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ALTERNATE BINAURAL LOUDNESS BALANCE WITH

TONES OF UNEQUAL DUTY CYCLE

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Finally, to my beloved wife, Esther, I express my deepest appreciation for her love, her encouragement and her faith.

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CHAPTER I

INTRODUCTION

The "psychological systems" through which the magnitudes of sensory inputs are evaluated are easily deceived. In one commonplace experience, an inanimate object appears to grow heavier as it is lifted and held despite the intellectual assertion that the object's physical weight is constant. When the object is periodically lifted away by some other person, the weight is perceived as lighter. If the object is held only 20 per cent of the time, it may appear lighter than if it is held 80 per cent or 100 per cent of the time.

The loudness of on-going auditory signals may change as time passes in a manner similar to the perceived weight of an object. Unfortunately, the use of the classical psychophysical methods has yielded little information regarding the loudness of on-going pulse trains or on-going continuous sounds over long periods of time. By experimental design, loudness judgments are generally based upon samples which occur within relatively short discrete time periods. The test period is presented during which both reference and comparison signals may be sampled. Then the test period is terminated and a new test period is begun which is disconnected in time from the former period.

The results of experiments employing established psychophysical methods suggest that the relationship between time and intensity (temporal integration) for the loudness of sounds is complete at or near on-durations of 200 msec. Using the method of limits, Bekesy (3, p. 154) found that the loudness of an 800-Hertz (Hz) tone at 80-decibels (dB) sound pressure level (SPL) decreases when duration is shorter than 180 msec. Munson (46), using a forced choice method of constants, observed that a 200-msec tone of 1000 Hz presented at 70-dB SPL was approximately 2 phons softer than a 1-sec reference tone. Garner (19), using a method of adjustment, found that a 200-msec tone was only 1 phon fainter than a 500-msec 70-dB SPL reference tone. At 40-dB SPL there was no detectable difference in the loudness of 200-msec and 500-msec tones.

The self-recording Bekesy audiometer has made it possible for psychoacousticians to study the loudness of on-going signals which extend over relatively long periods of time. Bekesy audiometric tests yield unique results for experimental conditions in which subjects attempt to track loudness, i.e., to maintain a condition of constant loudness over a specified period of time. In this situation, loudness increases above or decreases below the reference point when the subject fails to respond. When the signal grows louder than the reference loudness, the subject decreases the signal's intensity in order to maintain a condition of constant or equal loudness. The opposite occurs when the signals grows too weak.

Loudness tracking data suggest the possibility that a regularly repeated interruption of an acoustic signal reduces the long-term loudness of the signal. It is unknown whether this loudness reduction is due to faulty loudness memory or to an averaging of acoustic energy by the auditory system over extended periods of time. The data of Hattler (23, 25, 26) suggest that within a period of three minutes the auditory system judges a repeated 200-msec tone louder when it fills 90 per cent of the listening period than when it fills only 20 per cent of the period. Perhaps a judgment of greater magnitude is allotted to signals with high duty cycles (percentage of time the sound is on) than to signals with low duty cycles, even when the on-durations surpass 200 msec. Hattler noticed that loudness-tracking levels were inversely related to the duty cycle of a 1000-Hz tone. It appeared that loudness level decreased 14 phons (at 50-dB SPL) and 9 phons (at 80-dB SPL) as the duty cycle was changed from 100 per cent to 20 per cent. On-durations ranging from 40 to 200 msec, when duty cycle is held constant, had a negligible influence on loudness-tracking levels. Other temporal parameters such as interruption rate (1 to 50 impulses per second, ips) and off-duration (20 to 800 msec) also had insignificant effects on loudness tracking independent of the duty cycle effects.

Rintelmann and Carhart (57) reported that interrupted signals with on-durations of 200 msec and with a duty cycle of 50 per cent are judged approximately 18 phons less loud than sustained tones of the same intensity when measured by a recalled-loudness task via the Bekesy audiometer. This would suggest a decrease to less than one-half loudness for a halving of the duty cycle. Hattler (23, 24), using loudness-adapted ears, found similar loudness changes. When the duty cycle of 200-msec tones was 50 per cent, the interrupted signals were 9.3 phons and 7 phons fainter than sustained tones at 50-dB and 80-dB SPL, respectively. The loudness of an interrupted signal with a 200-msec on-duration and a 20-per cent duty cycle diminished by 13.8 phons (at 50 dB) and 8.7 phons (at 80 dB) relative to the loudness of sustained tones.

The present investigation is designed to gather further knowledge of normal loudness perception during relatively long periods of time. It is hypothesized that the auditory system averages loudness over extended periods of time possibly for periods as long as several minutes. Furthermore, the auditory system may use information related to a signal's duty cycle in the long-term analysis of loudness. It may be found that a signal which fills 20 per cent of the total time is judged only one-half as loud as the same signal which fills 40 per cent of the total time and one-fourth as loud as the same signal with an 80-per cent duty cycle. The procedure to be employed involves the loudness matching or balancing of two alternating signals, a fixed-intensity reference signal and a variable-intensity comparison signal. If loudness is directly influenced by duty cycle, binaural signals will be balanced for loudness at different SPL's when there is a disparity of duty cycles and at similar SPL's when duty cycles are identical.

If the loudness of on-going sounds is, in part, determined by duty cycle, prior research in which it has been assumed that equal intensities yield equal magnitudes of loudness regardless of temporal conditions must be re-evaluated. Knowledge of the relationship between loudness and temporal parameters cannot be considered complete until the discrepancies between the results of loudness tracking experiments and the findings obtained by other methods of measurement are explained.

Chapter II contains a review of articles dealing with the major factors which tend to influence performance on loudness balancing via the Bekesy tracking procedure. Subsequent chapters include a detailed description of the procedures employed in these experiments and the results obtained, followed by a discussion of those results and conclusions drawn therefrom.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

The auditory system utilizes information relative to the loudness of steady-state or repeated acoustic events for a variety of purposes. Loudness mechanisms serve to warn us of the impending danger of high-intensity noises. Auditory monitoring can yield vital information as to the speed and location of an oncoming vehicle which is beyond visual range. In some instances minute changes in loudness serve as clues in the operation of man-machine guidance systems (15).

Temporal characteristics of acoustic events have a marked influence on the perception of loudness. The influence of brief durations upon loudness is well documented. Recent data (23, 25, 26, 27, 56, 57) suggest that temporal conditions may have far greater influences upon perceived loudness than current theories (86) predict when the sounds are received over an extended period of time.

The Alternate Binaural Loudness Balance (ABLB) test is a useful procedure to determine the nature of loudness function. The ABLB test was originally described by Fowler (16) to detect the presence of sensorineural hearing impairment. When the ABLB procedure is used in conjunction with an auditory-tracking device such as the Bekesy audiometer, changes in the loudness of an on-going train of interrupted signals can be measured as time passes. The self-recording ABLB task employs a pursuit loudness-tracking paradigm in which the observer must adjust the intensity of one (comparison) signal to attain loudness equal to that of the fixed intensity (reference) signal.

This chapter contains a review of the available knowledge regarding the parameters which are likely to influence the accuracy of ABLB performance via auditory-tracking methods. Each of the factors which affects the subject's tracking efficiency is delineated under the topic "correlates of auditory tracking skill." Loudness balancing involves the perception of gradual and often minute changes of sound intensity. Repeated stimulation of the auditory system for the ABLB is known to produce various amounts of "loudness adaptation." The partial interference in the perception of one sound by another sound is termed "forward or backward masking" when the two signals do not overlap in time. Forward and backward masking are known to have interaural influences, and they must be considered in a discussion of ABLB. Loudness changes which are due to the "loudness-duration" and "loudness-duty cycle" relationships must also be considered.

The remainder of Chapter II delineates those factors, listed above, which are cogent to "alternate binaural loudness balancing" via the Bekesy loudness tracking method.

Correlates of Auditory Tracking Skill

With the advent of mechanized transportation, the psychophysical laboratory became the site of investigations into man's ability to manipulate a machine which continually changed position in relation to some desired, or target, position. Psychoacousticians adapted tracking procedures to arrive at values of differential sensitivity, absolute threshold and equation of magnitudes (73).

The present investigation employs a commonly used auditory tracking device called the Bekesy audiometer to study the ability of trained normally-hearing subjects to balance the loudness of two alternating binaural tones. The self-recorded ABLB test is an example of the pursuit auditory tracking mode. Pursuit tracking employs two components, the target or reference loudness and the comparison loudness which is linked to the subject's control system (2). The target is an auditory signal of fixed intensity which appears in the reference ear. The contralateral ear receives the comparison signal which is modified in intensity by the Bekesy audiometer. The comparison signal continually changes loudness relative to the target loudness in the absence of a response from the subject. The subject determines the direction of the movement by appropriate manipulation of a hand switch. His task is to respond such that the comparison loudness is either equal to or approaching the target loudness.

Pikler and Harris (48) investigated loudness tracking skill by employing a pursuit tracking procedure in which subjects attempted to match pre-programed changes of signal intensity to one ear by manipulating the signal intensity to the opposite ear. They reported that the average tracking error was 3.3 dB for the dichotic pursuit loudness track. There was no apparent difference in the error for right and left ears in tracking performance. In another experiment (22), performance was studied as a function of attenuation rate at speeds from 0.35 dB to 1 dB per second. For all subjects the optimum performance was attained with the highest rate of attenuation.

Practice

The subject's skill in producing negligible tracking error is directly related to his familiarity with the task (54). The Bekesy-ABLB task has certain features which minimize tracking error and practice effects are easily stabilized. For example, the subject can predict the locus of both target and pursuit signals for he controls the direction of the pursuit's motion, and the rate of change is constant. Briggs and Waters (4) found that whole-task training of simple one dimensional tracks was superior to a training scheme in which the various components of the track were initially separated and then gradually combined as proficiency was developed.

The initial demands placed upon an unpracticed subject tend to determine his eventual performance accuracy. Adams (1) recommends that initial training sessions consist of several short tracking periods not exceeding 1 minute. Tracking accuracy improves more rapidly and reaches asymptotic levels within the second day of training when practice consists of short trials with rest periods during which feedback information can be given (1). Smode (66) reported that high amounts of information feedback appear to intensify subject motivation.

The training scheme suggested by Adams and recommended by Smode eliminated significant trial effects for the Bekesy loudness track (23, 26). Melnick (40) as well as Rintelmann and Carhart (57) employed untrained subjects in experimental designs which did not consider practice effects. Melnick observed "noticeably greater variance for the first three test sessions" than for the final two sessions. Harris and Pikler (22) recognized a marked practice effect for two of the four subjects in their experimental group who were retested. While it appears that the

ABLB-tracking task with its high degree of predictability requires a minimal amount of practice, the practice effect cannot be overlooked as a source of variability (54).

Reaction Time

A portion of the momentary tracking error on Bekesy-ABLB tasks is due to the effects of reaction time. During the time lapse between a judgment of difference in loudness and the execution of the appropriate mechanical response, the comparison signal drifts away from the target resulting in tracking error. There are no data available on the duration of reaction times in response to auditory tracking tasks. However, information regarding reaction times in response to the on-set and off-set of auditory signals may be pertinent. Teichner (79) suggests that reaction time involves several time lags:

1) The latency of build up of stimulation at the receptor end organ.
2) Control transmission of sensory impulses to motor fibers.
3) Time lag in muscle contractor.

Chernikoff et al. found that reaction times in response to the termination of most auditory signals were between 190 and 209 msec (8). Reaction times grew longer when duration was less than 100 msec, approximately one-half the duration required to attain full loudness (46). Reaction times also lengthened as the signal duration was lengthened from 100 to 240 msec (8). With a signal duration of 100 msec, the mean reaction time in response to a complex noise at 71-dB SPL reached a minimum value of 192.5 msec. It was 196.7 msec for a signal duration of 200 msec, and it was 209 msec when the signal was approximately 2,500 msec long.

The inverse relationship which exists between intensity and reaction time is well documented (9, 68, 70). Reaction times averaged approximately 200 msec when the eliciting signal intensity was at or slightly above 15-dB sensation level (SL). Reaction times for auditory signals which rise out of silence were equal at equal phon levels regardless of frequency (9). Chocholle found that reaction times were approximately 140 msec at the 60-phon level (9).

Reaction time effects are manifested in the width of Bekesy-ABLB pen excursions. Correspondingly, the width of Bekesy loudness tracings for continuous tones are nearly identical to the difference limen for intensity (DL_I) when the tracing error due to reaction time is subtracted from both high-intensity and low-intensity sides of the target loudness (23, 24).

The influence of reaction time is related to the predictability of the signals (35). Because predictability is a function of practice, reaction times tend to decrease with trial repetition (62). The Bekesy audiometer, by design, yields maximal degrees of predictability. Reaction time effects can be considered minimal and stable after sufficient practice (54).

Differential Sensitivity for Interaural Signals

Binaural loudness judgments are remarkably accurate and reliable. The difference limen for changes of intensity (DL_I) appear to be somewhat larger for alternating signals than for simultaneous signals. Roland and Tobias (60) found that for simultaneous signals the dichotic DL_I was 0.07 dB larger than the monotic DL_I for a 50-dB HL, 200-Hz tone. The dichotic DL_I was 0.72 dB. As predicted, the binaural DL_I decreased with an increase of frequency and intensity. The interaural DL_I's reported by Stokinger, Cooper and Lankford (76) varied as a function of the silent interval separating the two signals. The smallest DL_I was 0.58 dB for the 1600-msec tone, 400-msec silent-interval condition. The largest DL_I was 1.14 dB occurring in the 200-msec tone, no-interval condition. In general, an increase of interval time to 800 msec yielded a smaller DL_I with a sharp decrease between the intervals of 0 and 200 msec. Differences between delay conditions of 400 and 800 msec were non-significant. The size of the DL_I was not influenced by the choice of which ear received the comparison or reference tones (76).

In contrast to the interaural DL_I, the binaural and/or monaural DL_I's are relatively unaffected by changes of interstimulus intervals from 0 to 1 second (21), from 1 to 6 seconds (53) or from 1 to 20 seconds (50). Bekesy (3) found the monaural DL_I to deteriorate by approximately 20 per cent when interstimulus interval was increased from 0.25 to 5 seconds.

When there is a floating-standard for loudness, in which the comparison signal is employed as the reference loudness for subsequent judgments, subjects are forced to rely upon their memory of the original reference signal. Consequently, according to Pollack (50), the DL_I deteriorates if the interval between the original reference loudness and the floating loudness is greater than 1.25 seconds. Pollack suggests that the results reflect the absence of a stable framework against which the comparison signal may be judged. He writes that in this situation, "the perceived loudness remains very nearly unchanged despite a series of small, discrete and additive changes of intensity." Small (64) describes a similar situation which commonly occurs under different circumstances: "It is as though the listener had neither an internal loudness standard nor an effective memory and thus is able to compare the loudness of the stimulus in a particular segment of time only with the loudness of the stimulus in the immediately preceding segment . . . ."

Lawrence et al. (38) studied loudness discrimination for a type of floating-standard sustained tone which gradually changed intensity. The rate of change was from +3 to -3 dB per minute. The reference signals, 1000-Hz tones at 15-, 70- or 80-dB SL were presented then slowly incremented or decremented. Thirty seconds later, the trial was ended and subjects reported whether the signal had grown "louder" or "softer". The DL_I's were biased by what appeared to be a drifting of loudness in the control or 0 dB/min condition. The bias was two-fold. At 15-dB SL subjects tended to judge that the constant intensity signal grew fainter, but at 70-dB SL, they judged that it grew louder. The data deviated significantly from chance-response levels. The "fainter" judgment at 15-dB SL might be explained on the basis of loudness adaptation, but the 70-dB SL "louder" judgments are contrary to adaptation effects.

Garner (17) found that loudness judgments are less variable when binaural simultaneously-presented tones are interrupted than when the tones are sustained. Within the interrupted mode, variability increased with increases of repetition rate, but there was no lucid relationship between variability of loudness judgments and signal duration. Some of the normal-hearing subjects required an intensity difference between ears of 25 dB for equal loudness balances. A point which Garner re-emphasized in subsequent research is best expressed in his own words. "Equal loudness at the two ears corresponds very poorly to physical equality."

Loudness Adaptation from Repeated Signals

A series of repeated sounds produces some degree of loudness adaptation depending upon the length of stimulation time and recovery time. Carterette (6) varied the pulse rate of an interrupted broad-band noise from 1 to 12.5 impulses per second (ips) and measured the amount of adaptation relative to adaptation from a sustained noise. On- and off-durations were inversely related to the rate of interruption because duty cycle was held constant at 50 per cent. The amount of adaptation increased in a linear fashion with higher pulse rates. By extrapolation of his data Carterette was able to predict that adaptation from a signal with an interruption rate of 25 ips (20 msec on- and off-times) would equal adaptation from a sustained signal. Carterette concluded that 20 msec was within the critical off time which prohibits partial recovery between pulses. Thermal noise at 90-dB SPL yielded 5.2 dB of loudness adaptation when on- and off-times were 250 msec (6).

Sergeant and Harris (63) varied on- and off-times independently to arrive at several duty cycle conditions in order to study the adaptation and recovery phenomena of 1000-Hz interrupted tones. Results showed a trend toward greater adaptation with longer on-times and shorter off-times. Said differently, the amount of adaptation was directly related to the duty cycle. When the adapting tones were shorter than 1 second, adaptation occurred unless off-times were longer than on-times (i.e., unless duty cycles were less than 50 per cent). It follows that whenever on-durations were below 1 second, the rate of adaptation exceeded the rate of recovery (63). When on- and off-durations were equivalent and surpassed 1 second, no adaptation occurred. By use of a simple formula, Sergeant and Harris were able to predict the amount of adaptation from the duty cycle alone when durations and silent intervals were between 0.3 and 10 seconds long.

Binaural Masking: Backward and Forward Masking

The automatic-ABLB task is most easily instrumented with no delay interval between pulses. With some instrumentation, the stimulation may overlap during rise and decay segments of the pulses. Simultaneous binaural interaction is expected to be minimal for the ABLB paradigm when short rise and decay times are employed. Nevertheless, the loudness of one signal may interfere with or partially mask the loudness of the alternate signal when there is no silent interstimulus interval. Backward masking occurs when an intense sound acts as a masker prior to its presentation. Forward masking is a process by which a tone may yield some degree of masking efficiency after its termination.

Both forward and backward masking are capable of contralateral masking with backward masking being the more effective process (11, 13, 14). The contralateral backward masking value for a threshold-level maskee has been determined to be approximately 15 dB whereas forward masking equals approximately 5 dB when the masker is set at 90-dB SPL and there is no silent interval between masker and maskee. While forward masking at 70-dB SPL was 0 dB, backward masking accounted for a 10-dB threshold shift. The interaural effects of backward and forward masking can be detected 150 msec prior to and following the presentation of a masker burst.

The influence of interaural forward and backward masking upon loudness judgments cannot be specified at this time. The loudness of the second of two contralateral tones is overestimated whenever the tones are separated by less than 240 msec. Conversely, there is a slight underestimation of the second loudness whenever the silent interval is greater than 400 msec (77). The average overestimation at 0 msec interval was

2.1 dB in equivalent intensity with the right ear showing significantly greater effects than the left. At an interval of 240 msec, the overestimation fell to 0.77 dB.

Alternate Binaural Loudness Balance

The alternate binaural loudness balance (ABLB) test was first described by Fowler (16) who recommended it as a test to differentiate conductive from sensorineural impairments. For the ABLB test the loudness-growth function in the sensorineural impaired ear is compared with that in the normal ear. The same tones are alternately applied to both ears, and their intensities are manipulated to produce a sensation of equal loudness. Jerger and Harford (33) observed that the ABLB test yields grossly different loudness functions than procedures which employ simultaneous binaural tones. They noted that simultaneous balances may actually involve localization judgments in which a "phantom image" appears at the skull midline when in-phase binaural signals are balanced. For normal observers the difference between alternate balances and midline judgments were less than 1 to 2 dB.

A recent controversy has developed over the clinical efficiency of the ABLB test in detecting the presence of cochlear dysfunction. Jerger (31) reports that of 20 patients with substantiated Meniere's disease only 10 demonstrated complete recruitment on the ABLB test. In contrast, Hood's (30) analysis of 424 cases of Meniere's disease revealed that 415 had recruitment. A number of procedural differences exist between methods of ABLB testing which were employed by the two investigators. Jerger's (31) instrumentation provided alternate electronic switching of pure tones from ear to ear. The duration of alternating tones was 500 msec with 50 msec rise-decay times during which the tones overlapped. The patient was given control of the signal intensity which he adjusted until he was satisfied that the tones were equally loud at the two ears. The Hood (30) method, which was originally described by Fowler (16), employs manual switch and attenuator manipulation by the audiologist. Hood describes the signal as "approximately" 3 seconds long with 6 seconds off in each ear. A silent interval between signals of approximately 1.5 seconds resulted from manual manipulation of the audiometer controls. According to current psychophysical data, differences in on-times from 1/2 to 3 seconds cannot account for the discrepancy between the results from the two methods. Hood contends that the long silent interval is necessary to allow full recovery of the neuronal action potential thus allowing full loudness perception in the impaired ear. According to Hood, Jerger's 500-msec rest period for each ear was insufficient to avoid partial cumulative adaptation of the impaired ear. Hood recommended a silent interval of no less than 1 second. Another potentially important temporal parameter of Jerger's signals may be the 50 msec rise-decay time during which the signals occur simultaneously at the two ears. This overlap period may provide clues as to the location of a brief binaurally-fused signal, thus confusing the perception of loudness with a perception of localization. Hood also offered the possibility that constant-rate alternations may introduce adverse variables related to attention and motivation. At present, there are no psychophysical data to substantiate Hood's concern and recommendation for a long silent-interval time during ABLB testing.

Automatic and self-recording devices have been adapted for administration of the ABLB test, although such methods have found only limited clinical utility. Landis (37) described the use of a subject-operated rotor-type attenuator for loudness balances with a fixed intensity reference tone to the opposite ear. Miskolczy-Fodor (44) converted the Bekesy audiometer for administration of the variable tone of the ABLB test. Thus he was able to record the variability of loudness balances as well as the amount of recruitment. His method also had the advantage of testing the loudness-balance function of the entire intensity range in a continuous "sweep" manner instead of at a few discrete points as with the manual Fowler method. For the Bekesy loudness balance task, the subject responded when the moving comparison tone was either too loud or too soft relative to a condition of equal loudness in the two ears.

Miskolczy-Fodor (44) noticed an unexpected trend when test retest results were compared. The ascending-reference and descending-reference balances were not always equal. When an ascending reference tone was employed, the tracing usually showed an asymptotic recruitment in cochlear-impaired ears. The descending reference tone yielded either a "delayed" straight line or a mixed type of loudness growth (44). The discrepancy was often as large as 20 dB at moderate loudness levels. Long rest periods between ascending and descending runs served to reduce the discrepancy, but the apparent "bias" could not be eliminated.

Carver (7) reports a similar loudness bias for an automated ABLB task. Carver's reference loudness slowly increased from below threshold to 100-dB HL at which point it automatically reversed direction and began to descend approaching threshold once more. Loudness tracings appeared to lag behind the changes in the reference tone intensity.

Loudness and Duration

As early as 1929, Bekesy (3) reported that tones became less detectable when durations were shortened below a critical point. Garner and Miller (20) found that the critical duration was 200 msec for a shift in the threshold of masked tones. Miskolczy-Fodor (45) and later Hattler and Northern (27) observed that threshold shifted as a function of duration only when duration was less than 150 msec.

The duration-loudness relationship is less well defined than the duration-threshold relationship perhaps because loudness is affected more than threshold by parameters such as the method of measurement, repetition rate and duty cycle.

Reichart and Niese (55) recently cautioned investigators to select carefully appropriate temporal conditions for the purpose of studying loudness function. They suggested that signal on-time should be long enough to surpass the critical duration which governs the temporal-integration process. At the same time, the signal must be short enough to avoid loudness adaptation. They also recommend use of silent inter-signal intervals which are long enough to avoid "interference" between the two sounds yet the interval should be short enough to avoid loudness-memory deficits. Reichart and Niese also warned against what they termed the "roughness effect" resulting in annoyance or loss of attention due to use of rhythmic signal presentation patterns. The recommendations of Reichart and Niese for artifact-free loudness data include on-times of 250 to 500 msec, silent-interval times of 500 to 1000 msec, and duty cycles less than 66 per cent. Many of these factors may be inconsequential in ABLB testing because both ears are stimulated in the same way. The ABLB procedure is sensitive only to loudness changes in one ear relative to changes in the contralateral ear (16, 33). Consequently, the ABLB test is insensitive to any loudness modifications which occur bilaterally and simultaneously.

When normal loudness function is measured by means of classical psychophysical techniques such as the method of limits, adjustment or constant stimuli, loudness samples are given for relatively brief time segments and judgments are called for as to the relative magnitude of reference and comparison signals. Following the judgment, the sequence is repeated and a new test period is begun which is disconnected in time from all other trials. Many everyday loudness experiences deal with on-going signals. There is some evidence to suggest that the temporal integration process for the loudness of suprathreshold signals is not the same as for threshold-level signals whenever on-going sounds are evaluated. Established psychophysical methods may be insensitive to some of the relationships between loudness and time because they employ short, discrete test periods.

Single Pulses

Bekesy first noted that the loudness of single tone bursts was dependent upon duration (3, p. 324). It appeared that the growth of loudness approached its maximum value asymptotically over time. A decrease in the loudness of an 80-dB 800-Hz tone occurred when it was terminated prior to 180 msec.

Using a forced-choice method of constant stimuli, Munson (46) found that a loudness loss occurred if tonal durations were less than 250 msec, a longer critical duration than Bekesy observed. The maximum loudness loss was 33 dB in equivalent intensity for a reduction in duration from 250 to 5 msec. The amount of loudness loss due to short durations decreased as the intensity of the reference loudness was raised.

At 60-dB SPL, a 200-msec tone was 1 phon fainter than a 1000-msec tone in the same ear. At 40-dB SPL, a loudness loss of 3 phons was observed for the same 200-msec condition. The primary concern for the present experiment was the loudness of signals longer than 200 msec.

Garner's data (19) show a slightly different result for a monaural loudness matching task in which subjects adjusted a 1-dB step attenuator in order to attain equal loudness for a 500-msec reference tone and a variable-duration comparison tone of the same frequency. Subjects displayed two distinctly different types of behavior. One group showed a consistent change in loudness as a function of duration while the other group demonstrated almost no loudness loss. Garner reports a maximum loudness loss of only 12-dB equivalent intensity in contrast to Munson's finding of 33 dB and Bekesy's finding of 8.5 dB. Garner, like Bekesy, used signals with fast rise-decay times. Perhaps transient clicks, which are present in signals with abrupt onset and offset influence loudness when durations are shorter than 150 msec.

Creelman (10) attempted to obviate the effects of transients by presentation of a loudness balance task in the presence of a 40-dB SPL broad-band noise. He employed Garner's experimental procedure except that subjects adjusted the comparison signal instead of the reference signal which was fixed at 320-msec duration. The slope of the resultant loudness-duration function was 6.5 dB per decade change of duration. Creelman's data show considerably more loudness loss for longer durations than the data of either Garner or Munson. For extremely short durations, Creelman reports slightly more loss of loudness than does Garner and considerably less loudness loss than does Munson.

Small, Brandt and Cox (65) employed a method of adjustment in which subjects changed the level of a short noise burst in order to make it equal in loudness to a 500-msec burst. Critical durations were 50 msec at 10-dB SL and as short as 15 msec at 60-dB SL. These critical durations are approximately 2.5 times shorter than those in the Garner (19) and Miller (41) studies. Furthermore, for durations shorter than the critical duration, the slope of the loudness function was -12.5 dB/decade decrease in duration, a steeper slope than the -8.8 dB which Miller had reported and the -8.0 dB/decade observed by Garner. Small et al. may have limited the transient response of their instrumentation by electro-acoustic methods, thus allowing the ear to integrate only the wide-band noise which was relatively free of transient signal.

Ekman et al. (12) used a magnitude estimation task to determine the loudness of a 1000-Hz tone at 33 dB (re: 4×10^{-4}V). A signal which was 200 msec long was approximately 2 phons less loud than a 500-msec tone. At the 50-msec duration point the loudness loss equaled 5 phons. Stevens and Hall (75) observed a critical duration of 150 msec above which duration had negligible effect on loudness for a wide range of SPL's. Port (52) employed a loudness-matching task and found that the loudness of a 2000-Hz tone was unaffected unless durations were less than 100 msec.

The latter result supports a mathematical model based upon the assumption that the loudness-duration relationship is a by-product of neural summation at some high central nervous system site (86). The temporal decay (or fast adaptation) of neural firing is thought to be responsible for overcoming the nonlinear relationship between sound intensity and the growth of neural excitation. The neuromathematical hypothesis is based upon the observation that the critical duration for temporal integration is approximately 200 msec near threshold and decreases to about 100 msec at moderate or high sensation levels. One of the three basic assumptions of the model is the existence of a linear temporal integrator with a time constant near threshold of 200 msec located within the central auditory nervous system. The critical duration, below which loudness decreases, is probably reflected in the slow wave activity of the cortex (86).

Repeated Pulses

Fewer data are available regarding the loudness of repeated bursts than the loudness of single bursts, perhaps because additional dependent variables are encountered with repeated bursts. Garner (18) found that the loudness of repeated short tones is dependent upon the following conditions:

1) The intensities of the reference and comparison tones.
2) The signal frequency.
3) The duration of short signals.
4) The repetition rate of short signals.

Later studies (23, 25, 26, 57) have implied that duty cycle is also a determinant of loudness for repeated sounds. Garner's repeated tones had abrupt on-sets and off-sets and probably contained energy from switching transients. Even though overall energy was equated, repeated tones were judged louder than sustained tones at sound pressure levels in excess of 60 dB. At levels below 60 dB the repeated tones were fainter than sustained tones. Garner writes:

> Two tones of equal energy will not be equally loud unless their durations and repetition rates are equal. At high intensities tones with faster repetition rates and shorter durations are louder . . . . At low intensity levels signals with slower repetition rates and longer durations are the louder.

Pollack (49) found that the relationship between sensation level and loudness holds for repeated bursts of noise in the same way as for repeated tones. Maximum loudness values were attained when the repetition rate was between two and ten ips provided that the duty cycle remained a constant 45 per cent. Thus, Pollack's data like those of Garner reveal that loudness may be enhanced by pulsing or interrupting a steady-state signal. It is doubtful that switching transients accounted for the loudness enhancement of broad-band noise signals observed by Pollack.

Carter (5) agreed with the conclusion of Garner that the loudness of triangular click transient signals is underestimated at low SL's whereas at high levels the loudness of transients is overestimated. He found that an equivalent of 3-dB loudness increase resulted for each doubling of repetition rate or whenever duty cycle was increased by one log unit. When Carter attempted to predict the loudness of transients by use of loudness-calculation formulas (72, 73) the prediction was in error by as much as 8 phons. Stevens and others often caution against the use of loudness calculation methods with any but sustained signals. Some calculation methods assume relatively stringent limitations of intensity fluctuation. The limitation of calculation methods to sustained signals is apparently based upon empirical evidence that such calculations are in remarkable disagreement with sound-jury loudness estimates of pulsed signals (5). It is possible that all the factors affecting the loudness of repeated pulsed signals are not accounted for in the calculation formulas.

Perhaps the auditory system processes the loudness of on-going signals differently than the loudness of brief one-burst stimulations. It is possible that the auditory system averages acoustic energy over a relatively long period of time. For example, a greater loudness may be allotted when 80 per cent of the listening period is filled with sound than if the signal fills only 40 per cent of the time. Classical psychophysical methods in which loudness judgments are based upon short, discrete sampling times may be insensitive to a long-term integrating or averaging process. Data reported by Lawrence et al. (38) and Hattler (23, 25) have suggested the possibility that the influence of duty cycle is sufficient to override the effects of loudness adaptation, repetition rate and on-duration.

Loudness and Duty Cycle

Whenever Bekesy tracings are produced at suprathreshold levels based upon judgments of equal recalled loudness, the duty cycle (or percentage of time the sound is on) becomes extremely important (23, 25). Early indications that duty cycle might influence loudness came from clinical reports of Bekesy audiometry (30, 56, 57, 68). A peculiar tracing (the Type V Bekesy pattern) consistently emerged when patients exaggerated their hearing loss on the Bekesy test probably by attempting to match a criterion loudness instead of tracing their true audiometric threshold. The distinctive feature of the Type V was that pulsed-signal tracings (200 msec on/200 msec off, 50% duty cycle) were remarkably higher in SPL than tracings for sustained tones (100% duty cycle). The Type V pattern resulted from both sweep-frequency and fixed-frequency loudness tracks regardless of signal frequency (40, 57).

Rintelmann and Carhart (57) explored two techniques of loudness tracking. In the "Recalled Loudness" (RL) technique subjects were given a 20-second 1000-Hz tone as a reference for tracking. The other technique allowed S's to choose their own reference loudness at some "most comfortable level" (MCL) which they attempted to maintain via Bekesy tracking. The tones traversed the frequency range from 100 to 10,000 Hz as the intensity was modulated by the Bekesy at a rate of 2.5 dB/second. Interrupted-signal loudness was consistently traced at higher SPL's than sustained signals although the differences were somewhat more dramatic for the MCL than the RL paradigm. The largest mean separation was 23.3 dB for the MCL task. For the RL paradigm mean separations of 6.5 dB to 15.7 dB were produced. Tracking levels were highest for both techniques when the interrupted signal preceded the sustained signal.

Melnick (40) reported much less difference between tracings for sustained and interrupted signals when the reference tone was given at intervals during loudness tracking. The method of monaural-loudness matching employed the presentation of a 10-second sustained reference tone prior to the tracking period and again every subsequent 20 seconds for the entire 3-minute period. Reference tones of 1000 Hz were presented at sensation levels of 20, 40 and 60 dB. The interrupted tones consisted of three pulsed conditions. The on- and off-durations in msec were 100/250, 200/150 and 300/50 when the 25-msec rise and decay times were subtracted from the silent interval (40). The duty cycles of interrupted signals were 28, 57 and 85 per cent, respectively. The 28-per cent duty cycle signal yielded an average of 4- to 5-dB loudness loss relative to sustained (100 per cent) signals. The difference dropped to only 1 or 2 dB for the 57 *vs*. 100 per cent comparison depending upon the intensity level of the reference tone. At 20-dB and 40-dB SL the 85-per cent sound was 3 dB fainter than sustained tones. At 60-dB SL the difference was approximately 2 dB.

Melnick concluded that these data were commensurate with the data on loudness loss due to shortened durations. The data for the 300-msec duration deviated from the expected value for no apparent reason. Melnick's results led to his assertion that the loss of loudness due to interrupting the pure tones is probably due to a biased or faulty memory of a nonavailable reference tone. Furthermore, the data suggest that when the reference tone is available at intervals, duty cycle has only a slight (maximum of 5 dB) influence on loudness.

Recent loudness tracking data (23, 25) have demonstrated the existence of a linear relationship between loudness tracking levels and signal duty cycle when the reference loudness is not available during tracking runs. Well-trained normal trackers were instructed to maintain, during the tracking period, the loudness of a 5-second sustained reference tone. The seven signal conditions which were employed are listed in Table 1. Tracking levels were significantly affected by the signal's duty cycle regardless of "on" duration. For example, pulsed tones with on/off times of 200/800 and 40/160 yielded equivalent loudness tracking levels despite differences in on duration, off duration and repetition rate (1 to 5 ips). The two signals have a 20-per cent duty cycle. Furthermore, on/off conditions of 200/20 and 200/800 yielded significantly different loudness tracings despite their identical on-times. Duty cycles were 91 per cent and 20 per cent, respectively. Further comparisons tended to negate any relationship between on-duration and tracking level.

Munson (46) observed that the loudness loss due to shortened durations increased as the reference-intensity level was increased. Loudness tracking data reveal less loudness loss for pulsed tones at the higher than at the lower intensity level (23, 25). Moreover, there was no apparent relationship between loudness and interruption rate similar

TABLE 1

MEAN DIFFERENCES (dB) IN BEKESY LOUDNESS TRACING LEVELS[a]

	Bekesy Tone Characteristics - Duty Cycle (on Time/off Time)						
50-dB SPL Reference	100% Continuous	90% (180/20)	91% (200/20)	50% (100/100)	50% (200/200)	20% (40/160)	20% (200/800)
100% (continuous)	--	5.18[b]	6.15[b]	7.06[b]	9.30[b]	11.20[b]	13.77[b]
90% (180/20)		--	.97	1.88	4.12	6.02	8.59[b]
91% (200/20)			--	.91	3.15	5.05	7.62[b]
50% (100/100)				--	2.24	4.14	6.71[b]
50% (200/200)					--	1.90	4.47
20% (40/160)						--	2.57
20% (200/800)							--
80-dB SPL Reference	100% Continuous	90% (180/20)	91% (200/20)	50% (100/100)	50% (200/200)	20% (40/160)	20% (200/800)
100% (continuous)	--	3.72[b]	3.84[b]	5.58[b]	7.00[b]	7.59[b]	8.76[b]
90% (180/20)		--	.12	1.86	3.28[b]	3.97[b]	5.04[b]
91% (200/20)			--	1.74	3.16[b]	3.85[b]	4.92[b]
50% (100/100)				--	1.42	2.11	3.18[b]
50% (200/200)					--	.69	1.76
20% (40/160)						--	1.07
20% (200/800)							--

[a] Taken from Hattler, K.W., 1967 (23)
[b] Significantly different at the .05 level of confidence

to that observed by Garner.

The loudness tracings reported by Hattler (23, 25) were generally overlapped at the commencement of tracking, but they gradually separated as time passed. Within approximately 15 to 30 seconds the tracings for pulsed and sustained tones moved in opposite directions away from the loudness-reference level. The sustained-tone tracings grew less intense suggesting a growth in loudness perception as time passed. Pulsed-tone tracings, on the other hand, progressed to higher intensities generally reaching asymptote within 1 minute after commencement of tracking. The rate and degree of loudness drift was contingent upon the signal's duty cycle.

The influence of the duty-cycle on loudness tracings is remarkable. A decrease of duty cycle from 100 per cent to 20 per cent resulted in a drop of loudness equivalent to 13.8 phons at 50-dB SPL and 8.8 phons at 80-dB SPL (23, 25). These loudness decrements represent decreases of loudness perception by factors of 5 and 2, respectively, when loudness-scaling data are examined (74, p. 223). Thus, at 50-dB SPL, a signal with 100-per cent duty cycle may appear to be five times louder than the same signal which is on only 20 per cent of the time. At 80-dB SPL the former sound is twice as loud as the latter sound.

Four investigations (23, 38, 43, 78) which employed different methods apparently agree that the loudness of relatively intense sustained signals appear to grow as time passes. The procedure employed by Lawrence et al. is described on page 13. At 15-dB SL subjects tended to judge that the loudness of a fixed-intensity sustained tone diminished indicating the presence of loudness adaptation. At 70-dB SPL, subjects judged that the loudness grew in magnitude. These data suggest the presence of a process of loudness growth upon sustained stimulation which is contrary to the expected effects of loudness adaptation. The loudness growth at 77-dB SPL was 0.5 dB in equivalent intensity over a 30-second period. Assuming a constant rate of loudness growth, three minutes of stimulation would have yielded a total loudness growth of 3-dB equivalent intensity.

Stokinger et al. (78) employed delayed-balance and single-simultaneous-balance methods in the study of loudness adaptation yielded by sustained tones with duration times (T) from 1 to 30 seconds. In the delayed-balance data, the investigators observed a trend toward "negative adaptation" which grew in magnitude during stimulation with 1000-Hz tones at 80-dB SPL. "Negative adaptation" appeared to be the result of a growth in the loudness of the sustained adaptor tone. At T=16 seconds the loudness growth was approximately 1.5 dB and at T=30 seconds, it was approximately 3.5 dB. Loudness growth was not, in general, observed when the adaptor signal was delivered at 30-, 50- or 100-dB SPL.

Hattler (23, 25) and Mirabella et al. (43) employed methods of compensatory loudness-memory tracking via a recording attenuator. In the former study, when subjects tracked the loudness of an 80-dB SPL sustained tone via the Bekesy audiometer there was a loudness growth of 3.46 dB during 3 minutes of stimulation. Normal ears were preadapted for 30 seconds prior to tracking runs. Hattler found that 50-dB SPL sustained tones did not appear to undergo loudness growth within the 3-minute tracking period. The results of both the Hattler and Lawrence et al. studies were attributed to a bias in the loudness-memory process which occurs in the absence of a reference loudness for direct comparison.

Mirabella et al. also used monaural loudness tracking in an attempt to study the loudness adaptation process at several SPL's. Adaptation occurred for noise and 3500-Hz tones at and below 70-dB SPL as evidenced by a gradual increase in tracking level SPL as time passed. At 90-dB SPL, in contrast, the SPL of the tracings decreased indicating that loudness perception for sustained signals had grown over the time period. The maximum increase in loudness was approximately 3 dB of equivalent intensity within a 2- to 4-minute tracking period. The finding of 3-dB increase of loudness perception over a 3 minute period of sustained exposure at SPL's above 70 dB is consistent in the results of Lawrence et al. (38), Hattler (23, 25) and Mirabella et al. (43). Furthermore, current psychophysical understanding of the loudness-duration or the temporal integration process fails to explain these findings.

Robinson (59) described an "unexpected" result for an experiment in which subjects judged the loudness of repeated comparison tones which alternated with repeated reference tones at 6 sound-field loudness levels from 30 to 100 phons. Subjects were asked to adjust the loudness level until it equaled either 1/2 or 2 times the loudness of a fixed reference tone. The silent period between reference and comparison tones was varied from 300 to 3000 msec at random during the investigation. Reference and comparison tones had on-times of 1500 msec, thus the duty cycle of the reference-comparison tone pulse train decreased from 83.3 to 33.3 per cent as a consequence of lengthening interval times while on-time was fixed. Loudness was judged to decrease systematically as the silent interval was increased (and the duty cycle was decreased). Robinson's own research suggested that the loudness influence due to the order effect was nonexistant when the silent interval surpassed 1000 msec. Nevertheless, he concluded that order effects probably explain this apparent influence of duty cycle on loudness. The duty cycle effect continued for the full extent of the silent interval periods (300 to 3000 msec) used by Robinson.

The same tendencies follow for tolerance-level thresholds where it appears that a pure-tone signal can be tolerated at higher SPL's if it is pulsed than if the same tone is sustained (71). Tolerance thresholds via the Bekesy audiometer were 108-dB SPL for pulsed tones and 101-dB SPL for sustained tones. At these high SPL's, an intensity increment of 7 dB is perceived as an approximate 3-fold increase of loudness (74). Furthermore, loudness-duration function, as it is understood at the present time, cannot account for the 3-fold change in loudness. Stephens (71) employed tones with 500-msec on- and off-times, durations far in excess of the critical duration for loudness loss (3, p. 386; 10; 12; 19; 46; 53; 83; 84). The data of Stephens are commensurate with other data that suggest loudness is directly related to duty cycle even when the 200-msec critical duration is surpassed, despite the alleged tendency of loudness adaptation to reduce the loudness of high duty-cycle signals.

Kryter and Pearsons (36) reported that judgments of "noisiness" or "inacceptability" of narrow-band signals are not coincident with loudness judgments. They emphasized the result that noisiness increased when the durations of fixed-SPL signals were lengthened beyond the 200-msec point. This was contrary to what would be expected from loudness judgments. Loudness, it was observed, reached a constant level in less than 200 msec, and it tended to decrease slightly as duration was prolonged beyond the 500-msec point.

One recent study (26) clearly demonstrated that duty-cycle manipulations affect suprathreshold Bekesy tracings whereas threshold tracings are unaffected. By use of a "Lengthened Off-Time" (LOT) signal with 200-msec "on durations" and 800-msec "off durations," Bekesy tracings for pulsed-LOT and continuous tones differentiated organic (threshold) responses from nonorganic (suprathreshold) responses. When administered to 725 clinic patients, the procedure correctly classified patients as to organic vs. nonorganic hearing loss with an efficiency of approximately 98 per cent (28, 29). These results suggest that the influence of duty cycle on loudness tracings is a reliable psychophysical phenomenon which can be observed for the large majority of unpracticed clinical patients. Hattler and Northern (27), while investigating threshold temporal-integration processes, observed that a decrease of pulsed-tone duty cycle from 60 per cent to 9 per cent failed to yield substantial threshold shifts in cochlear-impaired ears. Whatever process is responsible for the loudness-duty cycle function, it appears to be a separate phenomenon from that which mediates the time-intensity trading relationship at absolute auditory threshold.

One neurological model (10) in explanation of loudness-duration processes incorporate hypothesized mechanisms for the counting of neural input spikes during the course of acoustic stimulation. The mechanism presumably would count neural spikes only during the on times of pulsed signals and would be idle during off times. The mechanism assumes full input knowledge of starting and terminating times, on-off durations and an excellent memory. The counting model lends itself to the prediction of greater variability with increasing silent interval times. Creelman (10) asserted that a simple accumulator mechanism could store neural impulses long enough to evaluate and count them just as a reverberation circuit can store an electric charge. The mechanism may react like an electric clock which runs only when it is stimulated or activated. The estimation of loudness magnitude may, in part, be determined by the ratio of stimulated vs. nonstimulated time periods. Loudness estimations may be an "averaged" value which is influenced by "filled" and "silent" time segments. This model may assist in explaining the loudness-tracking and tolerance-level results (23, 25, 71) which appear to be independent of the common loudness-duration phenomena.

Karlin (34) may have predicted a direct relationship between loudness and duty cycle as early as 1942. He observed that two sounds with equal intensity may initially have equal loudness. The ear, he observed, integrates the total perceptual mass between on- and off-times. When one sound is longer than the other, the integral will be larger for the sound with the wider limits (or the higher duty cycle). Perhaps duty cycle is a major determinant of loudness magnitude when the auditory system is given time for the averaging process to develop.

Comment

More data are needed before it can be concluded that loudness magnitude is directly related to duty cycle. Prior research on the duty cycle-loudness relationship employed recalled loudness or loudness memory tasks in which the reference loudness was available only at the commencement of the listening period. It could not be determined if the loudness of pulsed and sustained tones actually drifted away from each other over time or if the absence of the reference tone resulted in a bias of loudness memory as the reference signal was gradually removed in time from the loudness track.

The present investigation is designed to study the normal loudness function for interrupted sounds which extend over relatively long time periods. Use of the ABLB task minimizes the potential influence of loudness memory. Direct evidence may be obtained from loudness balancing to either support or negate the presence of a duty cycle-loudness contingency. If duty cycle is a determinent of loudness, the ABLB will be influenced by conditions of equality vs. disparity of duty cycle. The differential influence of duty cycle on loudness adaptation, however small, should be controlled by counterbalancing high- and low-duty cycle conditions. Binaural interactions including forward and backward masking may be avoided by placing a silent interval between alternating pulses. Furthermore, the possible influence of practice, reaction time and the interaural intensive difference limen must also be considered.

Chapter III contains a description of the instrumentation and procedures which were employed to obtain information relative to the loudness-duty cycle relationship. The procedures include attempts to limit the influence of variables other than duty cycle on the loudness of pulsed signals.

CHAPTER III

INSTRUMENTATION AND PROCEDURE

Introduction

The present investigation was designed to study the influence of duty cycle on alternate loudness balances over an extended period of time. If the loudness of interrupted signals is contingent upon duty cycle, conditions of equality and disparity of duty cycle should influence the intensity at which two signals are loudness-balanced. It may be expected that the greater the disparity of duty cycle, the greater will be the intensity difference between the loudness-balanced sounds. On the other hand, if duty cycle has no unique influence on loudness, two signals will be loudness-balanced at equal SPL's regardless of similarity or disparity of duty cycle. An experiment was constructed to determine the influence of four primary factors on loudness balances:

1) Equality *vs.* disparity of duty cycles.
2) Interval *vs.* no-interval between alternating tones.
3) Duty cycle of the reference signal *vs.* duty cycle of the comparison signal.
4) The amount of time after commencement of tracking.

Information as to the influence of duty cycle on long-term loudness balances may lead to further hypotheses regarding possible temporal "averaging" properties of the auditory system.

Subjects

The experimental group consisted of 12 audiometrically normal males between the ages of 20 and 44, mean age 24.2 years and median age of 24.5 years. All subjects were staff members of the Army's Audiology and Speech Center, Walter Reed General Hospital, Washington, D.C. Normal hearing was defined as monaural sensitivity thresholds no greater than 15 dB (ANSI 1969 Standard) for each ear at octave intervals between 250 and 8000 Hz. Further requirements were a negative history of otologic pathology and hearing levels bilaterally symmetrical within 5 dB at 1000 Hz.

Instrumentation

Acoustical Environment

All audiological screening, training and experimental sessions were conducted in the same acoustically treated test chamber at the Army Audiology and Speech Center, Walter Reed General Hospital, Washington, D.C. The subject's chamber was of single-walled construction with an acoustically-damped window. The subject's chamber contained the subject's earphones and response switch while all other instrumentation was located in the experimenter's room.

Ambient-noise levels of the subject's chamber were measured with all experimental apparatus in operation at the usual time of testing. Measurements were obtained at the approximate locus of the subject's ears on a sound level meter (Bruel and Kjaer, Type 2203) when coupled to an octave band analyzer (Bruel and Kjaer, Type 1613). Levels in the critical band centered at the test frequencies from 125 to 8000 Hz were all below those essential for pure-tone threshold testing when the average attenuation of the earphone cushions (MX-41/AR) was considered.

Experimental Test Equipment

All training, audiometric screening and experimental loudness balancing were conducted on the equipment which is schematically illustrated in Figure 1. The output of a 1000-Hz audio oscillator (Hewlett-Packard, Model 200 BR) was passed through a divider circuit and into electronic switches 1 and 2 (Grason-Stadler, Model 829E, A-in and B-in, respectively). From the output of switch 1, the reference signal entered a fixed attenuator (Daven, Type T-690-A, 500 Ω-in, 600 Ω-out) and through a transformer into a TDH-39 earphone. The comparison signal passed from the output of switch 2 to the Bekesy audiometer (Grason-Stadler, Model E800), alternate-in position) set to modulate the signal's intensity at a rate of 2.5 dB/sec. The comparison signal then entered a second TDH-39 earphone which was matched as to response and distortion characteristics to the earphone receiving the reference signal. The 1000-Hz signal, when divided and applied to both earphones, was 180° out of phase (antiphasic). The electronic switches were triggered by phase-locked interval timers 1 and 2 (Grason-Stadler, Models 471-1). Interval timer 1 initiated the reference tone, terminated the reference tone and triggered interval timer 2 after a specified delay period. The trigger pulse from timer 1 (pulse-gate output) entered the delay circuit of an electronic stimulator (Grass Instruments, Model S4A). From the stimulator's output, the triggering pulse entered the external input of timer 2. Timer 2 provided initiating and terminating pulses for the contralateral tone.

All temporal conditions were held to specified values within

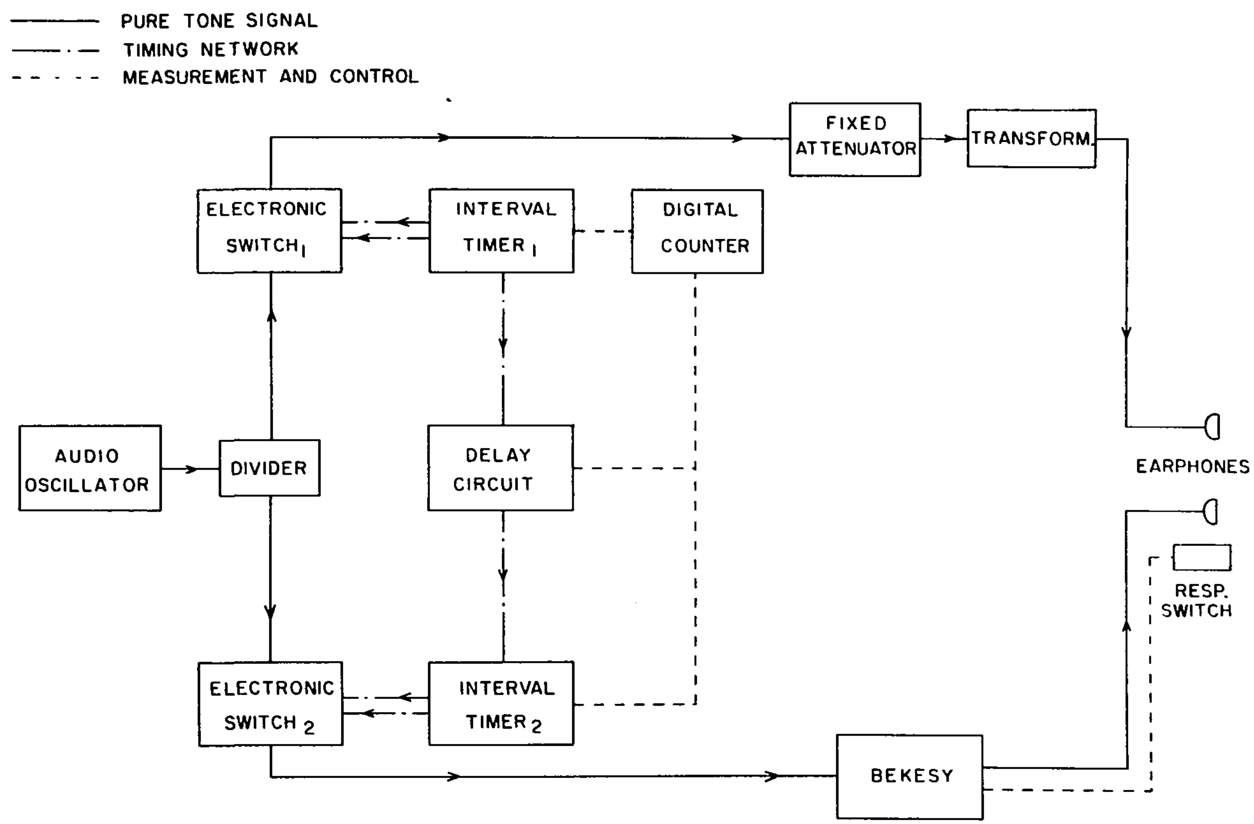

Fig. 1.--Schematic illustration of the experimental apparatus.

either 1 msec or 0.05 per cent, whichever was smaller, with the aid of a 2-channel digital counter (Beckman-Berkeley, Model 5203 BP). Reference and comparison signals including their 10-msec rise-decay times were monitored via an oscilloscope (Tektronix, Type 503). During calibration and experimental runs, the oscilloscope was connected to the output of one or the other electronic switch. The electronic switches were balanced at weekly intervals using the oscilloscope in a manner recommended by the manufacturer. All reference and comparison signals were free of audible click transients. Specified frequency and sound pressure levels were checked prior to and following each test session and were maintained within 1 Hz and 0.1 dB, respectively.

Calibration of sound intensity was performed in the following way prior to each experimental session (not sooner than one-half hour after the instruments were turned on) and immediately following each session. An intensity level (70-dB SPL) was chosen for the sustained Bekesy signal which peaked the VU meter on the face of the audiometer at 0 dB. The pen was carefully placed on the face of the Bekesy audiogram (Grason-Stadler, Form C F2 A). The fixed-intensity tone was sustained at 70-dB SPL to match the 70-dB SPL position of the Bekesy attenuator for calibration. All pre- and post-session calibrations were checked on a Rudmose (RA 106A) artificial ear with two standard 6cc couplers (9A). This instrument was periodically equated to the Bruel and Kjaer calibration unit.

The Bekesy attenuator rate was calculated to be 2.4 dB/sec employing a method previously described (23). The chart of the Bekesy audiometer traveled at a speed of 0.53 mm/sec. This information was used to determine the time after commencement of the loudness balance period for any point along the tracing.

Collection of Data

Tracking levels were traced by the Bekesy recording attenuator on the fixed-frequency Bekesy audiogram. An extra-fine-point pen (Kohinoor, Rapiodgraph No. 0) was used for the write-out mechanism in order to obtain accurate calibration and appraisal of tracking levels. The width of the line which was drawn by the pen was equal to 0.1 dB on decibel-graduated paper.

The experimenter quantitatively evaluated the loudness-balance tracings at various time intervals during the 4-minute track. The high-intensity and low-intensity peaks of the Bekesy tracings were estimated to the nearest 0.1 dB at time points of 1/4, 1/2, 1, 2, 3 and 4 minutes after the commencement of loudness balances. The examiner employed a magnifying glass (approximately 2.5 power) and a specially constructed Bekesy ruler. The Bekesy ruler consisted of chart paper (Technical Charts, Form 5A) graduated in one-decibel steps.

The experimenter's accuracy and his reliability in evaluating the loudness tracings have been verified in prior research (23). In that study, three individuals other than the investigator read the intensity peaks of a tracing which was selected from the data in a semi-random fashion. The combined mean midpoint obtained by the three readers was 48.94 dB as compared with the investigator's estimate of 48.99 dB. All individual midpoint values were within six one-hundredths decibels of the combined mean. The reliability of the investigator's reading of loudness tracing peaks was found to be quite high. The mean midpoints of 98 excursions for the first and second readings were 63.68 and 63.66 dB, respectively. This difference was nonsignificant, and the standard error of the mean was 0.017 dB, suggesting that estimation of each intensity peak to the nearest one-tenth decibel was quite reliable. In summary, evaluation techniques were considered to be adequate.

The mean midpoint was calculated for each of the six pre-selected time-analysis points. Two high- and two low-intensity peaks immediately preceding and two high and two low peaks immediately following the analysis point were averaged. Each tracking level represented an average of 8 high- and low-intensity peaks which surrounded the point. In all, the data consisted of 216 loudness-balance tracings (12 subjects x 2 trials x 9 balances in each trial). Inasmuch as each tracing contained six analysis points, 1272 bits of data were calculated based upon intensity readings of 10,276 pen-excursion peaks.

Procedure

Screening and Training

Each subject's threshold was measured by fixed frequency Bekesy audiometric tests at frequencies from 250 to 8000 Hz at octave intervals. Subjects were seated in the test chamber, wearing earphones. The following instructions were given:

> You will now hear an interrupted sound in one ear. When you hear the sound, press and hold the switch until the sound disappears. When the sound is gone, release the switch, and so forth.

Following the threshold tests, the first of two thirty-minute training sessions was conducted. During the training sessions, subjects were instructed to loudness-balance a bilaterally alternating 1000-Hz tone with equal interaural duty cycles (50% for no-interval trials and 16% for silent-interval trials) and with dissimilar interaural duty cycles (20%

vs. 80% for no-interval trials and 6.6% *vs*. 66.6% for silent-interval trials). Subjects were screened for basic ability to maintain a stable loudness-balance tracing from 2 to 4 minutes after commencement of tracking with equal duty cycles at the ears. By the end of the final practice session, the subjects were able to reproduce loudness balances within 5 dB of one another when the comparison signal was initiated at an intensity level 20 dB below or 20 dB above that of the reference signal.

Experimental Sessions

The experiment was divided into two parts in order to study the effects of employing relatively high- *vs*. relatively low-duty cycle reference tones. Part I preceded Part II in the sequence of testing for each of the subjects.

Part I: High Duty Cycle Reference, Low Duty Cycle Comparison Signals. In Part I subjects were presented with a 50-dB SPL 1000-Hz reference tone (R) to the right ear and a 1000-Hz comparison tone (C) to the left ear. The comparison tone passed through a Bekesy attenuator which continuously varied the intensity in 0.25 dB steps at a rate of 2.5 dB/sec. Reference and comparison tones, when presented simultaneously, were 180° out of phase with one another at the earphones. This was done to minimize localization clues which might occur during the rise and decay times of the alternating tones in the no-interval conditions. The temporal parameters of the reference and comparison tones were adjusted to derive differences (D) in duty cycle between the signals at the two earphones of 0, 30, 60 and 80 per cent. Table 2 contains a delineation of the temporal parameters both for those conditions with a silent interval between signals and for those with no silent interval. The signals for

TABLE 2

TEMPORAL PARAMETERS OF ALTERNATE LOUDNESS BALANCE SIGNALS

Disparity of Duty Cycle %	High Duty Cycle On Time msec	High Duty Cycle Off Time msec	High Duty Cycle Rep. Rate IPS	High Duty Cycle Duty Cycle %	Low Duty Cycle On Time msec	Low Duty Cycle Off Time msec	Low Duty Cycle Rep. Rate IPS	Low Duty Cycle Duty Cycle %	Silent Interval Between Pulses msec
No Silent Interval Conditions									
D_0	200	200	2.5	50	200	200	2.5	50	0
D_{30}	375	200	1.75	65	200	375	1.75	35	0
D_{60}	800	200	1.0	80	200	800	1.0	20	0
D_{80}	1800	200	0.5	90	200	1800	0.5	10	0
Silent Interval Conditions									
D_0	200	1000	0.83	16.6	200	1000	0.83	16.6	400
D_{30}	714.3	1000	0.58	41.6	200	1514.3	0.58	11.6	400
D_{60}	2000	1000	0.33	66.6	200	2800	0.33	06.6	400
D_{80}	5000	1000	0.16	83.3	200	5900	0.16	03.3	400

the no-interval conditions are illustrated in Figure 2. The rise-decay segments of these signals overlap at the two ears for their 10 msec duration upon each alternation. Figure 3 is an illustration of the signals employed in the silent-interval conditions. A 400-msec silent interval separated reference and comparison signals so that no portion of the signals overlapped.

During Part I trials, all subjects received the signal with the higher duty cycle in the right ear at 50-dB SPL as a reference loudness (R_H). The lower duty cycle comparison signal (C_L) was presented to the left ear and its intensity was adjusted to produce a loudness equal to that of the reference signal. Subjects 1-6 were given the no-interval conditions and subjects 7-12 were given the silent-interval conditions during Part I (R_HC_L) of the study. Subjects were alternately assigned to the first group (numbers 1-6) and the second group (numbers 7-12) in order to avoid any biasing artifacts related to the date of testing.

Counterbalancing of the 4 pairs of temporal conditions, given in Table 2, was achieved in a manner which allowed use of D_0 tracings as control data to determine the relative influence of a discrepancy of duty cycle. Each trial consisted of three sets of tracking paradigms. The initial and final conditions in each set contained tones of equal interaural duty cycle (D_0). Signal pairs with dissimilar interaural duty cycles (e.g. D_{60}) occurred between the two D_0 trials. The following is a typical array of experimental conditions: D_0 - D_{60} - D_0; D_0 - D_{30} - D_0; and D_0 - D_{80} - D_0. These sets, each composed of three trials, were then arranged in a counterbalanced order for subject groups 1-6 and 7-12. Data were collected on all three sets in a single session.

Five seconds prior to each ABLB-tracking period, a warning light

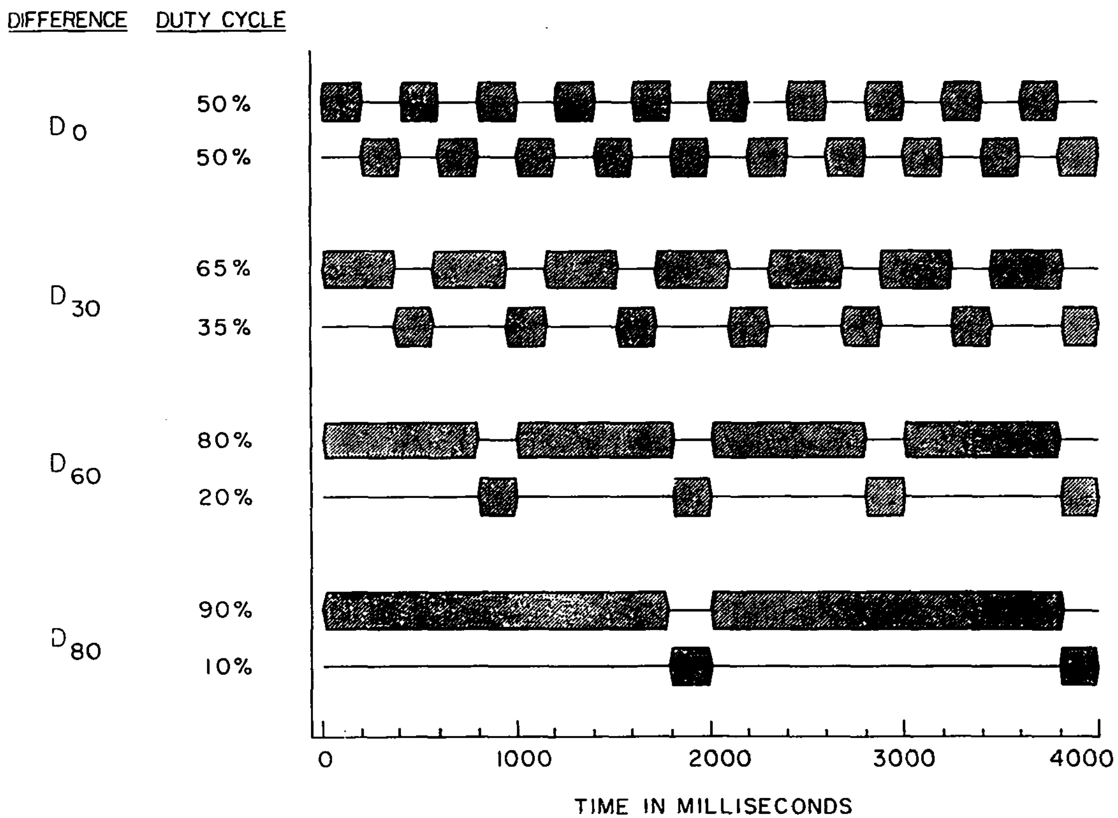

Fig. 2.--Schematic representation of the four signal pairs employed during no-interval alternate binaural loudness balances.

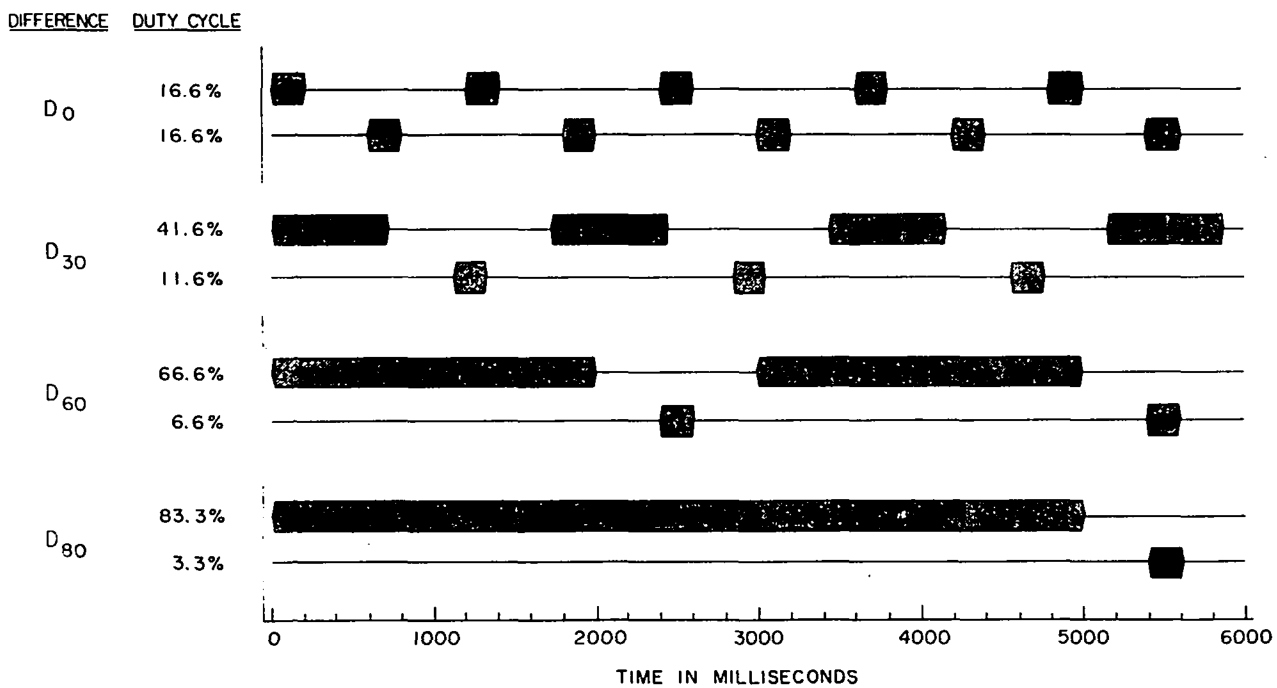

Fig. 3.--Schematic representation of the four signal pairs employed during silent-interval alternate binaural loudness balances.

was activated to alert S's that a test was about to begin. The light ended with the commencement of the 4-minute loudness balance period. Both reference and comparison signals were initially presented at 50-dB SPL. The comparison signal increased in intensity until the subject depressed the Bekesy switch. The signal then diminished in intensity until the subject released the switch. The four-minute balancing periods were separated by one-minute rest periods during which the earphones were left in place. After the third tracking period in each set, the earphones were removed and the subjects were given a 10-minute rest period. Total time for instructions, testing and rest periods was one hour and 15 minutes.

The following instructions were given at the commencement of each test session and following the 10-minute rest period:

> You will now hear a tone in each earphone alternating back and forth between your ears at various pulse rates. Please listen closely to the tone in your right ear and attempt to maintain an identical loudness in your left ear by manipulating the hand-switch.
>
> When the sound in your left ear grows louder than the sound in your right ear, press the switch and hold it until the sound in your left ear is too soft to maintain a balance. At this point, release the switch, and so forth. Listen only to the loudness of these sounds and disregard other factors such as pitch, quality, fuzziness, comfort or pressure at the ears.
>
> Unless you have any questions, the signals will commence 5 seconds after the warning light comes on.

<u>Part II: Low Duty Cycle Reference, High Duty Cycle Comparison Signals</u>. The procedures for Part II were identical to those of Part I. During Part II, however, the low duty cycle signal was fixed at 50-dB SPL and delivered to the right ear as a reference loudness (R_L), and the high duty cycle comparison signal (C_H) was delivered via the Bekesy

audiometer to the left ear. Subjects 1-6 received silent-interval balances and subjects 7-12 received the no-interval conditions during Part II ($R_L C_H$) of the experiment.

Summary

The primary purpose of the present investigation was to determine the influence of duty cycle on loudness when comparison and reference signals were alternately available for judgments of equality or difference in loudness over a relatively long time period. Signals were presented under eight conditions of equality and disparity of duty cycles in Parts I and II of the experiment. During four of the conditions, signals were presented in a "no-interval" ABLB paradigm in which rise-decay times overlapped. Under the remaining four conditions, a 400-msec "silent interval" separated reference and comparison signals so that no portion of the alternating signals overlapped. Differences between the reference and comparison signal duty cycles for the 4 "no-interval" and the 4 "silent interval" conditions equaled 0, 30, 60 and 80 per cent. The signal with the higher duty cycle served as the reference loudness (R_H) in Part I, and that with the lower duty cycle served as the reference loudness (R_L) for Part II. The reference loudness was always presented to the right ear at a 50-dB SPL fixed intensity. The comparison signal intensity was adjusted by the subject via a Bekesy audiometer. The subjects were instructed to make the appropriate adjustments for a criterion of equal loudness at the two ears. One-half of the subjects received the "no-interval" balances during Part I and the "silent-interval" balances during Part II. The order of testing was reversed for the other subjects. Testing order of the duty cycle difference (D) conditions was also counterbalanced. Pursuit auditory loudness tracking was conducted for each of 4 duty cycle difference conditions during a four-minute period after the commencement of tracking. Procedures, methods of instruction and test sessions were identical for Parts I and II.

The experimental procedures constitute a combination of the method of limits and adjustment in which well-trained normal-hearing male subjects are employed in a pursuit-loudness tracking task. The task constitutes an equation of magnitudes in order to effect loudness balances for bilaterally alternating tones.

CHAPTER IV

RESULTS, ANALYSIS AND DISCUSSION

Introduction

The present investigation was designed to determine the influence of duty cycle upon the loudness of pulsed tones. Normal male listeners were instructed to maintain a binaural loudness balance between a reference tone, which was fixed in the right ear at 50-dB SPL, and a variable-intensity comparison tone in the left ear. On- and off-durations of the alternating tones were set to deliver interaural duty cycle differences (D) of 0, 30, 60, and 80 per cent. All duty cycle conditions were counterbalanced and presented in a manner which allowed comparison of D_0 and each of the other conditions. Thus the D_0 tracings for each subject served as baseline or reference data for each corresponding condition in which the alternate tones had unequal duty cycles. The final data represent relative loudness values in dB which may be attributed to the effects of unequal duty cycles at the ears.

The four principal factors under investigation included duty cycle differences, the presence or absence of a silent interval between alternating tones, the use of high duty cycle tones as the reference (R_H) loudness vs. the use of low duty cycle tones as the reference (R_L) loudness and the passage of time after commencement of tracking.

Reference Data

Reference data for each subject were obtained by presenting alternate binaural loudness balances in which the duty cycles were equal (D_0) at the ears. D_0 balances were administered prior to and following each condition in which the duty cycles were unequal at the ears. The comparison-tone tracking levels for the two D_0 runs were averaged and employed as reference data for the calculation of the duty cycle-loudness effect. This procedure eliminated that part of the variability in the data due to possible asymmetical loudness function among the individual subjects.

Tables 11 and 12 and Figures 15 and 16 (see Appendix A, pages 99 to 102) contain the mean tracking levels (in dB SPL) for D_0 conditions. Although a substantial difference is noted between the silent-interval and no-interval conditions in Part I of the experiment (R_HC_L), the difference fails to reach statistical significance (see Appendix B, Table 13, page 104). This difference between silent-interval and no-interval conditions increased over time, thereby leading to a significant interval-by-time interaction. Other factors in Part I had little effect on the data. In Part II of the experiment (R_LC_H), none of the investigated factors had a consistent influence on the comparison-tone tracking levels.

Experimental Data

Results

Modifications in the loudness perception of either the 50-dB SPL reference signal or the variable comparison signal were reflected in changes of the comparison-signal tracking level. Measurements of the comparison-signal intensity were extracted from the Bekesy tracings at various time points along the four-minute tracking period.

Interaural duty cycle differences were found to have a profound effect on loudness. Although this effect was related to the time after commencement of tracking, it was relatively uninfluenced by the other factors explored in the experiment. The loudness disparity increased rapidly during the first minute of tracking with the rate of increase being greater for the greater duty cycle difference (D). After two minutes, the loudness disparity averaged about 5 to 6 dB for all three duty cycle D conditions, changing little over the subsequent two minute period. Figure 4 depicts the effect of tracking time on loudness differences with the interaural duty cycle D as the parameter. In the figure, as in the associated Table 3, the results are averaged over conditions with and without a silent interstimulus interval and over Parts I and II of the experiment. The following sections include a more detailed description of these findings and an analysis and discussion of the results.

Part I: R_HC_L Balances. In Part I the reference signal had the higher duty cycle (R_H) and the comparison signal had the lower duty cycle (C_L) whenever the experimental trials called for an interaural disparity of duty cycles. For R_HC_L data (Part I) the comparison signal tracking levels for appropriate D_0 runs were subtracted from tracking levels for D_{30}, D_{60} and D_{80} runs.

The upper half of Table 4 contains the mean intensity difference scores and standard errors attributable to duty cycle disparity within no-interval conditions. The mean difference in loudness attributable to duty cycle increased from 2.2-dB equivalent intensity to 3.1 dB and 8.3 dB as the discrepancy in interaural duty cycle was increased from 30 per

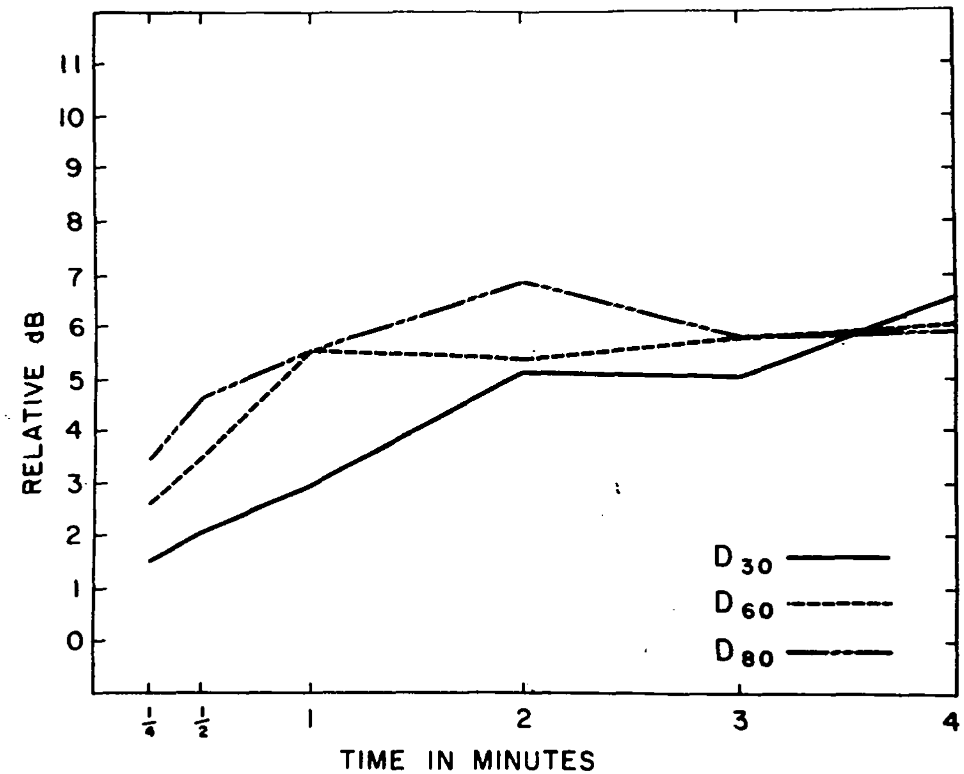

Fig. 4.—Intensity differences (relative dB) for equal loudness as a function of time averaged over all conditions. The parameter is the difference in duty cycle.

TABLE 3

MEAN INTENSITY DIFFERENCES (dB) FOR EQUAL LOUDNESS AS A FUNCTION OF TIME AND DUTY CYCLE DIFFERENCES

Time After Start of Tracking (min)	Difference in Duty Cycle (%) D_{30}	D_{60}	D_{80}	Mean
1/4	1.5	2.6	3.4	2.5
1/2	2.0	3.4	4.6	3.3
1	2.9	5.5	5.5	4.6
2	5.1	5.3	6.8	5.7
3	5.0	5.8	5.8	5.5
4	6.5	6.0	5.9	6.1
MEAN	3.8	4.7	5.3	4.6

TABLE 4

MEAN INTENSITY DIFFERENCES (dB) FOR EQUAL LOUDNESS AS A FUNCTION OF TIME AND DUTY CYCLE DIFFERENCES IN PART I ($R_H C_L$)

Time After Start of Tracking (min)	Difference in Duty Cycle (%) D_{30}	D_{60}	D_{80}	Mean
	No Silent Interval			
1/4	-0.9	2.0	5.1	2.1
1/2	0.1	1.8	7.3	3.0
1	0.7	5.1	8.7	4.8
2	3.7	2.2	9.7	5.2
3	4.2	4.0	8.2	5.5
4	5.5	4.9	11.1	7.2
MEAN	2.2	3.1	8.3	4.6
SE_M	0.9	2.0	1.4	
	Silent Interval			
1/4	3.1	3.7	8.3	5.0
1/2	2.9	3.9	9.0	5.3
1	2.9	5.2	10.7	6.3
2	7.2	7.9	11.0	8.7
3	7.5	7.3	8.4	7.7
4	7.6	7.5	6.6	7.2
MEAN	5.2	5.7	9.0	6.7
SE_M	1.8	3.2	2.7	
GRAND MEAN	3.7	4.4	8.7	5.8

cent ($R_{65}C_{35}$) to 60 per cent ($R_{80}C_{20}$) to 80 per cent ($R_{90}C_{10}$). During the tracking period, duty cycle-loudness effects steadily increased from 2.1 dB at T=1/4 minute to 7.2 at T=4 minutes. The mean effect attributable to duty cycle differences was 4.6 dB for no-interval balances within Part I.

The data which appear in the upper portion of Table 4 are illustrated in Figure 5. The shift in comparison-tone tracking level due to duty cycle differences (i.e., relative dB) increased steadily as time progressed from 1/4 to 4 minutes. The data for D_{30} and D_{60} conditions were nearly overlapped at T=2 and beyond, whereas the D_{80} tracking levels were clearly separated from the others for the entire tracking period.

A second ABLB condition in Part I included the presence of a 400-msec silent interval between each presentation of reference (R) and comparison (C) signals. The data for silent-interval balances appear in the lower portion of Table 4. Duty cycle-loudness effects of 5.2-dB equivalent intensity were observed for D_{30} ($R_{41.6}$ $C_{11.6}$), 5.7 dB for D_{60} ($R_{66.6}$ $C_{6.6}$), and 9.0 dB for the D_{80} trials ($R_{83.3}$ $C_{3.3}$). The mean loudness effects attributable to duty cycle increased from 5.0 dB at T=1/4 to 8.7 dB at T=2. Beyond T=2 there was a subsequent decrease in overall duty cycle effects on loudness. The average overall effect of duty cycle was 6.7 dB for silent-interval balances within Part I.

The data of Table 4 (lower portion, silent-interval balances) are plotted in Figure 6. Prior to T=3, silent-interval trials yielded substantially different loudness levels for all three D conditions. For this portion of the results, there was an orderly increase in the interaural loudness disparity as the size of the duty cycle disparity was increased from D_{30} to D_{80}.

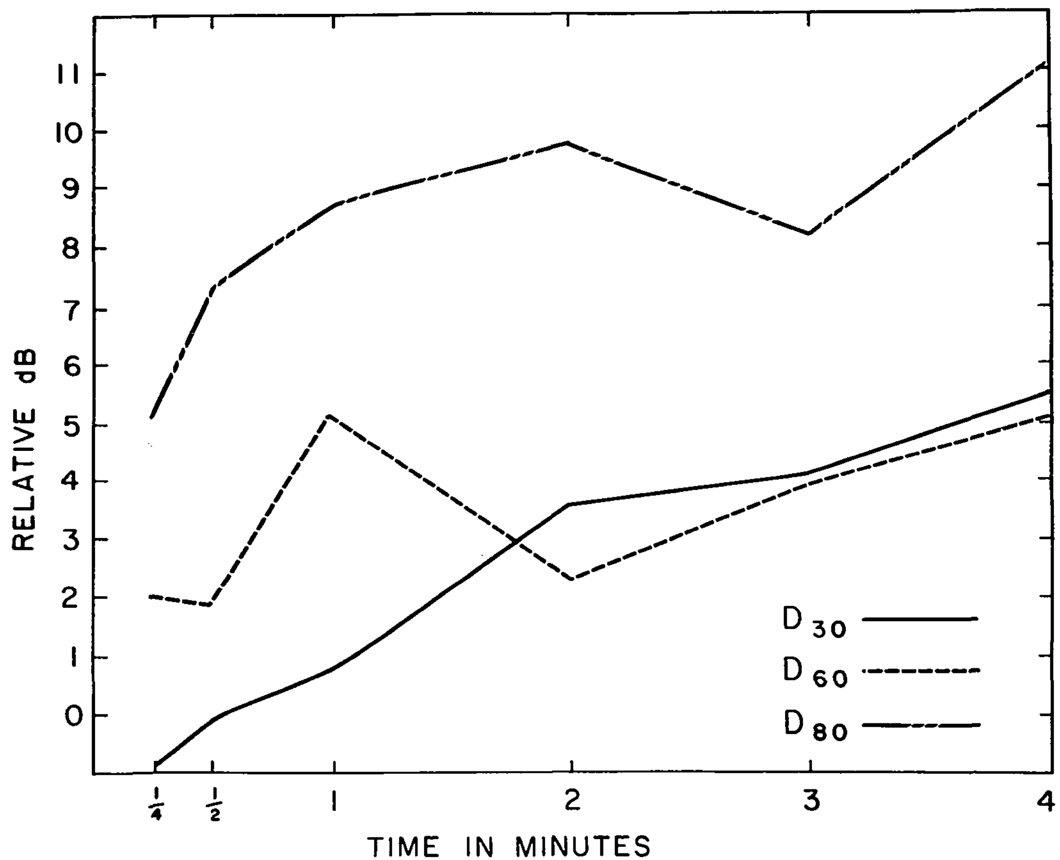

Fig. 5.--Intensity differences (relative dB) for no-interval conditions in Part I as a function of time. The parameter is the difference in duty cycle.

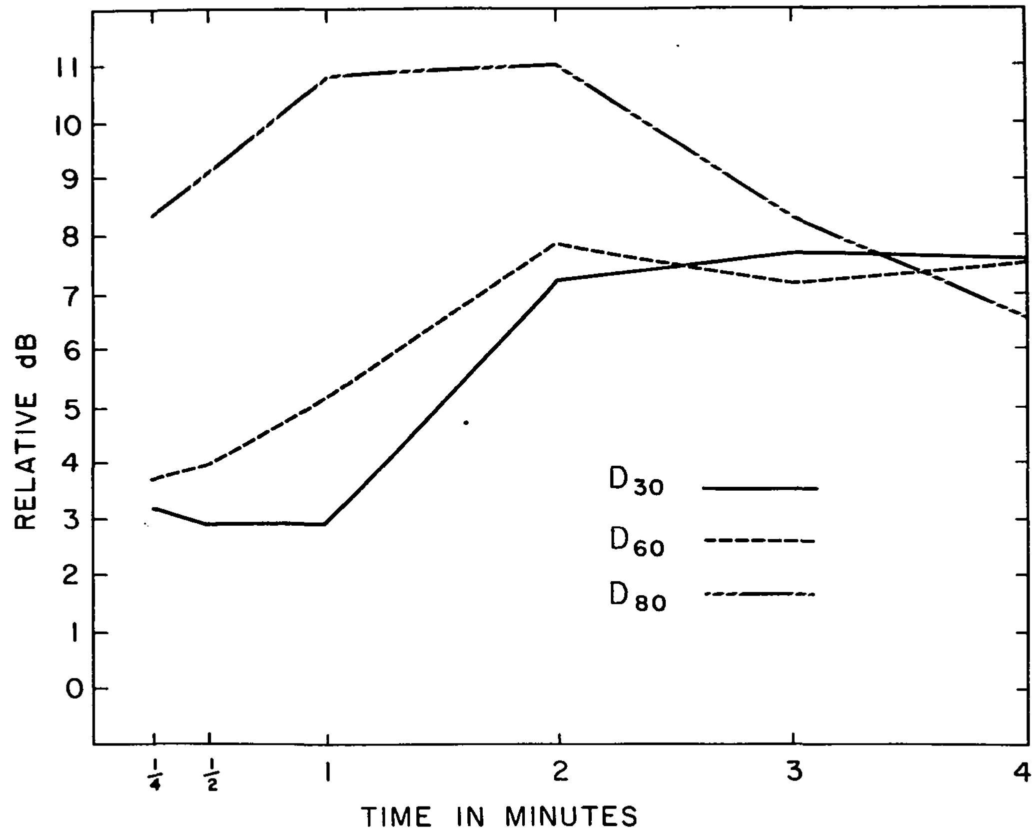

Fig. 6.—Intensity differences (relative dB) for silent-interval conditions in Part I as a function of time. The parameter is the difference in duty cycle.

For the D_{30} and D_{60} conditions, time had no additional effect on interaural loudness relations beyond T=2. However, for the D_{80} condition, the interaural loudness disparity decreased beyond T=2.

The fact that the numbers in Table 4 and in Figures 5 and 6 are mostly positive indicate that for nearly all experimental conditions, the pulse train with the higher relative duty cycle was judged louder than the pulse train of lower duty cycle when the two signals had identical intensities. In Part I, subjects compensated for the loudness imbalance by tracing the lower duty cycle comparison signals at greater SPL's than the 50-dB SPL reference signal.

Part II: R_LC_H Balances. In Part II the reference consisted of the lower duty cycle (R_L) signal and the comparison signal had the higher duty cycle (C_H) whenever the experimental trials called for unequal interaural duty cycles. For R_LC_H data (Part II) the comparison-signal tracking levels for D_{30}, D_{60} and D_{80} balances were subtracted from tracking levels for the corresponding averaged D_0 runs.

The data located in the upper portion of Table 5 represent the mean loudness effects (in dB equivalent intensity) attributable to a disparity of duty cycle for no-interval balances within Part II. The mean loudness differences due to duty cycle decreased from 4.0 dB to 3.1 dB to 1.9 dB as the duty cycle D was increased from D_{30} to D_{60} to D_{80}. There was a slight increase in the duty cycle-loudness effect from 2.1 dB to 3.5 dB as time increased from T=1/4 to T=2. The duty cycle-loudness effect remained essentially unchanged from T=2 to T=4. These data are illustrated in Figure 7 for no-interval balances within Part II. Data for D_{30} and D_{60} runs were overlapped from T=1/4 to T=3. At T=4, the loudness

TABLE 5

MEAN INTENSITY DIFFERENCES (dB) FOR EQUAL LOUDNESS AS A FUNCTION OF TIME AND DUTY CYCLE DIFFERENCES IN PART II ($R_L C_H$)

Time After Start of Tracking (min)	Difference in Duty Cycle (%) D_{30}	D_{60}	D_{80}	Mean
	No Silent Interval			
1/4	2.7	2.0	1.7	2.1
1/2	2.7	2.6	2.7	2.7
1	3.9	3.7	0.5	2.7
2	4.5	4.5	1.4	3.5
3	3.7	3.9	2.5	3.4
4	6.3	2.0	2.3	3.5
MEAN	4.0	3.1	1.9	3.0
SE_M	1.5	3.7	2.9	
	Silent Interval			
1/4	1.2	2.8	-1.4	0.9
1/2	2.3	5.1	-0.6	2.3
1	4.2	7.8	2.0	4.7
2	4.8	6.7	5.1	5.5
3	4.6	7.9	3.9	5.5
4	6.5	9.4	3.6	6.5
MEAN	3.9	6.6	2.1	4.2
SE_M	1.8	1.4	2.2	
GRAND MEAN	4.0	4.9	2.0	3.6

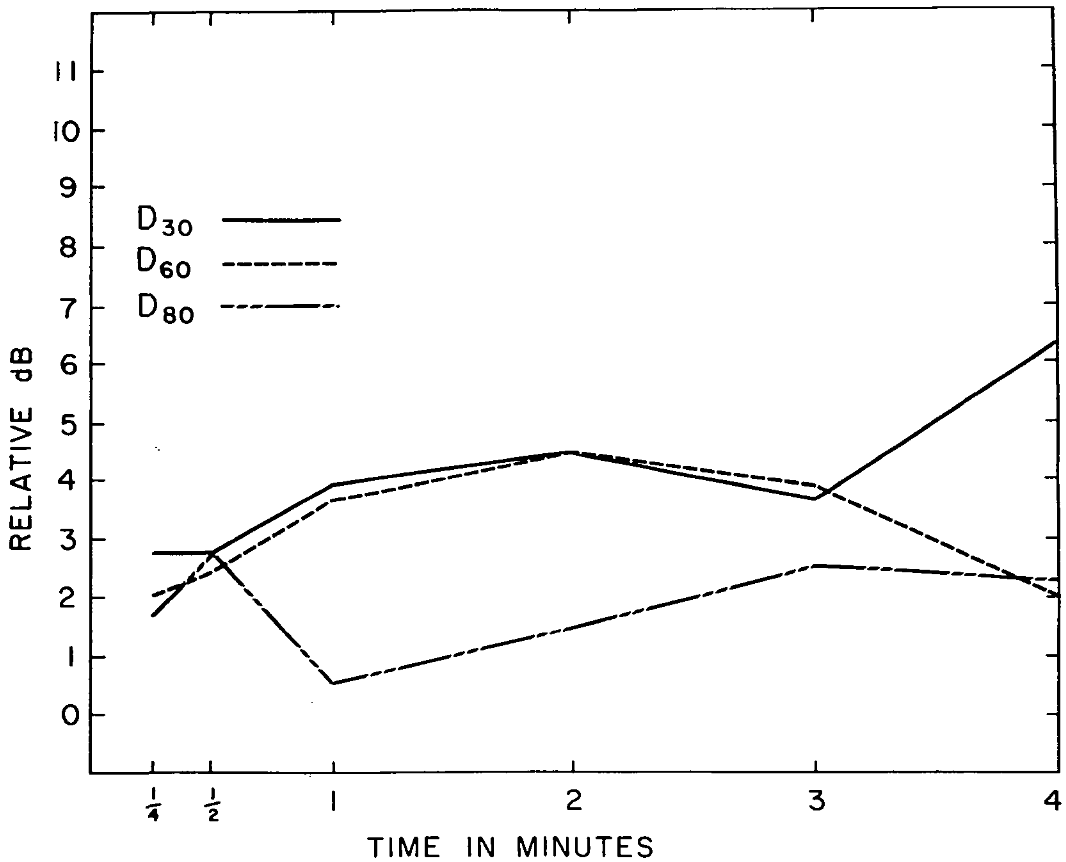

Fig. 7.--Intensity difference (relative dB) for no-interval conditions in Part II as a function of time. The parameter is the difference in duty cycle.

disparity increased for D_{30} balances and decreased for D_{60} balances. Loudness disparity for D_{80} trials was generally less than for other D conditions within the no-interval balances of Part II.

Data for silent-interval trials within R_LC_H conditions appear in the lower portion portion of Table 5. Duty cycle-loudness effects were 3.9 dB for D_{30}, 6.6 dB for D_{60} and only 2.1 dB for D_{80}. Time after commencement of tracking had a large and progressive effect on the mean duty cycle-loudness function growing from 0.9 dB at T=1/4 to 6.5 dB at T=4. The overall mean loudness difference attributable to duty cycle disparity was 4.2 dB for silent-interval balances in Part II.

The silent-interval data of Table 5 are plotted in Figure 8. Time appears to have an influence on relative dB measurements for the entire four-minute tracking period. Both D_{30} and D_{60} conditions yielded progressively greater duty cycle-loudness effects with the largest increments occurring between T=1/4 and T=1. D_{60} balances yielded consistently greater loudness disparity than either D_{30} or D_{80}. The D_{80} condition yielded a steep growth in loudness disparity during the first two minutes of tracking. Beyond T=2 the D_{80} tracings tended to decrease slightly.

The data for all D conditions were averaged independently for the silent-interval and no-interval balances and these data are plotted in Figure 9. For no-interval conditions in Part II it appears that interaural loudness differences increased only slightly throughout the four-minute tracking period. For the silent-interval trials the interaural loudness difference increased dramatically through T=1, and more gradually thereafter, paralleling the growth for no-interval conditions beyond T=1.

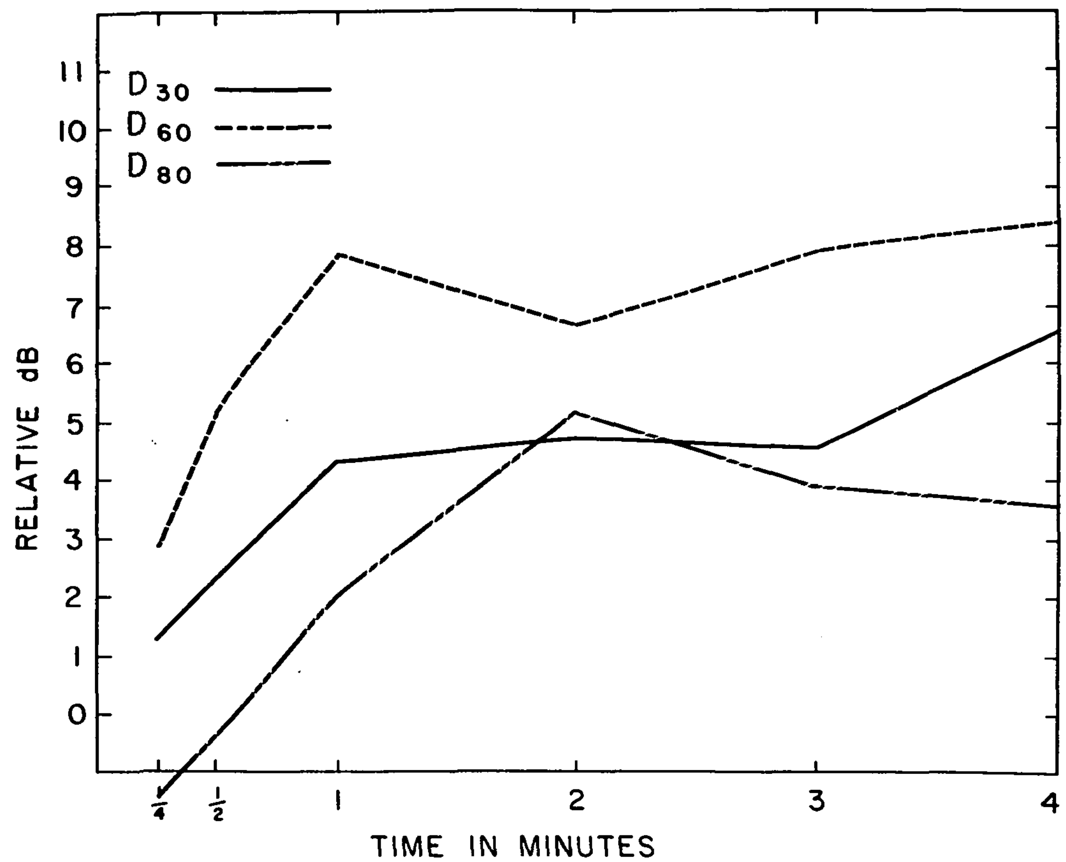

Fig. 8.—Intensity differences (relative dB) for silent-interval conditions in Part II as a function of time. The parameter is the difference in duty cycle.

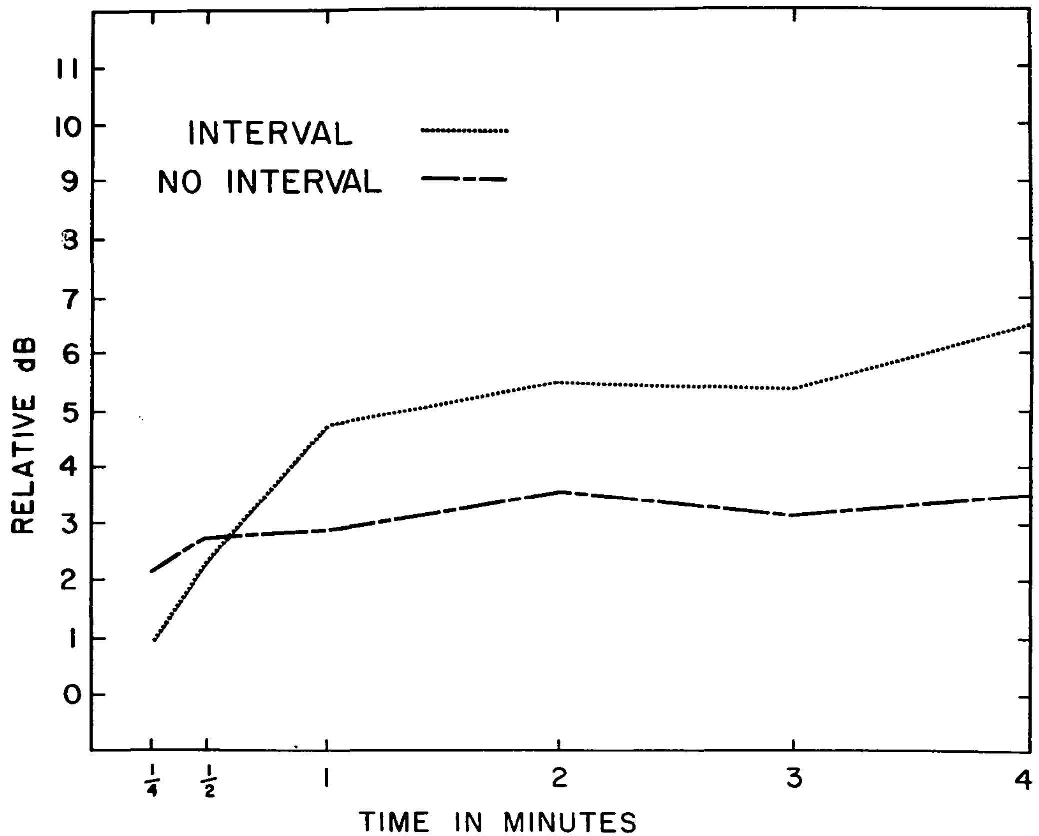

Fig. 9.—Intensity differences (relative dB) for silent-interval and no-interval conditions in Part II.

Comparison of Data from Part I and Part II. The total loudness effects attributable to duty cycle for R_LC_H balances (Part II) were subtracted from the duty cycle-loudness effects within R_HC_L balances (Part I). If, in fact, the matter of fixing high or low duty cycle signals is inconsequential, then R_HC_L-R_LC_H difference should be 0 dB. The resulting data, given in the upper portion of Table 6, represent these differences with no-interval trials. The difference between R_LC_H and R_HC_L trials tended first to change from negative to positive and then to increase as duty cycle D was increased. During D_{30} balances the difference averaged -1.5 dB. For D_{60} balances it was 0.3 dB and for D_{80} balances it increased dramatically to 6.5 dB.

The discrepancy between Parts I and II increased over time from 0.3 dB at T=1/4 to 3.7 dB at T=4. Increases in relative dB over time occurred for all three of the D balances in which duty cycles were unequal at the ears. The overall mean difference between the data of Part I and Part II for no-interval balances was 1.8 dB. The data of Table 6 for no-interval balances are illustrated in Figure 10. A wide discrepancy between the data for D_{80} and the data for the other D conditions is readily apparent.

Comparable data for Parts I and II with the silent-interval balances appear in the lower portion of Table 6. In contrast to the data of D_{30} and D_{60} which differed by only 1.5 dB and -1.1 dB from Part I to Part II, D_{80} data differed by a remarkable 6.9 dB. The greater duty cycle effects on loudness occurred in Part I. Differences between Parts I and II were greater during the early portion of the tracking period and appeared to lessen as the tracking continued. This trend appears in the average data but was evidenced only for the D_{80} data. The D_{30} and D_{60} data did

TABLE 6

DUTY CYCLE EFFECTS IN PART I (R_HC_L) MINUS DUTY CYCLE EFFECTS IN PART II (R_LC_H)

Time After Start of Tracking (min)	Difference in Duty Cycle (%) D_{30}	D_{60}	D_{80}	Mean
	No Silent Interval			
1/4	-3.4	0.8	3.4	0.3
1/2	-2.6	-0.9	4.6	0.4
1	-3.2	1.4	7.7	2.0
2	-0.9	-2.3	8.2	1.7
3	0.3	0.1	7.3	2.6
4	0.7	2.7	7.8	3.7
MEAN	-1.5	0.3	6.5	1.8
SE_M	0.8	0.8	0.9	
	Silent Interval			
1/4	2.1	0.9	9.7	4.2
1/2	0.2	-1.2	9.6	2.9
1	0.0	-2.7	8.7	2.0
2	2.5	-1.2	6.0	1.9
3	2.9	-0.4	4.5	2.3
4	1.2	-2.0	3.0	0.7
MEAN	1.5	-1.1	6.9	2.4
SE_M	0.5	0.6	1.3	
GRAND MEAN	0.0	-0.4	6.7	2.1

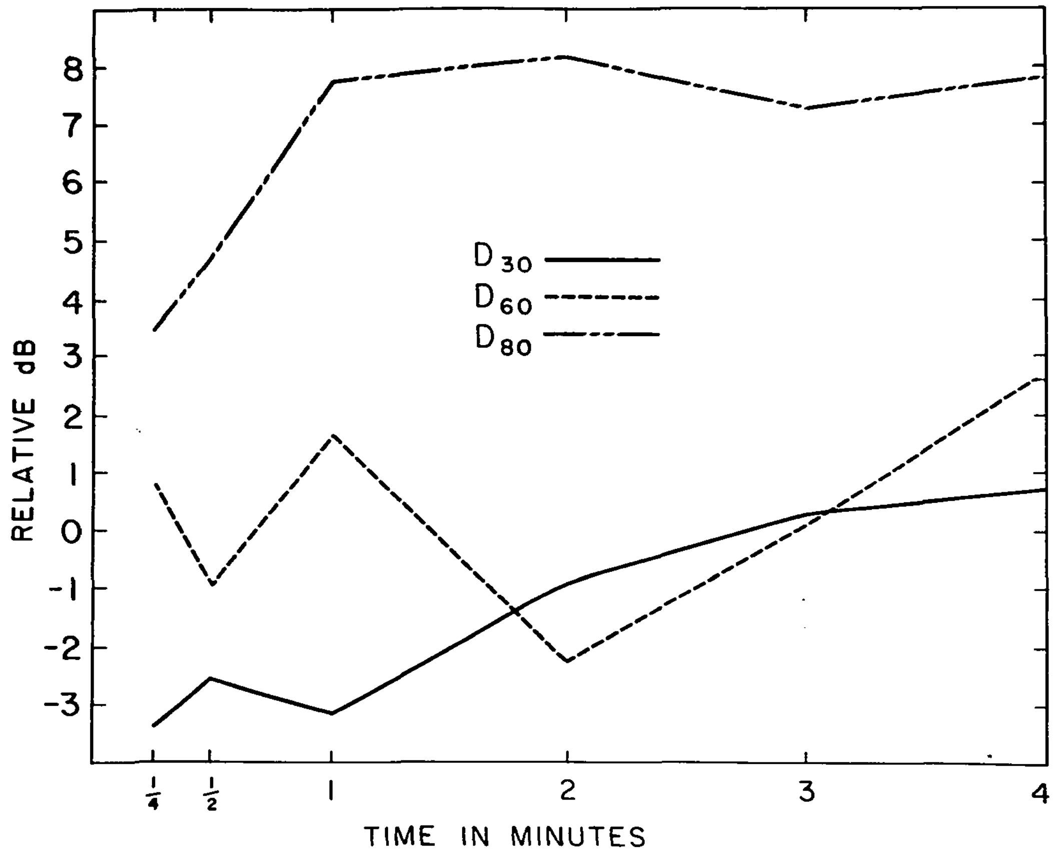

Fig. 10.—Duty cycle effects (relative dB) in Part I minus duty cycle effects in Part II, within no-interval conditions.

not show any progressive changes over time. The average difference decreased from a mean of 4.2 dB at T=1/4 to 0.7 dB at T=4. The overall mean difference between duty cycle effects for silent-interval balances of Parts I and II was 2.4 dB in favor of greater loudness disparity in Part I.

The data of Table 6 for silent-interval balances are illustrated in Figure 11. The difference data for D_{30} and D_{60} conditions approximated the 0-relative decibel level suggesting that the effect of the transition from R_HC_L to R_LC_H balances was negligible. The D_{80} effects, however, were remarkably larger and they warrant further description.

Table 7 contains a comparison of the duty cycle-loudness effects for only the D_{80} balances. The upper portion of Table 7 deals only with no-interval balances and the lower portion contains data for silent-interval balances. The greatest loudness difference due to duty cycle disparity was consistently observed for R_HC_L balances (Part I). The discrepancies between Parts I and II for D_{80} balances appear to be related to time as illustrated in Figure 12. The difference increased from 3.4 dB at T=1/4 to 8.2 dB at T=2, at which point the loudness difference peaked and subsequently decreased. This change in the Part I-Part II difference over time is primarily due to the increasing loudness difference as a function of tracking time in Part I.

The silent-interval balances yielded differences between Parts I and II for D_{80} runs which appear in the lower portion of Table 7 and also in Figure 12. The D_{80} effects diminished sharply from 9.7 dB at T=1/4 to 3.0 dB at T=4. This tendency is in contrast to that observed under the no-interval balance conditions. The overall mean difference was 6.9 dB for silent-interval balances as compared with 6.5 dB for

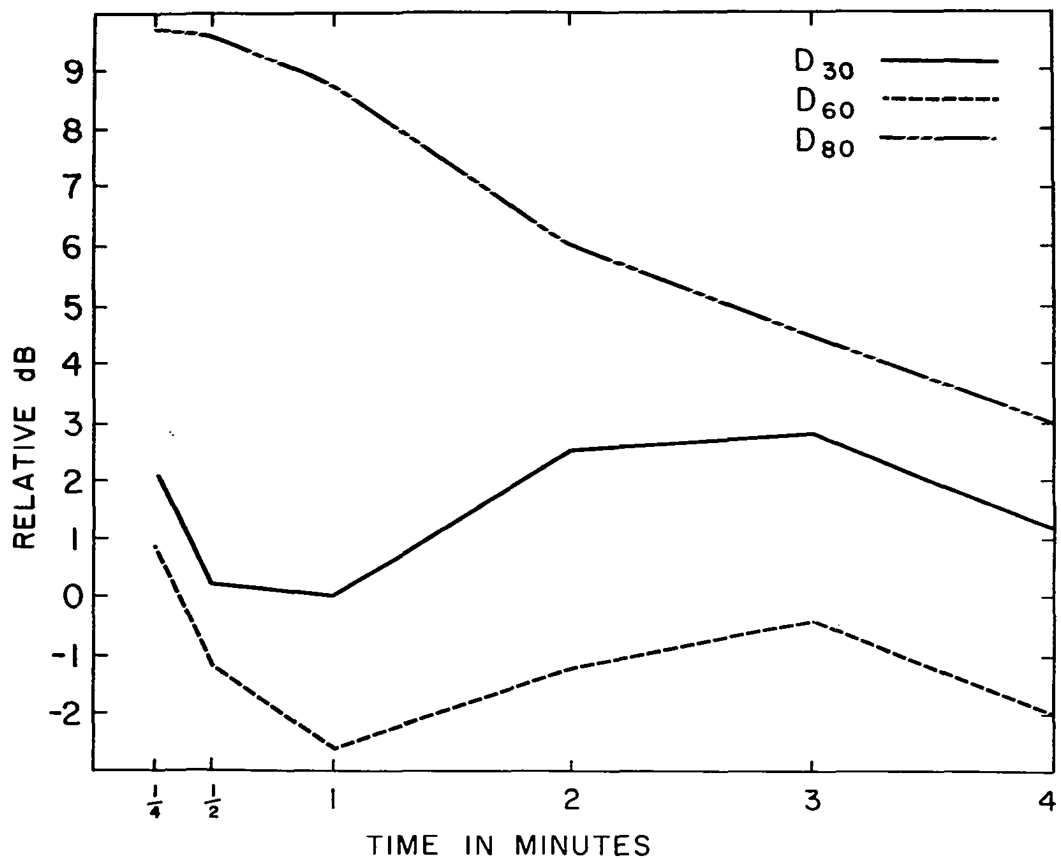

Fig. 11.--Duty cycle effects (relative dB) in Part I minus duty cycle effects in Part II, within silent-interval conditions.

TABLE 7

A COMPARISON OF THE LOUDNESS EFFECTS ATTRIBUTABLE TO DUTY CYCLE FOR D_{80} BALANCES WITHIN PART I AND PART II

Time After Start of Track (min)	Part I	Part II	Difference
	No Silent Interval		
1/4	5.1	1.7	3.4
1/2	7.3	2.7	4.6
1	8.7	0.5	7.7
2	9.7	1.4	8.2
3	8.2	2.5	7.3
4	11.1	2.3	7.8
MEAN	8.3	1.9	6.5
SE_M	1.4	2.9	
	Silent Interval		
1/4	8.3	-1.4	9.7
1/2	9.0	0.6	9.6
1	10.7	2.0	8.7
2	11.0	5.1	6.0
3	8.4	3.9	4.5
4	6.6	3.6	3.0
MEAN	9.0	2.1	6.9
SE_M	2.8	2.2	
GRAND MEAN	8.7	2.0	6.7

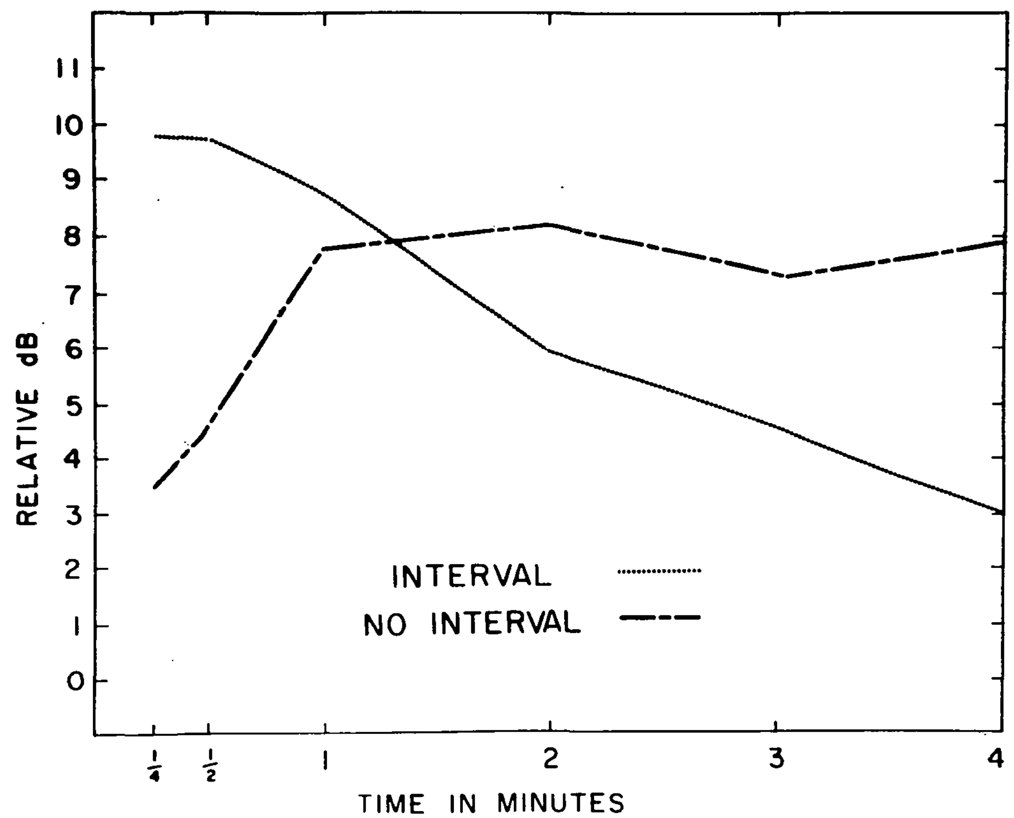

Fig. 12.--Duty cycle-loudness effects in Part I minus the duty cycle-loudness effects in Part II for D_{80} balances, within silent-interval and no-interval conditions.

no-interval balances.

Additional Comparisons. In Figure 13, the average relative-dB data within Parts I and II are plotted as a function of the difference in duty cycle between R and C signals. The relative-dB data were again calculated with reference to individual performance on D_0 balances. During R_HC_L balances (Part I), there was a progressive increase in loudness difference as the duty cycle D was increased. During R_LC_H balances (Part II), the relative dB values increased between D_{30} and D_{60} and then decreased for D_{80}.

The overall influence on interaural loudness disparity of the silent-interval period between alternating pulses merits comment. Figure 14 contains the intensity difference in relative dB plotted with respect to the difference in duty cycle between R and C signals. The parameter is the interval condition. At D_{30} the difference between interval and no-interval conditions averaged approximately 1.5 dB, with the greater duty cycle-loudness effect for the silent-interval balances. The maximum difference between interval and no-interval conditions (nearly 3 dB) was observed for D_{60} trials. The difference was only 0.4 dB for D_{80} balances. The mean relative loudness of the experimental signals under interval and no-interval conditions (combined) increased as the duty cycle difference was increased.

Analysis of the Results

The experimental design of the present investigation called for a split-plot (or nested) statistical procedure for analysis (67).

Part I: R_HC_L Balances. A summary of the analysis of variance for ABLB procedures with unequal interaural duty cycles in Part I

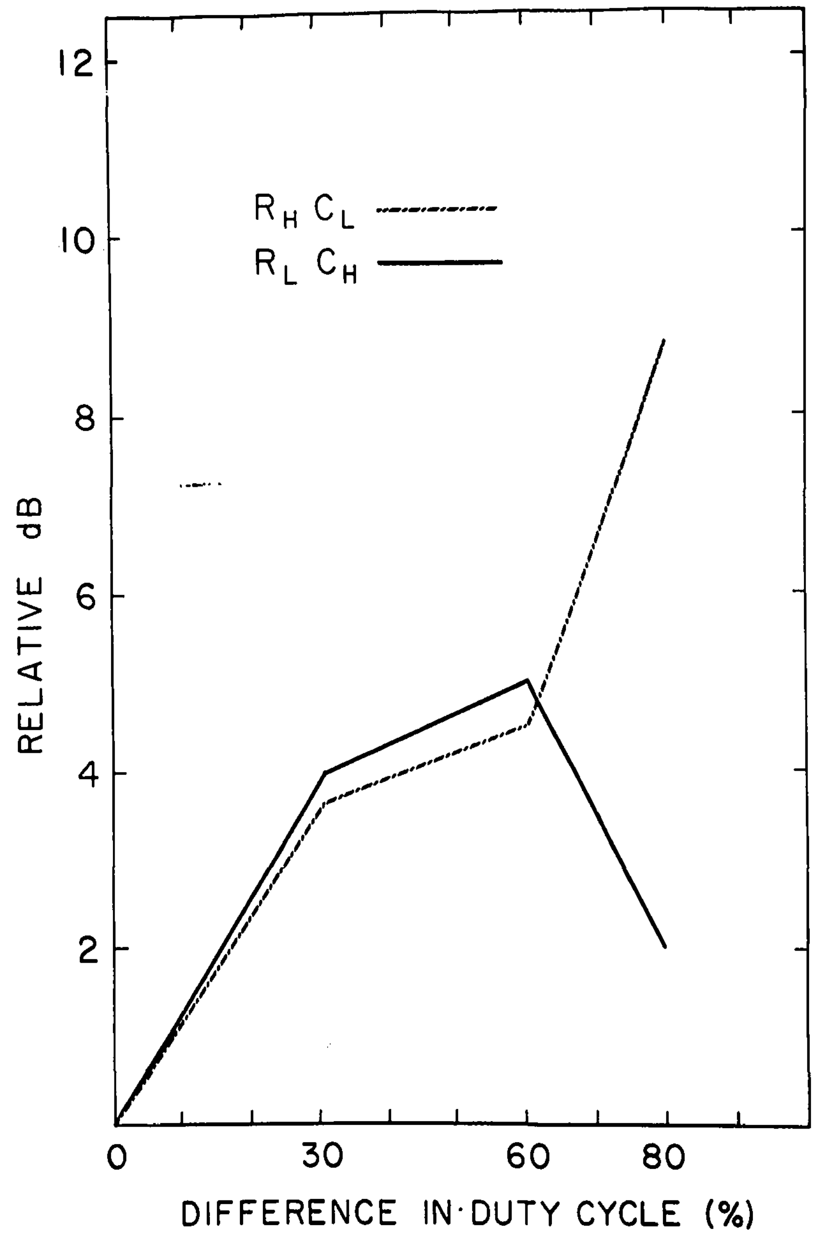

Fig. 13.--Intensity differences (relative dB) as a function of duty cycle difference for Part I (R_HC_L) and Part II (R_LC_H).

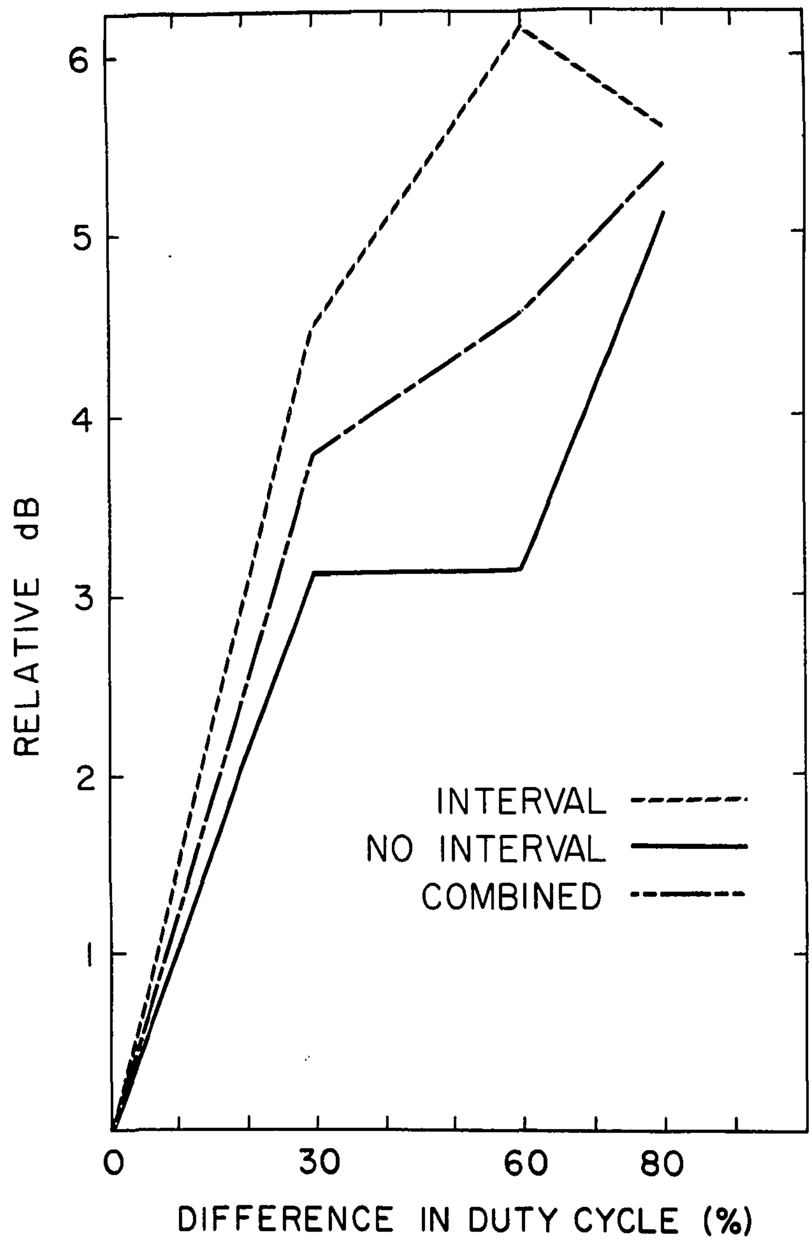

Fig. 14.--Intensity differences (relative dB) as a function of duty cycle difference for silent-interval and no-interval conditions.

appears in Table 8. The data upon which this analysis was based were corrected for individual tracking performance with equal interaural duty cycles (D_0). The analysis reveals that variations due to two of the main factors, duty cycle and time, were significantly large ($p < 0.01$, Table 8). The effect of the presence or absence of the 400-msec silent intervals was nonsignificant. Comparable loudness-balance behavior was observed under interval and no-interval conditions provided that duty cycle D was held constant despite interaural differences of on-duration and off-duration. None of the interactions between main effects reached significant proportions for R_HC_L balances.

<u>Part II: R_LC_H Balances</u>. The analysis of variance for R_LC_H balances (Part II) is summarized in Table 9. The effects of duty cycle and of time on the interaural loudness balances were significantly large ($p < 0.01$ and $p < 0.05$ respectively) while the influence of the presence or absence of a silent interval was nonsignificant ($p > 0.05$). The interaction between the effects of interval and time was significant ($p < 0.05$). This interaction is illustrated in Figure 9 (page 65).

<u>Comparison of Data from Part I and Part II</u>. The results of an analysis of variance for the comparison of high-duty cycle reference (R_HC_L) and low-duty cycle reference (R_LC_H) conditions is given in Table 10. The factor of time did not have a significant effect on the difference between Parts I and II. Furthermore, the interval factor failed to reach statistical significance on the R_HC_L-R_LC_H relationship. The influence on the data attributable to interaural duty cycle differences is significant at the 0.01 level of confidence. None of the interactions between main effects reached significance for the comparison of Parts I and II.

TABLE 8

SUMMARY OF THE ANALYSIS OF VARIANCE FOR R_HC_L SPLIT-PLOT EXPERIMENT IN PART I

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Between Subjects	5	1477.54		
Within Subjects	210			
Interval (I)	1	101.96	101.96	< 1
Error [Subjects (S) x Interval (I)]	5	1308.01	271.60	
Duty Cycle (D)	2	962.23	481.11	6.77[a]
Interval (I) x Duty Cycle (D)	2	14.06	7.03	< 1
Error [(S x D) +	20(10)	1421.42	71.07	
(S x I x D)]	(10)			
Time (T)	5	353.48	70.70	6.96[a]
Interval (I) x Time (T)	5	52.87	10.57	1.04
Duty Cycle (D) x Time (T)	10	129.51	12.95	1.26
I x D x T	10	73.87	7.39	< 1
Error [(S x T) +	150(25)	1523.53	10.16	
(S x I x T) +	(25)			
(S x D x T) +	(50)			
(S x I x D x T)]	(50)			

[a] Significant at the 0.01 level of confidence

TABLE 9

SUMMARY OF THE ANALYSIS OF VARIANCE FOR $R_L C_H$ SPLIT-PLOT EXPERIMENT IN PART II

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Between Subjects	5	2613.05		
Within Subjects	210			
Interval (I)	1	6.51	6.51	< 1
Error [Subjects (S) x Interval (I)]	5	830.44	166.09	
Duty Cycle (D)	2	519.88	259.94	4.63[a]
Interval (I) x Duty Cycle (D)	2	66.04	33.02	< 1
Error [(S x D) +	20(10)	1121.97	56.10	
(S x I x D)]	(10)			
Time (T)	5	188.44	37.69	2.84[b]
Interval (I) x Time (T)	5	209.70	41.94	3.16[a]
Duty Cycle (D) x Time (T)	10	60.37	6.04	< 1
I x D x T	10	109.19	10.91	< 1
Error [(S x T) +	150(25)	1991.43	13.28	
(S x I x T) +	(25)			
(S x D x T) +	(50)			
(S x I x D x T)]	(50)			

[a] Significant at the 0.01 level of confidence

[b] Significant at the 0.05 level of confidence

TABLE 10

SUMMARY OF THE ANALYSIS OF VARIANCE FOR COMPARISON OF PARTS I AND II, $[(R_H C_L)-(R_L C_H)]$

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Between Subjects	5	3722.94		
Within Subjects	210			
Interval (I)	1	96.40	96.40	< 1
Error [Subjects (S) x Interval (I)]	5	1655.13	331.03	
Duty Cycle (D)	2	1826.28	913.14	6.76[a]
Interval (I) x Duty Cycle (D)	2	181.51	90.76	< 1
Error [(S x D) +	20(10)	2701.61	135.08	
(S x I x D)]	(10)			
Time (T)	5	80.90	16.18	< 1
Interval (I) x Time (T)	5	152.28	30.46	1.07
Duty Cycle (D) x Time (T)	10	232.69	23.27	< 1
I x D x T	10	192.47	19.47	< 1
Error (S x T) +	150(25)	4262.22	28.41	
(S x I x T) +	(25)			
(S x D x T) +	(50)			
(S x I x D x T)]	(50)			

[a] Significant at the 0.01 level of confidence

Discussion of the Present Results and Comparison with Previous Investigations

Balances with Unequal Interaural Duty Cycles

The results of the present investigation support the hypothesis that loudness perception is directly influenced by the duty cycle of repeated tones. Within the limits explored in this study, the relationship between duty cycle and loudness is apparently unaffected by differences of on-duration or off-duration between loudness-balanced signals provided that the duty cycle differences (D) between signal pairs is held constant. For example, in Part I (Table 4, page 56), D_{80} balances yielded duty cycle-loudness effects of 8.3 dB and 9.0 dB for no-interval and silent-interval trials, respectively. The 0.7-dB discrepancy was not significantly large despite the different on-durations (1800 msec and 5000 msec) employed for the reference signals. In both conditions, 200-msec comparison tones were employed for loudness balances. Off-times of the reference signals were 200 msec for no-interval trials and 1000 msec for silent-interval trials. Furthermore, the off-times for comparison signals were 1800 msec and 5800 msec during no-interval and silent-interval balances respectively. In general, a progressively wider duty-cycle disparity between reference and comparison signals resulted in a larger disparity of loudness. In Part I (R_HC_L) the subjects compensated for the loudness imbalances by producing progressively higher SPL comparison-tone (C_L) tracings. In Part II (R_LC_H) the comparison-tone tracing level was decreased in SPL in order to achieve equal interaural loudness with the reference signal. As the duty cycle of the signals increased, the perceived loudness also increased. The only exception to this trend occurred in Part II for D_{80} balances, during which relatively long-duration comparison signals (C_H=5000 msec) were adjusted via the Bekesy audiometer.

Another finding in the present study was that the relationship between duty cycle and perceived loudness changed remarkably over a long time period, often more than four minutes.

These data suggest that the Bekesy loudness-memory phenomenon, the Type V Bekesy pattern, and the LOT-Bekesy phenomenon are determined, at least in part, by a direct relationship between duty cycle and loudness. The ABLB technique was employed in this experiment in order to eliminate the need for subjects to rely upon long-term memory of the reference loudness. The discovery of the duty cycle influence on loudness raises some questions concerning prior research, primarily that in the area of loudness adaptation. Generally, investigators have assumed that pulsed and continuous signals at equal intensities yielded an equal perceived loudness provided that the pulse duration exceeded 100 to 250 msec. The present data imply that such an assumption may be misleading under loudness-balance conditions. Review of the literature concerning loudness adaptation reveals that a wide variety of pulsed-tone duty cycles have been employed for loudness balancing with continuous adapting tones. This may partially explain the wide variety of results obtained by those who have attempted to describe the process of loudness adaptation.

The present data revealed that a larger duty cycle-loudness effect was measured for R_HC_L balances (Part I) than for R_LC_H (Part II) despite the possibility that artifacts due to cumulative loudness adaptation might tend to produce the opposite result. The results of previous investigators (63) suggested that the loudness adaptation effect was greater when the duty cycle was increased. The data of this investigation, however, indicated that the relatively high duty cycle tones were consistently judged to be louder than lower duty cycle tones regardless of which signal was fixed and which signal was adjusted. Furthermore, the presence of a silent-interval between signals failed to have a significant effect on the data for either R_HC_L or R_LC_H balances. Longer rest periods during silent-interval ABLB procedures would be expected to result in less loudness adaptation than is produced with ABLB procedures in which no interval occurs between pulses. Apparently, loudness adaptation has a negligible influence on the loudness-duty cycle relationship.

It appears that modulation of the signal intensity is an important factor in the duty cycle-loudness relationship. The effect of duty cycle disparity was much greater for R_HC_L balances than for R_LC_H balances, especially for D_{80} conditions. It appears that a low duty cycle signal diminishes in loudness to a greater extent when the intensity is continually modulated via the Bekesy attenuator than when it is fixed.

The reduction in perceived loudness due to lowered duty cycle can not account for the total duty cycle-loudness effect which was measured during previous investigations with loudness-memory tracings (23, 25, 26, 57). The average loudness decrement due to a reduction of duty cycle from 100 to 20 per cent (D_{80}) was 13.7 dB for 1K-Hz signals presented at a reference 50-dB SPL (23, 25). The maximum duty cycle effect on loudness in the present study for D_{80} balances was 9.7 dB. This 4-dB difference between the present data and the data of the loudness-tracking study may be attributed to a combination of events. It is possible that during the loudness-memory tracking the duty cycle-loudness effects observed in the present data are combined with the effects of memory biases for the reference loudness. Another factor which may influence loudness judgments is the modulation of the comparison signal. Thus, the Type V and LOT-Bekesy phenomena can not be attributed solely to a bias in loudness memory.

Balances with Equal Interaural Duty Cycles

An unexpected trend occurred in the data for D_0 balances (balances in which R and C signals had equal duty cycles). In Part I, in which the R_HC_L conditions were investigated, silent interval D_0 balances yielded remarkably higher comparison-signal tracking levels than the no-interval D_0 balances. Conversely, during Part II (R_LC_H), no-interval D_0 tracings were at a higher intensity level than the silent-interval D_0 tracings. The test conditions and the instrumentation for the D_0 balances were identical for Parts I and II. The discrepancies in the data appear inexplicable on the basis of present knowledge concerning loudness balance behavior.

Despite the large differences in the mean comparison-tone tracking levels observed between interval and no-interval D_0 balances in both Parts I and II, results of the statistical analyses suggest that the differences are not significantly large. One reason for the failure of the differences to reach significance may be the nature of the experimental design. The design allowed for only six comparison on interval effects leaving only five degrees of freedom for the interval factor. It is possible that the addition of more subjects in the experimental group might have yielded a statistically significant interval effect. Secondly, some of the subjects were affected by the change from silent-interval to no-interval balances, whereas other subjects were unaffected. Thus, the error term for interval effects contained a relatively substantial amount of variability.

The relationship between D_0 balances with and without silent-interval time between alternating signals is worthy of further investigation. These results serve to accentuate Hood's (30) concern for the methodological differences between the Fowler (silent-interval) method and the automatic (no-interval) method of ABLB testing.

Apparently the mechanism responsible for the observed differences between D_0 balance conditions is unrelated to the mechanism responsible for the relationship between duty cycle and loudness. Regardless of the baseline D_0 tracking levels, a disparity of duty cycles resulted in modification of comparison-tone tracking levels which corresponded to loudness changes.

Time effects are conspicuously absent among the D_0 balance data for both interval conditions. It is apparent from other results in this study that loudness gradually decreases when the ear is stimulated at a low duty cycle (i.e., 16.6 per cent) as during D_0 silent-interval balances. The decrement in loudness may be less extensive and take place more slowly when the duty cycle is 50 per cent as in D_0, no-interval trials. It is possible that by the end of a four-minute tracking period in which both ears receive 16.6 per cent stimulation, both R and C signals are considerably softer than at T=4 in trials for which the two signals are at 50 per cent. Theoretically, the decrement in loudness should be simultaneous and equal in magnitude at the two ears when both ears receive the same duty cycle. The ABLB technique is sensitive only to relative changes in interaural loudness, thus the tracings do not reveal drifts in loudness which may be bilaterally symmetrical. Therefore, the factor of time had no significant effects on the data for D_0 balances.

General Comments

The direct relationship between duty cycle and loudness supports a hypothesis which postulates that the auditory mechanism of magnitude estimation in some way analyzes information concerning both the on-duration and off-duration of the auditory signal. The hypothesis states that the auditory system derives an "average" loudness value by integrating or computing on- and off-durations of the repeated auditory signal. Thus, if the signal is present during a relatively high percentage of the total time, it is judged louder than if it is present during a relatively low percentage of the total time. The "loudness averaging" properties of the auditory system require long periods of time to develop fully. During a substantial number of the trials, "averaging" did not reach asymptotic values by the end of the four-minute test period. "Loudness averaging" effects along with loudness-memory effects are thought to result in the Type V Bekesy and LOT-Bekesy phenomena which are based on the comparison of loudness tracings for signals with different duty cycles.

CHAPTER V

SUMMARY

Introduction

The results of previous investigations (23, 24, 25, 26, 38, 71) indicate that duty cycle could be expected to influence loudness judgments for repetitive pulsed auditory signals which continue over a relatively long period of time. During the present investigation the alternate binaural loudness balance (ABLB) technique was employed to study the influence of four factors on interaural loudness relations. The factors under study included the difference (D) of duty cycle between reference (R) and comparison (C) signals: the presence *vs*. the absence of a 400-msec silent-interval period between alternate signals; the use of a reference signal with a relatively high duty cycle (R_H) *vs*. the use of a reference signal with relatively low duty cycle (R_L) whenever experimental trials called for unequal interaural duty cycles at the ears; and finally, the passage of time (T) after commencement of loudness balances. The data obtained lend insight into the Type V Bekesy and LOT-Bekesy phenomena and they also reveal that signal duty cycle exerts a profound influence on the psychophysical process of loudness-magnitude estimation.

Procedure and Experimental Design

During four-minute experimental trials, subjects were required to make repeated judgments of loudness equality and disparity between a fixed intensity (50-dB SPL) reference signal presented to one ear and a variable-intensity comparison signal presented alternately to the opposite ear. Both reference and comparison signals were 1000 Hz in frequency. In one-half of the experimental conditions, 400-msec silent intervals separate the signals from one another while in the other half of the conditions (no interval), alternate signals overlapped during their 10-msec rise-decay times. Under each of the interval conditions, the temporal parameters of the alternate signals were manipulated to derive interaural duty cycle disparities of 0, 30, 60 and 80 per cent. During Part I of the experiment, the signal with a relatively high duty cycle served as reference and the comparison signal had a relatively low duty cycle ($R_H C_L$) whenever experimental trials called for an interaural disparity of duty cycles. During Part II of the experiment, the signal with a relatively low duty cycle served as reference and the signal with the relatively high duty cycle served as the comparison ($R_L C_H$). Subjects 1 through 6 performed the no-interval balances during Part I and the silent-interval balances during Part II of the experiment. Subjects 7 through 12 performed silent-interval balances in Part I and no-interval balances in Part II. Experimental conditions were counterbalanced to minimize the effects of the order of testing and the slight bilateral asymmetry of loudness function which is often observed among normal listeners (17). The average tracking levels of two runs for which duty cycles were equal at the ears (D_0) was employed as a measure of baseline loudness equality for each subject. The tracking-level balances which contained disparities of duty cycles were, thus, adjusted to compensate for individual loudness asymmetry and possible trial-to-trial fluctuations in the loudness function. The corrected data, therefore, represents the loudness imbalance (in dB of equivalent intensity) attributable to the disparity of duty cycles between the ears. These data were analyzed at six time (T) periods during the four-minute ABLB trials: T=1/4, 1/2, 1, 2, 3 and 4 minutes. The ABLB technique allows for periodic exposure to the reference signal, thus, the technique was expected to reveal the effects of duty cycle on loudness which might occur independently of long-term loudness-memory effects.

Results and Conclusions

Part I: R_HC_L Balances

The present data reveal that the loudness perception of repeated signals is directly related to the signals' duty cycle. This direct relationship between duty cycle and loudness was apparently independent of discrepancies in signal on-duration or off-duration provided that the difference of duty cycles (D) between signal pairs was held constant.

Several interrelationships among the data of Part I were analyzed resulting the following findings:

1) The low duty cycle comparison signal (C_L) was consistently judged to be softer than an equally intense reference signal which consisted of the higher duty cycle (R_H). Thus, the factor of duty cycle (D) produced a significantly large influence on the data ($p < 0.05$).

2) The factor of time also had a significantly large influence of the data ($p < 0.05$). The duty cycle-loudness relationship continued to develop for as long as four minutes during several of the conditions.

3) The factor of interval failed to have a significant influence on the data ($p > 0.05$) despite the fact that on-time and off-time differences resulted from the modification of the interval conditions.

4) During D_0 balances, the comparison-tone tracking level was

remarkably higher in dB SPL during silent-interval than during no-interval balances. This unexpected finding did not appear to influence the above described duty cycle-loudness relationship.

Part II: $R_L C_H$ Balances

The following is a summary of results for Part II in which the reference signal had a relatively low duty cycle (R_L) and the comparison signal had a relatively high duty cycle (C_H):

1) The high duty cycle comparison signal (C_H) was consistantly judged louder than the low duty cycle reference signal (R_L) at equal intensities. This factor had a significantly large influence on the data ($p < 0.05$).

2) The factor of time after commencement of loudness tracking also yielded significant effects at the 0.05 level of confidence.

3) The presence or absence of a 400-msec silent interval failed to have significant effects ($p > 0.05$).

4) The interaction between the factors of interval and time reached significant proportions. As time passed, the loudness-duty cycle effects increased steadily for the interval balances whereas, the data remained relatively stable for no-interval balances during the four-minute tracking period.

5) During D_0 trials the comparison-tone tracking levels for no-interval balances were slightly higher in SPL than silent-interval balance levels. The opposite tendency was observed in Part I.

Additional Comparisons

The duty cycle-loudness relationship was similar in Parts I and II for conditions of D_{30} and D_{60}. The D_{80} data, however, reveal a wide divergence between the results of Parts I and II. During Part I ($R_H C_L$), the loudness disparity due to dissimilarity of duty cycles increased from D_{60} to D_{80}. During Part II ($R_L C_H$), however, the loudness disparity diminished sharply between D_{60} and D_{80}.

Overall data revealed that silent-interval balances consistently yielded greater duty cycle-loudness effects than did no-interval balances. This relationship, however, did not reach statistical significance ($p > 0.05$).

Conclusions

A direct relationship between duty cycle and the perceived loudness of pulsed or repeated signals was defined in the results of the present investigation. Support was found for the hypothesis that the auditory system is capable of utilizing information relative to periods of both stimulation and silence, thus arriving at some "average" loudness value for repeated signals. The loudness "averaging" properties of the auditory system develop slowly over long periods of time up to, and perhaps beyond, four minutes. Knowledge of the loudness "averaging" properties of the auditory system seriously challenges the validity of the assumption, that pulsed and continuous signals are equally loud when frequency and intensity are equal provided that the pulsed signal duration is 250 msec or greater. The direct relationship of loudness to duty cycle appears to be manifested in the Type V Bekesy pattern and in the LOT-Bekesy phenomenon. The duty-cycle effects appear to be considerably greater during loudness-memory tracking (23, 24, 25, 26, 57) than during ABLB tracking (present data). It is possible that the tracker's ability to remember the actual loudness of reference signals may be biased or faulty, thus enhancing the duty cycle effect on loudness. Present results also suggest that the duty cycle more seriously affects the loudness of pulsed tones whenever the variable comparison signal, tracked via the Bekesy audiometer, has a relatively low duty cycle.

In conclusion, the previously observed Bekesy loudness-tracking phenomena cannot be attributed solely to a bias in loudness memory. Present data reveal that loudness perception itself is directly related to duty cycle of a signal. It also appears that fluctuation of the intensity via a recording attenuator may exert an influence on jüdgments of loudness. The Type V and Lengthened Off-Time (LOT-Bekesy) phenomena appear to be a product of some combination of these three parameters.

Suggestions for Further Research

More information is needed regarding the difference between silent-interval and no-interval balances within D_0 trials before definite conclusions about clinical ABLB procedures can be drawn. The wide discrepancies in the interval data of Part I failed to reach statistical significance. However, further study with a greater number of subjects would be expected to reveal a significant effect. Modification of experimental parameters such as reference-signal intensity and frequency and duty cycle differences should be explored.

Another approach to future investigation might involve the use of bi-frequency alternate monaural loudness balances with equal and unequal duty cycles. Monaural balances would eliminate factors related to binaural interaction.

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APPENDIX A

TABLE 11

MEAN TRACKING LEVEL (dB SPL) FOR THE AVERAGE OF TWO LOUDNESS BALANCES IN WHICH BOTH REFERENCE AND COMPARISON SIGNALS HAVE THE SAME DUTY CYCLE (D_D), PART I

Time After Start of Tracking (min)	Condition in which Data Occurred D_{30}	D_{60}	D_{80}	Mean
	No Silent Interval			
1/4	50.6	51.1	50.1	50.6
1/2	49.2	50.6	49.5	49.8
1	48.7	49.5	48.5	48.9
2	46.6	49.1	48.6	48.1
3	45.9	49.3	50.6	48.6
4	45.4	48.4	48.2	47.3
MEAN	47.7	49.8	49.1	48.9
SE_m	2.4	2.7	3.0	
	Silent Interval			
1/4	54.9	55.7	56.1	55.5
1/2	55.5	56.3	56.2	56.0
1	56.3	56.6	56.0	56.3
2	55.7	56.4	56.5	56.2
3	54.4	56.7	56.7	55.9
4	55.5	56.7	57.2	56.5
MEAN	55.5	56.4	56.4	56.0
SE_m	2.8	3.2	3.4	
GRAND MEAN	51.6	53.1	52.8	52.5

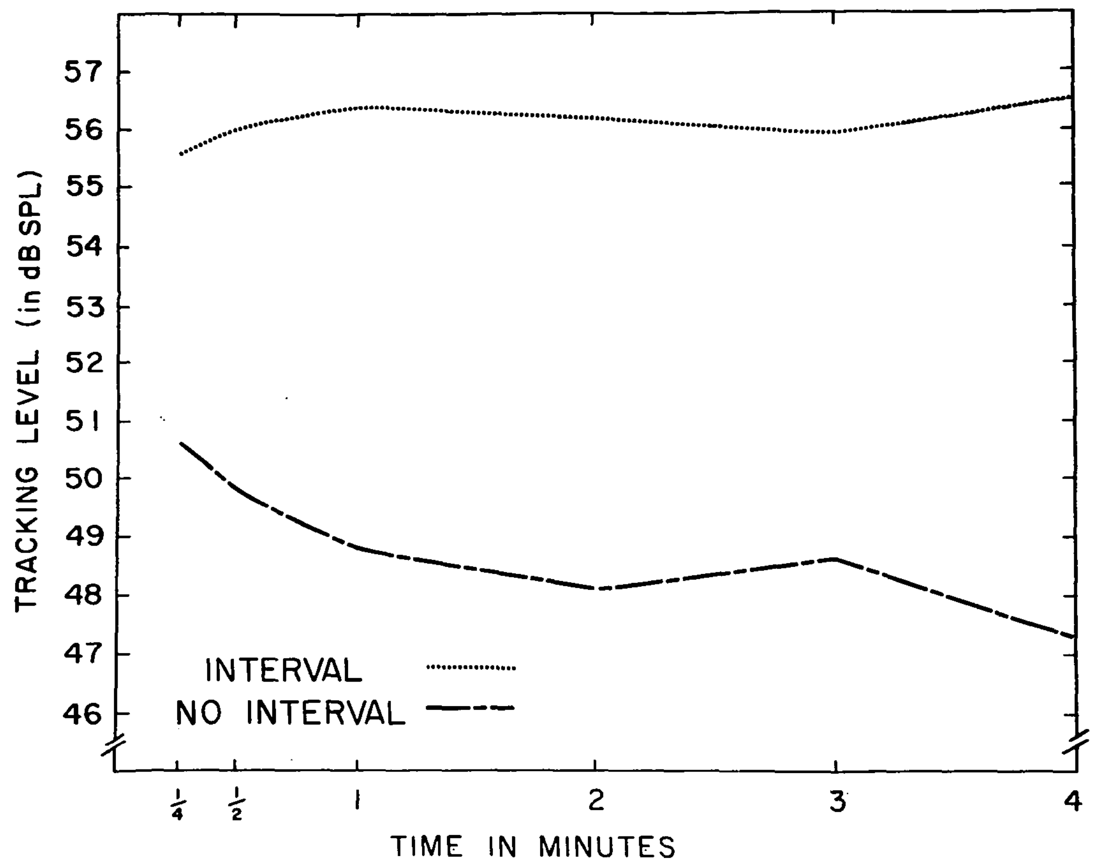

Fig. 15.--Tracking level (dB SPL) of the comparison tone for D_0 balances within Part I, silent-interval versus no-interval conditions.

TABLE 12

MEAN TRACKING LEVEL (dB SPL) FOR THE AVERAGE OF TWO LOUDNESS BALANCES IN WHICH BOTH REFERENCE AND COMPARISON SIGNALS HAVE THE SAME DUTY CYCLE (D_0), PART II

Time After Start of Tracking (min)	Condition in which Data Occurred D_{30}	D_{60}	D_{80}	Mean
	No Silent Interval			
1/4	53.5	52.0	53.6	53.0
1/2	52.4	52.0	53.6	52.7
1	52.9	52.7	52.5	52.7
2	52.5	51.8	52.3	52.2
3	52.5	51.3	51.8	51.9
4	53.2	49.9	51.4	51.5
MEAN	52.7	51.6	52.5	52.3
SE_M	2.9	2.1	2.3	
	Silent Interval			
1/4	50.4	51.6	50.2	50.7
1/2	50.7	51.6	50.0	50.8
1	51.3	51.1	50.8	51.1
2	50.7	51.7	51.1	51.2
3	51.5	51.0	48.8	50.4
4	51.1	51.4	49.4	50.6
MEAN	50.9	51.4	50.4	50.8
SE_M	2.6	2.3	2.8	
GRAND MEAN	51.8	51.5	51.8	51.5

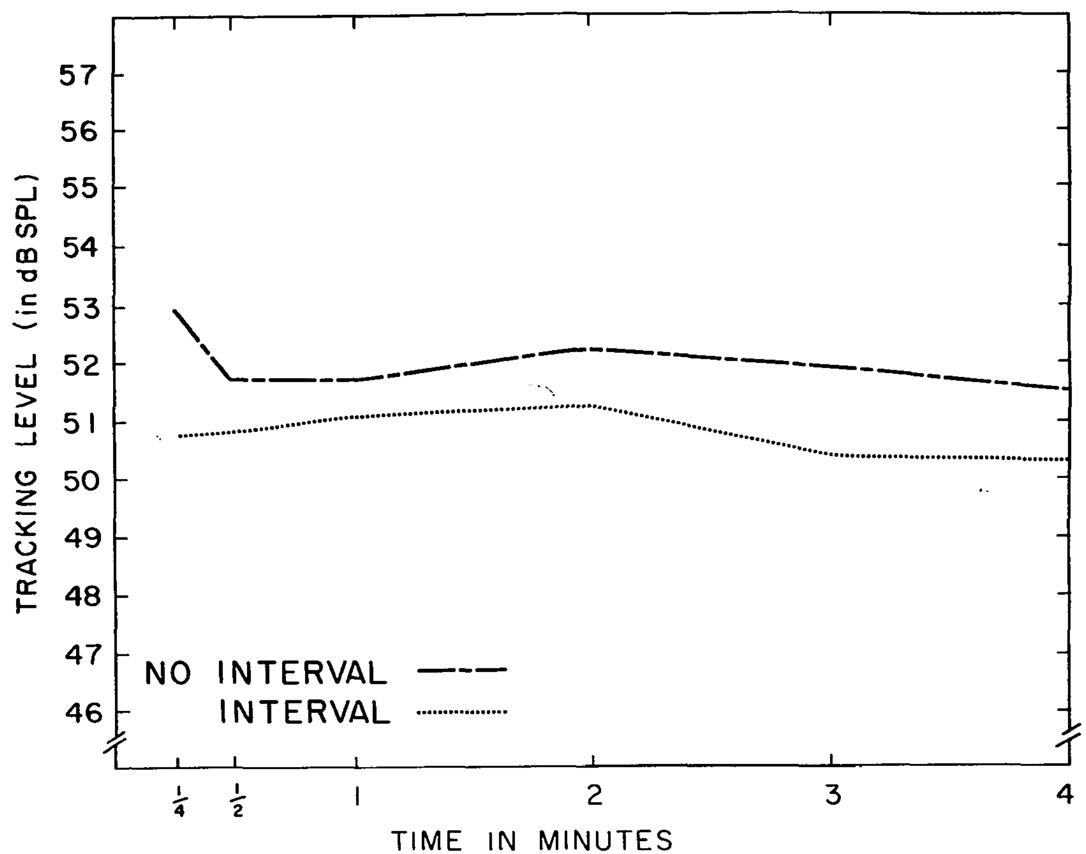

Fig. 16.--Tracking level (db SPL) of the comparison tone for D_0 balances within Part II, silent-interval versus no-interval conditions.

APPENDIX B

TABLE 13

SUMMARY OF THE ANALYSIS OF VARIANCE FOR LOUDNESS BALANCES IN WHICH REFERENCE AND COMPARISON SIGNALS HAVE THE SAME DUTY CYCLE (D_0), PART I

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Between Subjects	5	712.35		
Within Subjects	210			
Interval (I)	1	2826.79	2826.79	2.14
Error [Subjects (S) x Interval (I)]	5	6618.31	1323.66	
Duty Cycle (D)	2	86.74	43.37	1.82
Interval (I) x Duty Cycle (D)	2	7.82	3.91	< 1
Error [(S x D) +	20 (10)	475.91	23.80	
(S x I x D)]	(10)			
Time (T)	5	42.13	8.43	1.72
Interval (I) x Time (T)	5	100.58	20.12	4.11[a]
Duty Cycle (D) x Time (T)	10	47.21	4.72	< 1
I x D x T	10	10.37	1.04	< 1
Error [(S x T) +	150 (25)	734.10	4.89	
(S x I x T) +	(25)			
(S x D x T) +	(50)			
(S x I x D x T)]	(50)			

[a] Significant at the 0.01 level of confidence

TABLE 14

SUMMARY OF THE ANALYSIS OF VARIANCE FOR LOUDNESS BALANCES IN WHICH REFERENCE AND COMPARISON SIGNALS HAVE THE SAME DUTY CYCLE (D_0), PART II

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Between Subjects	5	2475.30		
Within Subjects	210			
Interval (I)	1	101.96	101.96	< 1
Error [Subjects (S) x Interval (I)]	5	2787.78	557.56	
Duty Cycle (D)	2	6.33	6.33	< 1
Interval (I) x Duty Cycle (D)	2	42.65	2.13	
Error [(S x D) +	20(10)	333.44	16.67	
(S x I x D)]	(10)			
Time (T)	5	14.23	2.85	< 1
Interval (I) x Time (T)	5	11.45	2.29	< 1
Duty Cycle (D) x Time (T)	10	23.82	2.38	< 1
I x D x T	10	19.39	1.94	< 1
Error [(S x T) +	150(25)	638.60	4.26	
(S x I x T) +	(25)			
(S x D x T) +	(50)			
(S x I x D x T)]	(50)			