt to be due to a detuning effect. This leads to an explanation for the difference in results obtained by the midline localization and equal loudness balance procedures. The localization balances are achieved with lower intensity comparison tones than the loudness balances. The midline tonal image is achieved when the level of the comparison tone produces neural activity equal to the activity in the adapted ear of those neural elements initially responsive to the test frequency. The detuning effect causes additional neural elements to contribute to the sensation. These elements do not enter into judgements of the localization of the tonal image. On the other hand, the subjects made loudness balances by utilizing the loudness of the entire complex of sensation in the adapted ear and not merely the loudness attributable to the neural fibers which are responsive to the initial pure-tone stimulus.

Egan (22) reports essentially equivalent results from procedures which utilize comparison tones of frequencies either the same as or different from the frequency of the adapting tone. This implies, according to Egan, that adaptation measures which employ simultaneous loudness balances and those which utilize midline localization balances produce the same results. An explanation for the difference between Egan's results and those of the present study might be found in the duration of the comparison tone. In the present study and that of Wright (111), one-second comparison tones were employed. The brief duration of these tones and the silent intervals between them permit the subject to perceive them as having a clear pure-tone quality. With longer comparison tones, however, the quality is lost and both the adapting and comparison tones are perceived as being noisy. With this similarity of the two stimuli, the fused sound image would not be tonal, as in the present study, but may instead involve all perceived components of both the adapting and comparison stimuli. If such is the case, one would expect equality of loudness at the two ears with a bilateral intensity relationship more nearly equal to that which yields a midline localization.

For some of the subjects of this study the loss of clarity of the adapting tone was not noticed until a comparison tone was introduced to the control ear, while for others the noisiness was perceivable without contralateral stimulation. One subject (Subject #2 of Part II) reported this quality change only in Part I of the study when his control ear was stimulated repeatedly with one-second tones. In this part of the study, he adapted as much as did the other subjects. In Part II of the study, where only one one-second comparison tone was used, Subject #2 did not adapt, nor did he note any loss of clarity of the adapting tone. Although this observation was not investigated directly, it suggests a relationship between the amount of adaptation and the loss of clarity of the adapting tone.

In the second part of this investigation, a significant difference is observed between the amounts of adaptation measured by the delayed and simultaneous loudness balance methods. Greater adaptation is reported (a less intense comparison tone is required) for simultaneous loudness balances than for the delayed. One or more of the following hypotheses may explain this observation.

First, there is summation of loudness. The comparison tone, when presented simultaneously with the adapting tone, sounds louder than when it is presented alone. Two explanations make use of this hypothesis: (1) The subject is comparing the loudness of the simultaneously presented comparison tone in the final second of the adapting period with the loudness of the adapting tone immediately preceding the onset of the comparison tone. It is assumed that the adapting tone loudness does not, in itself, change significantly in the final few seconds of its presentation; therefore, immediately before presentation of the comparison tone, the loudness of the adapting tone is the same in both the delayed and simultaneous balance methods. The comparison tones, when presented simultaneously, appear louder than when presented delayed. Therefore, the intensity of the comparison tone must be reduced by the amount of loudness summation to achieve a balance in the simultaneous condition. (2) The subject is comparing the loudnesses of the adapting and comparison tones at the time when both tones are on. If the judgement of the magnitude of the adapting tone is made during this period, as requested in the instructions, the summation effect must be assumed to occur unequally for the comparison and adapting tones.

Second, there is inhibition of loudness. The presentation of a stimulus to one ear causes the loudness of a tone in the contralateral ear to be reduced. With this hypothesis, one must again assume that the effect in normal and adapted ears is unequal.

Third, there is a combination of summation and inhibition factors. A combination of the above or other hypotheses might also be proposed. Since both summation (or facilitation) and inhibition have been demonstrated physiologically in the auditory system, it is possible that one or both may explain the difference observed between measures of adaptation made with delayed and simultaneous balances.

The difference observed between the simultaneous loudness balance results of Parts I and II is of interest. In Part II, an apparent asymptote is reached within 30 seconds, whereas in Part I, additional adaptation is measured at an adapting tone duration of more than five minutes. Two possible explanations are offered. (1) The longer duration of the adapting tone used in Part I causes greater adaptation than observed with either duration used in Part II. (2) The difference in procedure (one comparison tone as opposed to many) is responsible for the difference in the results obtained. Additional studies are needed to explore and clarify this apparent difference.

In conclusion, the results of the present investigation reveal that the amount of adaptation measured is dependent on the task requested of the subject and whether the comparison tone overlaps in time or follows the adapting tone. Four methods were employed in this study. The localization procedure apparently measures some form of adaptation other than loudness adaptation. Two other procedures based on equal loudness balances were made with simultaneous stimulation of the test and control ears. Both of these procedures apparently measure loudness adaptation, but the results are contaminated by some form of binaural interaction. The delayed balance method also measures loudness adaptation. This method is free of interactive effects since at no time are stimuli presented simultaneously to the two ears. Although the three simultaneous balance procedures do not provide independent measures of loudness adaptation, they may prove to be of value in psychophysical investigations of binaural interaction.

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APPENDIX A

Instructions for Part II

You are about to participate in a psychophysical experiment on loudness adaptation. You will be required to make judgements of the loudness of tones presented either simultaneously to the two ears or consecutively - first in one ear then in the other. In each experimental session there will be several runs involving each type of judgement.

At the beginning of each session several preadapting balances will be made. In this period, signals will be presented either alternately or simultaneously to your two ears. Following each pair of stimuli, you are to verbally report in which ear the tone was louder or that they were equal in loudness. When the signals are presented simultaneously, you will probably not be able to perceive two tones; instead, you will perceive a single sound image which will appear at some point between your two ears. You are to report to me the location of this sound image as being toward the right or toward the left ear or in the midline.

Following these balances, the first experimental run will begin. You will hear a steady tone for 30 seconds (2 minutes). Within five seconds of the end of this period, the light before you will flash on to signal you that a judgement is to be made.

The final balance will occur at the end of the adapting period. If it is a delayed balance run, a comparison tone will be presented after the adapting tone has terminated. You are to compare the loudness relationship of the final segment of the adapting tone with the comparison tone and report to me whether or not they are of equal loudness, and, if not, which is louder.

When the simultaneous balance is used, the comparison tone will be presented briefly and will terminate with the termination of the adapting tone. You are to judge the loudness relationship of the two tones when they are both on and report to me whether or not they are of equal loudness, and, if not, which is louder.

A rest period will follow each balance. During this period you are to remain silent and await the start of the next run. About half-way through the session, I will give you a five to ten minute break.

If you have any questions, please ask them now before we start the session.

APPENDIX B

INDIVIDUAL SUBJECT DATA FROM PART II OF THE PRESENT STUDY

Subject #	Trial I			Trial II			Grand Mean
	Condition			Condition			
	A del./sim.	B del./sim.	C del./sim.	A del./sim.	B del./sim.	C del./sim.	del./sim.
1	6[a]/25	16/29	10/22	4/20	13/25	15/26	10.67/24.50
2	-5/-5	-3/0	-4/-5	-3/0	-3/-5	-1/-5	-3.17/-3.33
3	11/18	8/16	9/20	5/15	9/13	8/14	8.33/16.00
4	2/9	3/19	1/14	1/3	1/9	1/9	1.50/10.50
5	10/17	8/17	6/13	5/9	4/9	3/15	6.00/13.33
6	5/14	18/21	11/19	3/10	10/15	7/14	9.00/15.50
Mean	4.83/13.0	8.33/17.0	5.50/13.83	2.50/9.50	5.67/11.0	5.50/12.17	5.39/12.75
Median	5.5/15.5	8.0/18.0	7.5/16.5	3.5/9.5	6.5/11.0	5.0/14.0	5.0/14.0
Mean with Subj. #2 excluded	6.80/16.60	10.60/20.40	7.40/17.60	3.60/11.40	7.40/14.20	6.80/15.60	7.10/15.97

[a]Each figure represents the mean adaptation measured in one experimental session