PERSTIMULATORY AND POSTSTIMULATORY FATIGUE IN PITCH PERCEPTION

by

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF SPEECH

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF ARTS

In the Graduate College

THE UNIVERSITY OF ARIZONA

1968

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ACKNOWLEDGMENTS

The greatest appreciation is expressed to Dr. Paul Skinner for his stimulating and capable teaching and guidance throughout my undergraduate and graduate work in audiology.

Appreciation is also extended to Dr. James D. Lambert, Head of the Department of Speech, for his encouragement and support, and to other members of the faculty, especially Mr. Kenneth Dimmick, for their instruction and guidance.

The writer also wishes to express his gratitude to Norla Marie Antinoro for her assistance in the preparation of this manuscript.

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ABSTRACT

The phenomenon of pitch perception during auditory fatigue was studied at the frequencies 250, 500, 550, 650, 850, 950, 1500, 2500, and 4500 Hz. Three experiments were conducted using a newly devised system which permits continuous recording of the subjects' perception of pitch under perstimulatory and poststimulatory conditions. In Experiment I, the effects of auditory fatigue on pitch perception were studied under per- and poststimulatory conditions with 60 and 90 dB SL signals. In Experiment II, pitch perception was examined after stimulation of 100 dB SPL for ten minutes. In Experiment III, 750 Hz for two minutes at 120 dB was used as the fatiguing stimulus. Pitch perception at adjacent frequencies was studied. No systematic change in pitch perception was observed under any of the experimental conditions. Since these findings were not in agreement with those reported by other researchers, special attention was given to procedural and theoretical reasons for the discrepancies.

INTRODUCTION

The phenomenon of pitch is a subject that has been studied for more than three hundred years. Early theories were formulated on the basis of pure speculation and gross observation of the hearing mechanism (Wever, 1949). Today, even with the aid of modern scientific technology, researchers still do not fully understand the mechanism of pitch. In the following section, the theories of pitch perception presented represent a considerably enlightened position with regard to understanding the perception of pitch. It is not unlikely, however, that these theories are preliminary steps to a true understanding of auditory pitch perception.

Review of Theories of Pitch Perception

Place Theories

Resonance Theory

The resonance theory as we know it today was first formulated by Hermann L. F. Helmholtz in 1857. The concept of resonance was integrated with Ohm's law of auditory analysis, Müller's doctrine of specific energies of nerves, and the anatomical discoveries of Corti to form the resonance theory of pitch perception. Ohm's law stated that the ear performs a Fourier wave analysis. Müller proposed that various physical causes, when brought to bear upon one sensory nerve, always give rise to one quality peculiar to the nerve concerned. Corti's discovery of the hair cells (which he did not recognize as hairs, but described as "teeth" anchored in the membrane) supplied the "resonators" themselves. Thus we have a system of tuned resonators, each responding to a different pitch and to that pitch only (Wever, 1949).

Wave Theory

The most important of the wave theories was Bekesy's traveling wave theory. Bekesy discovered, through direct observation, that a sound wave introduced into the cochlea "traveled" along the basilar membrane until it produced a point of maximum displacement of the membrane. The wave then died out within one or two cycles. At the point of maximum displacement, circular eddies were present in the cochlear fluid, which, according to Bekesy, established a steady pressure on the membrane and caused the excitation of the hair cells. The wave always began at the basal end of the cochlea and traveled toward the apical end. High frequency tones reached the point of maximum displacement close to the basal end, and low tones close to the apical end. Bekesy also found that for tones up to 300 Hz there was complete phase agreement in all the moving parts of the cochlea at the exposed position. For the low tones, the structures moved in phase with the stapes, and then as frequency was raised, the phase of the structures progressively lagged behind the stapes. Because one would not expect this sort of phase variation in a series of resonators, Bekesy felt that a system of tuned elements did not exist as Helmholtz stated, but rather, traveling waves whose wave length grows shorter as the frequency rises (Wever, 1949).

Volley Theory

The volley principle can best be understood by considering the response of a group of nerve fibers which are being exposed to rapidly recurring stimulation of a constant magnitude. After being stimulated, a specific fiber responds, and then goes into a refractory phase. During this refractory period, the fiber will not fire. After recovery, another of the stimulus pulses will excite the fiber, and it will fire again. There will then be another resting period, another impulse, and so on until stimulation is ceased or the fiber fatigues. As a result, there will be a series of fiber impulses, not at the excitation rate, but at a slower rate.

Meanwhile, a second nerve fiber, if exposed to the same excitation, will be responding in a like manner. If this second fiber fires a moment after the first fiber (while the first fiber is in its resting phase), then the silent intervals in the firing of the first fiber will be, in part, filled in by the firing of the second. The additional firing of several other fibers may occur within this interval. Therefore, a group of fibers working in rotation or sequence can respond to every excitation of a series, within certain upper limits, without any single fiber being overloaded. A schematic of this principle is shown in Figure 1.

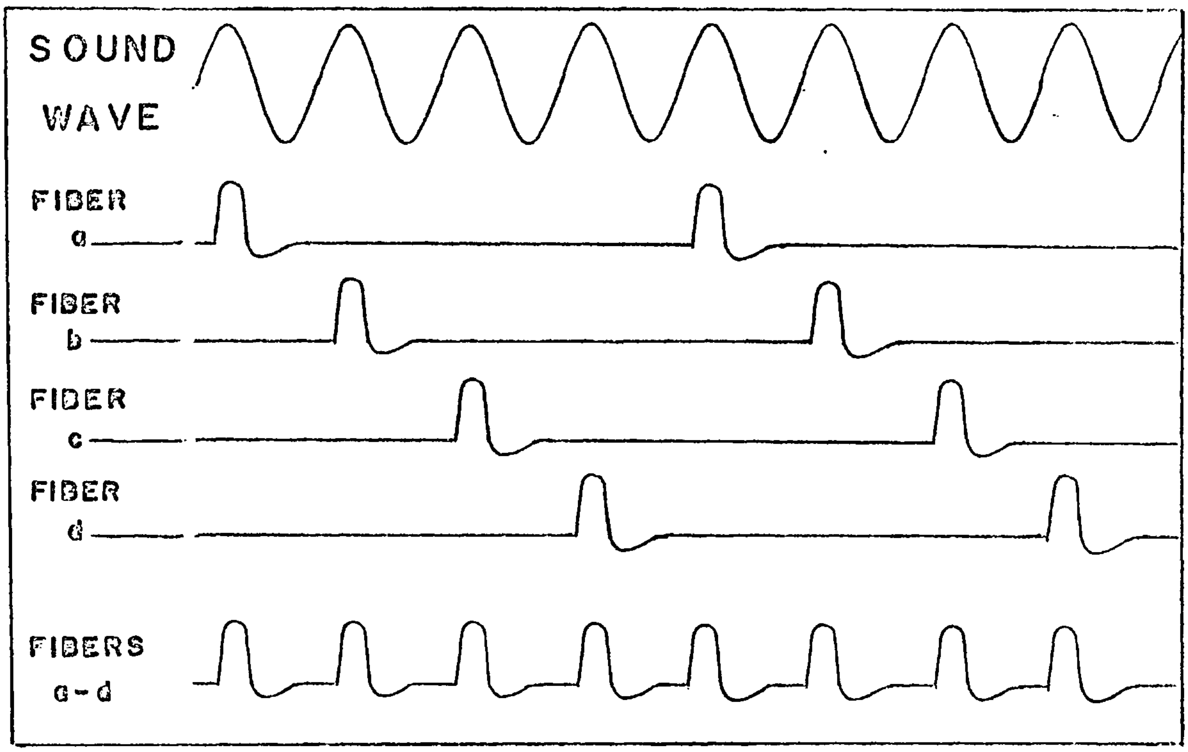


Figure 1. --The Volley Principle.

Each fiber responds to certain of the sound waves, and their total responses represent the full frequency of the wave. From Wever (1949).

If the intensity of the excitation is increased, the firing procedure will vary slightly from that mentioned above. At a higher intensity the fiber will no longer require the complete recovery period, but will fire sometime during its relative refractory period. As intensity is increased the rate of firing is increased until the absolute refractory period of the fiber is reached. A schematic of this increased firing is shown in Figure 2.

Volley theory, in effect, accepts place theory and frequency theory. Frequency theory states that the auditory nerve receives and transmits a pattern that corresponds in all essential details to the pattern of the external sounds. The ear therefore serves as a kind of relay mechanism for the characteristics of the stimulus (Wever, 1949). The low tones are served by frequency, the high tones by place, and the mid range by both.

Duplex Theory

In essence, the duplex theory of Licklider (1951) is that the auditory system uses frequency analysis, which takes place at the cochlea, and autocorrelational analysis, which takes place in the neural part of the system. The autocorrelational analysis is an analysis of nerve impulses coded by the cochlea.

The frequency analysis in the cochlea is essentially the same in the duplex theory as has been mentioned earlier in both place and volley theory, so it will not be discussed in detail in this section. What distinguishes the duplex theory from other theories is the process

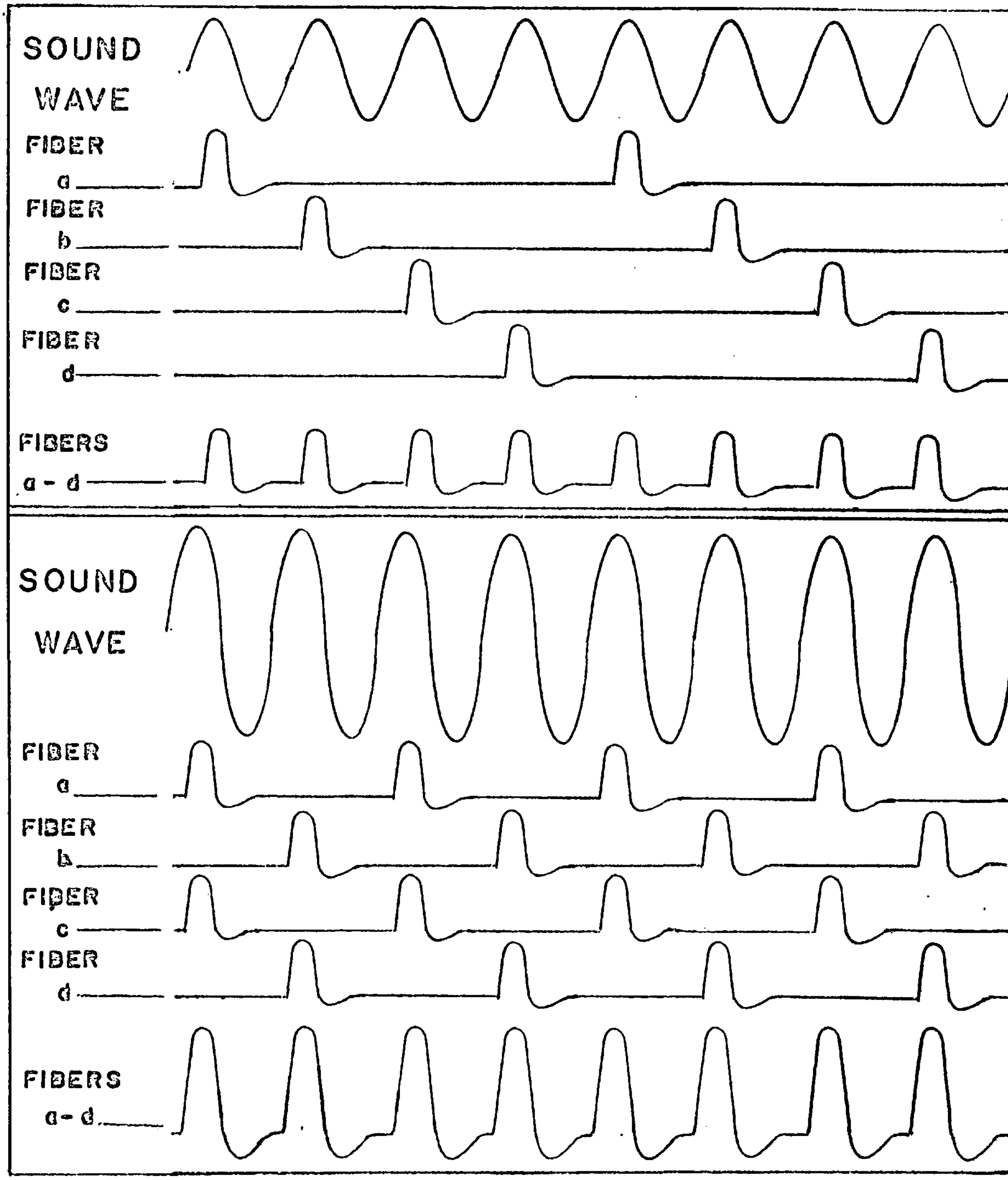


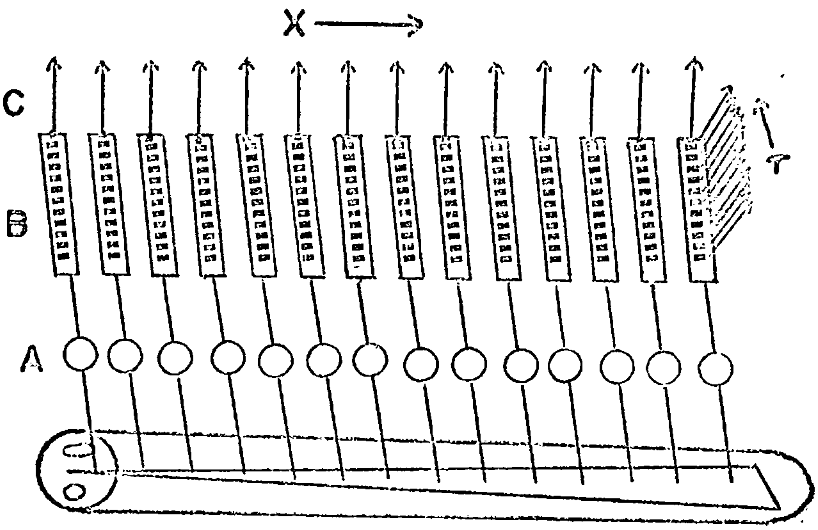
Figure 2. --Intensity Representation in the Volley Principle.

Above, the pattern of discharge in a group of nerve fibers at one intensity; and below, this pattern at a higher intensity. The frequency is represented in both patterns, but the discharge is larger in magnitude in the second. From Wever (1949).

of autocorrelation. In the autocorrelation process a running average (integral) of the acoustic stimulus is taken. Stated quite simply, autocorrelation is an analysis carried out within the time domain that produces the same information as the power spectrum obtained through analysis in the frequency domain. According to Weiner (1959) the autocorrelation and the power spectrum of a wave are a Fourier transform pair. In actuality, autocorrelational analysis does not reveal anything that cannot be obtained through frequency analysis. The main differences lie in the operations involved in the analysis. A schematic of the overall analyzer is shown in Figure 3.

Triplex Theory

Licklider (1959) extended the duplex theory into the triplex theory. According to triplex theory, mechanical frequency analysis takes place in the cochlea, and the nerve impulses are then subjected to a dual correlational analysis in an unspecified portion of the ascending auditory neural system. The first analysis, crosscorrelation, correlates the impulses from the two ears and mediates sound localization in phenomenal space. The second analysis, autocorrelation, exposes periodicities that may have appeared only in the envelope, and not necessarily in the actual waveform of the acoustic stimuli. A third step is then added, the basic operation of which is ascribed to a self-organizing neuronal network. Figure 4 shows a schematic representation of the system. As seen in the figure, there is a "random each-to-every network" between _H_ and _J_. It is assumed that each point of _H_



Cochlea

Figure 3. --Schematic Diagram of Overall Analyzer.

At the bottom is the uncoiled cochlea. Its lengthwise dimension and the corresponding dimension in the neural tissue above it is designated the $\underline{x}$-dimension. The cochlea performs a crude frequency analysis of the stimulus time function, distributing different frequency bands to different $\underline{x}$-positions. In the process of exciting the neurons of the auditory nerve, the outputs of the cochlear filters are rectified and smoothed. The resulting signals are carried by the groups of neurons $\underline{A}$ to the autocorrelators $\underline{B}$, whose delay- or $\underline{\tau}$-dimension is orthogonal to $\underline{x}$. The outputs of the autocorrelators are fed to higher centers over the matrix of channels $\underline{C}$, a cross-section through which is called the $(\underline{x}, \underline{\tau})$-plane. (Output arrows arise from all the spots; some are omitted in the diagram to avoid confusion.) The time-varying distribution of activity in the $(\underline{x}, \underline{\tau})$-plane provides a progressive analysis of the acoustic stimulus, first in frequency and then in periodcity . From Licklider (1951 p. 131).

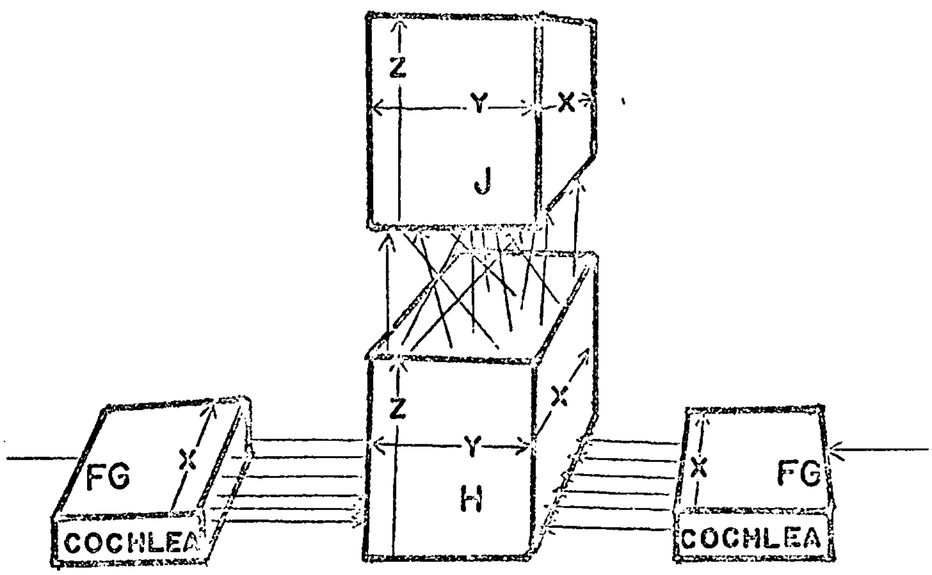


Figure 4. --Schematic Illustration of Hypothetical Auditory System.

The signals enter the two cochleas. The cochlear frequency analysis (F transformation) maps stimulus frequency into the spatial dimension x, and the ordinal relations along x are preserved in the excitation of the neurons of the auditory nerve (operation G). The time-domain analyzer H preserves the order in x but adds an analysis in the y dimension, based mainly on interaural time differences, and an analysis in the z dimension, based on periodicities in the wave envelope received from FG. In the projection from H to J, the x analysis is largely preserved, but each point in any frontal plane of H is, initially, connected to every point in the corresponding frontal plane of J. The H-J transformation organizes itself, according to rules imposed by the dynamics of the neuronal network, under the influence of acoustic stimulation. The patterns in J thereby acquire the properties that are reflected in pitch perception. From Licklider (1959 p. 95).

projects to every point of J, that a neuron of J is excited by coincidences of impulses from two or more of the H-J neurons that impinge upon it, and that some temporal and spatial spread of excitation exists.

As the H-J transformation organizes itself, it becomes a transformation from patterns to points. Each pattern in H excites a great deal of activity at one particular locus in J, but also excites, to a lesser degree, other points. Clear subjective pitch emerges through the activation of an isolated focus of tissue in J. Height of pitch depends upon location of the focus, and definiteness depends upon the degree of isolation.

Review of Studies Dealing with Temporary Pitch Shift

The study of induced pitch shifts has been used as one technique in the effort to evaluate peripheral coding of pitch in relation to the theories of pitch perception. Although it has been clearly established that auditory fatigue has an effect on both the perception of loudness and the perception of pitch, few researchers have adequately studied this phenomenon in pitch perception. Our understanding of damage-risk criteria, auditory pathology, and auditory theory of loudness sensitivity and acuity has been much enhanced by the study of the effect of auditory fatigue on loudness. Relatively little is known about pitch changes, and the limited research available is often contradictory. The direction of observed pitch shifts varies as reported from study to study. It is not known what relationship, if any, there is between temporary threshold shift (TTS) and temporary pitch shift (TPS), and if the same mechanism is involved. Our level of understanding pitch perception is such that any information that can be provided on this subject is significant merely because it is discovered.

Bekesy was among the first to study pitch shifts. Bekesy (1929) fatigued the ear with an 800 Hz tone for two minutes at the intensity of 94 dB (10 dynes/cm^2), and tested the frequencies 300, 400, 500, 600, 700, 900, 1000, 1100, 1200, and 1300 Hz. He found that the pitch of low frequencies (below 800 Hz) shifted downward 1.4% (4.2 Hz) to 5.6% (33.6 Hz), and the pitch of the high frequencies shifted upward 1.4% (18.2 Hz) to 9.1% (91 Hz). The greatest amount of shift occurred at 600 and 1000 Hz. Complete results appear in Table I.

Rüedi and Furrer (1946) found pitch shifts while studying the effects of noise on human ears. They fatigued with pure tones from 270 to 7000 Hz from two to four minutes at 130-140 dB. Upward pitch shifts of as much as 8% were found below 4000 Hz, and downward pitch shifts of as much as 10% were found above 4000 Hz. No pitch shifts were found at 4000 Hz.

Christman (1954) fatigued with the frequencies 400, 500, 600, and 800 Hz at 35 dB for one to two minutes. He then studied shifts at 600 Hz. He found that no shifts occurred after the one minute fatigue condition. After two minutes, however, he found that the pitch of the 600 Hz tone was lowered by the fatiguing tone of higher frequency and raised by tones of lower frequency. The amount of shift was not reported, but analysis of variance tests showed a significant shift beyond the .01 level.

Table I. --The Perecnt of Pitch Shift after Fatigue with an 800 Hz Tone for 2 Minutes at 94 dB.

From Bekesy (1929).

Frequency	Frequency Shift in %
300	-1.4
400	-2.0
500	-3.5
600	-5.6
700	-4.6
800	+0.1
900	+5.4
1000	+9.1
1100	+7.8
1200	+3.5
1300	+1.4

Christman later studied pitch shift using a wider range of fatiguing frequencies and examining the influence of time interval between the satiation tone and the standard tone (Christman and Williams, 1963). In the first experiment, fatiguing tones of 300, 425, 575, 625, 850, and 1200 Hz at 85 dB for one minute were used. A 600 Hz tone was then compared to 584, 588, 592, 600, 604, 612, and 616 Hz. It was found that the high frequency fatiguing tones (625, 850, and 1200 Hz) shifted the pitch upward, and the low frequency fatiguing tones (300, 425, and 575 Hz) shifted the pitch downward. The shift was approximately 5 Hz at all conditions. These results were opposite of those obtained in the earlier study (1954). Christman and Williams could not account for this discrepancy in any concrete manner. In the second experiment, the influence of time interval between 575 and 635 Hz fatiguing tones and a 600 Hz comparison tone was studied. Time intervals of 1, 2, 4, 8, 15, 30 and 60 seconds were used. Upward shifts occurred at the 575 Hz condition and downward shifts at the 635 Hz condition. The largest shifts for both conditions (8 Hz at 575 Hz and 6 Hz at 635 Hz) were at the one second time interval. The 8 to 60 second intervals all produced approximately the same shift (1 to 2 Hz). Complete results appear in Table II.

Table II. --Amount of Shift in Apparent Pitch as a Function of the Time Interval between Fatigue and Test Stimuli.

From Christman and Williams (1963).

Time Interval in Seconds	Amount of Shift in Hz	
	575 Hz	635 Hz
1	+8	-6
2	+4	-3
4	+3	-2
8	+2	-1
15	+2	-1
30	+2	-1
60	+1	-1

A study of pitch shifts at the frequencies 100, 150, 200, and 500 Hz was done by Ward (1963). He found shifts of 0 at 100, 2.5% (4 Hz) at 150, 4.5% (9 Hz) at 200, and 6.5% (32 Hz) at 500 Hz, after sufficient exposure to high intensity clicks to produce a temporary threshold shift of 20 dB or more at 4000 Hz. All shifts were downward.

Elliott, Sheposh, and Frazier (1964) studied pitch shifts at the frequencies 1800, 2000, 2800, and 5600 Hz. A 4000 Hz fatiguing tone was used for the 5600 Hz tone, and a 2000 Hz fatiguing tone for the other three frequencies. The fatiguing stimuli ranged from 100 to 120 dB SL for 2 to 12 minutes. Upward shifts were found below 4000 Hz, but no significant shift above. Elliott _et al_. concluded that, in view of the data obtained in their study, the results of Rüedi and Furrer must be questioned. They also criticized the lack of any statistical test in the Rüedi study.

In all of the above studies pitch shifts were reported. It is interesting to note, however, that directionality was not clearly established. Bekesy found a downward shift in the low frequencies (300-700 Hz) and an upward shift in the highs (900-1300 Hz). Rüedi and Furrer found an upward shift in the lows (270-3000 Hz) and a downward shift in the highs (5000-7000 Hz). Ward found a downward shift in the lows (100-500 Hz) and Elliott _et al_. found an upward shift in the lows (1800-2800 Hz) and no shift at all in the highs (5600 Hz). Christman found contradictory results in two different studies. The experimenters used a wide range of intensities (35 to 140 dB) and durations (2 to 12 minutes). All investigators used pure tones to induce fatigue and all reported a shift.

The following studies used noise bands rather than pure tones. They are important because the basilar membrane is stimulated over a larger area under these conditions.

Egan and Meyer (1950) used a narrow band of noise (90 Hz wide, centered at 410 Hz) as their fatiguing stimulus. Their subjects matched the pitch of a tone heard in the presence of that band of noise to the pitch of a tone heard alone. The partially masked tone was presented 20 dB above its masked threshold. Three experiments were conducted. In Experiment I, the frequencies 100, 200, 300, 420, 520, 620, 720, and 880 Hz were studied. Band pressure level of the noise was 80 dB, and pressure-spectrum level was 60.5 dB. It was found that the presence of the noise band lowers the pitch of the tones below the center frequency of the band (largest shift : 15 Hz at 300 Hz), and raises the pitch of those above the center frequency (largest shift : 20 Hz at 620Hz). In Experiment II, 300 and 620 Hz alone were studied under wide (47 dB pressure-spectrum level) and narrow band (60.5 dB pressure-spectrum level) conditions. Pitch shifts occurred under both conditions at both frequencies, with greater shifts occurring in the narrow band condition. At 300 Hz, shifts were as large as 14 Hz (narrow band) and 4 Hz (wide band), and at 620 Hz, 23 Hz (narrow band) and 2 Hz (wide band). In Experiment III, 300 and 620 Hz at 78 dB were studied using a larger number of subjects than in Experiments I and II. The band pressure level of the noise was 80 dB. The noise shifted the pitch of the 300 Hz tone downward on the average of 0.65 Hz, and the pitch of the 620 Hz tone upward on the average of 12.1 Hz.

A new method of pitch recording was introduced in a study by Webster and Schubert (1954). They used a system in which the frequency knob of their variable oscillator controlled a pen-writing mechanism, while the motor-driven standard oscillator controlled the paper drive. In this way they could get a continuous and running record of pitch matches with a continually changing standard frequency.

In this study, subjects made 90 matches per octave from 150 to 9600 Hz. Various types and degrees of hearing losses were ostensibly similated by masking noises (bands of 400 to 564, 1600 to 2260, and 50 to 9600 Hz were used). Pitch shifts tended to occur away from the region of hearing loss. Some downward shifts occurred, but the greatest shifts were in an upward direction. Shifts ranged from 1.4 Hz at 150 Hz to 112.5 Hz at 3000 Hz.

Statement of Purpose

All of the studies cited above have one thing in common - all judgments were made and recorded under poststimulatory conditions. Except for the last study, all subjects made individual pitch matches at various intervals after the cessation of the fatiguing stimulus. There was no method for recording possible pitch changes occurring over time. There is a definite need for a more precise method of recording changes in pitch due to auditory fatigue. A method is needed that will allow the recording of <u>all</u> changes, not just those that happen to occur at the particular interval arbitrarily chosen to make a pitch match.

In the following study, changes were recorded continuously under perstimulatory and poststimulatory conditions. In this way, all pitch information will be continuously recorded from the beginning of fatigue through the recovery period. This method of recording, which will be described fully in the instrumentation section, was developed by Dr. Paul Skinner of the Auditory Research Laboratory of The University of Arizona. It is our hope that this method will enable us to study changes that occur over time under auditory fatigue.

METHODOLOGY

Subjects

Six college students were used in this study. Their ages ranged from 19 to 24 years. Two were male and four were female, and all demonstrated normal thresholds to conventional and Bekesy audiometric testing. All subjects had participated in pitch studies for nine months prior to this study and were highly experienced in making pitch judgments.

Instrumentation

Pure tones were generated by two Hewlett-Packard 200 AB audio oscillators. Stimulus presentation and control were maintained by two Grason-Stadler model 829D electronic switches and model 471-1 interval timer. The signals were channelled through the necessary attenuation and impedance-matching networks to Grason-Stadler TDH-39 earphones.

The variable oscillator was driven by a Slo-Syn 1.5 rpm reversible motor controlled by the subject. The output of this oscillator was fed through a Hewlett-Packard 5512A electronic counter and 580 A digital-analog converter to a Moseley 7101 BM strip chart recorder with a 17501-A range module. In this way, changes in frequency of the variable oscillator were registered digitally on the frequency counter, translated by the digital-analog converter, and the voltage analog was presented graphically on the strip chart recorder. Changes in the subject's pitch judgment could then be recorded continuously under perstimulatory as well as poststimulatory conditions. A schematic of the apparatus is shown in Figure 5.

Preliminary Study

In order to investigate whether loudness differences between ears (due to TTS in the fatigued ear) had an effect on pitch judgments, a pilot study was done using the same subjects used throughout this study. In the pilot study, frequencies of 500, 2500, and 4500 Hz were matched in pitch, with loudness differences between ears. Loudness differences between ears ranged from 15 to 25 dB (this was the approximate range of TTS expected in the present study). Analysis of variance showed no significant difference in the matches at the .05 level for any frequency. Table III shows the results for a typical subject from two sessions with a 20 dB difference between ears, and one in which there was equal sensation level between ears. The standard stimulus (Ss) was 40 dB SL under all conditions, and the variable stimulus (Sv) ranged from 20 to 60 dB SL. Both Ss and Sv had a duration of one second and a rise-decay time of 50 msec. The two tones continuously alternated between ears with a 50% duty cycle.

Procedure

General Procedure

Under the perstimulatory condition, the subjects were given a continuous tone in one ear and a pulsing tone of 500 msec duration with

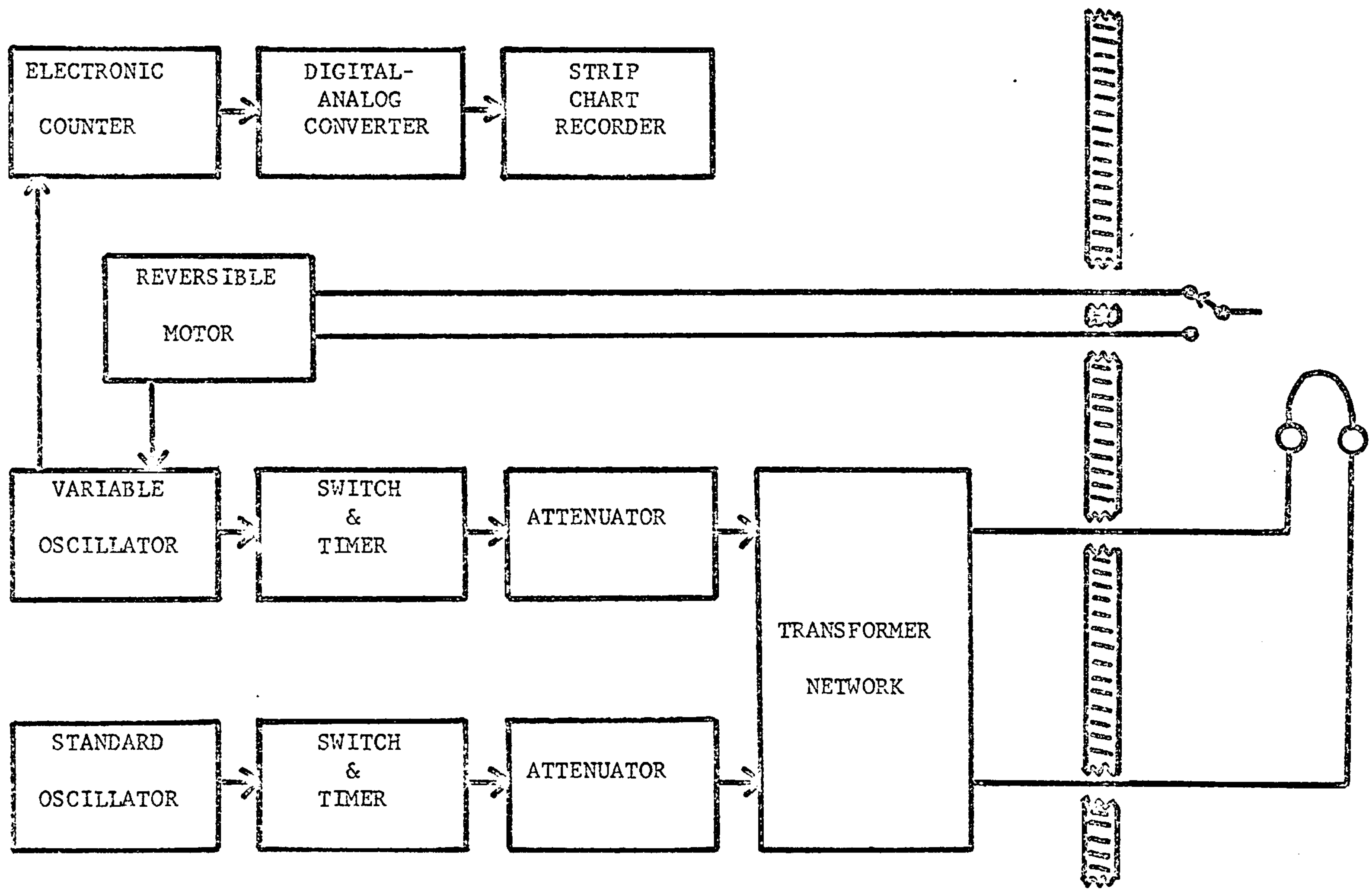


Figure 5. --Schematic of the Instrumentation for the Continuous Recording of Per- and Poststimulatory Pitch Judgments.

Table III. --Results of Pitch Matching with a 20 dB Intensity Difference between Ears.

Frequency	Sv = 20 dB Ss = 40 dB		Sv = 40 dB Ss = 40 dB		Sv = 60 dB Ss = 40 dB	
	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ
500	502.5	1.1	498.6	1.1	501.8	1.5
2500	2502.3	2.4	2495.2	4.3	2507.2	4.8
4500	4490.1	15.1	4491.9	10.2	4492.3	17.4

a 50 msec rise-decay time in the other. Duration and intensity of the steady tone were varied with frequency in order to stay within recommended damage-risk levels. Damage-risk contours for pure tones established by K. D. Kryter et al. (1966) were used as a guide.

Under poststimulatory conditions, the subjects were given 500 msec pulses which continuously alternated between ears with a 50% duty cycle. The rise-decay time of the pulses was 50 msec.

Three experiments were undertaken in this study: one examined primarily those changes which took place during fatigue (perstimulatory), and two examined those changes which took place immediately after cessation of the fatiguing stimulus (poststimulatory). In all experiments the frequencies of the two tones were set equal at the outset. The subjects would then "bracket" the standard (pulsed or continuous) with the variable tone. In other words, the subject would adjust the pitch of the variable tone until it was just noticeably higher or lower than the standard. When a difference became apparent, he would immediately switch in the opposite direction. The back and forth switching (JND higher, JND lower) was continued for the course of the experimental session. At times, the subject was asked to adjust the variable tone until the pitches of the two tones appeared to be equal. These points were marked and used to provide a more specific measure than the JND's.

Subjects were seated in a sound treated room, with their backs toward the observation window so that they could not obtain information from the electronic counter or strip chart recorder. They used a single-pole, double-throw switch to either raise or lower the variable pitch (all had experience with this type of switch from previous studies and were completely familiar with its use). All were given the instructions as they appear in the Appendix (these instructions were for the perstimulatory condition; the poststimulatory condition differed only in the fact that a pulsed tone was bracketed instead of a steady tone).

Each subject participated in one testing session per day, four days a week. Their hearing was tested periodically by Bekesy audiometry to make certain that thresholds did not change more than would normally be expected.

Control Condition

In this condition, the differences in JND size were studied under perstimulatory and poststimulatory bracketing procedures. The subjects were instructed to bracket continuous and pulsed standard tones for five minutes. In order to accurately analyze the results of the following three experiments, it is important to know the relationship of the size of the JND's under the two procedures. Taking this relationship into account during analysis should minimize the possibility of reporting that certain differences are due to the experimental conditions when, in fact, they are inherent in the two procedures.

Experiment I

In this experiment, the frequencies 250, 500, 1500, 2500, and 4500 Hz were tested. Perstimulatory changes were plotted using the bracketing method described earlier. The JND tracing was recorded for ten minutes with tones of 60 or 90 dB SL in each ear. Poststimulatory changes were then plotted until recovery occurred. For the purpose of this and the following experiments, "recovery" is defined as that point in the bracketing procedure when the JND's high and JND's low become equidistant from the standard frequency and remain that way for a period of two minutes. "Pitch shift" is defined as that point in the bracketing procedure when the JND's higher or lower shift a distance that is greater than that subject's JND's high and low prior to exposure (see Figure 6).

Experiment II

Poststimulatory fatigue was examined in this experiment after stimulation of 100 dB SPL at 250, 500, 1500, 2500, and 4500 Hz for ten minutes. No bracketing was done during the fatigue condition. Immediately at the cessation of the fatiguing stimulus the subject began

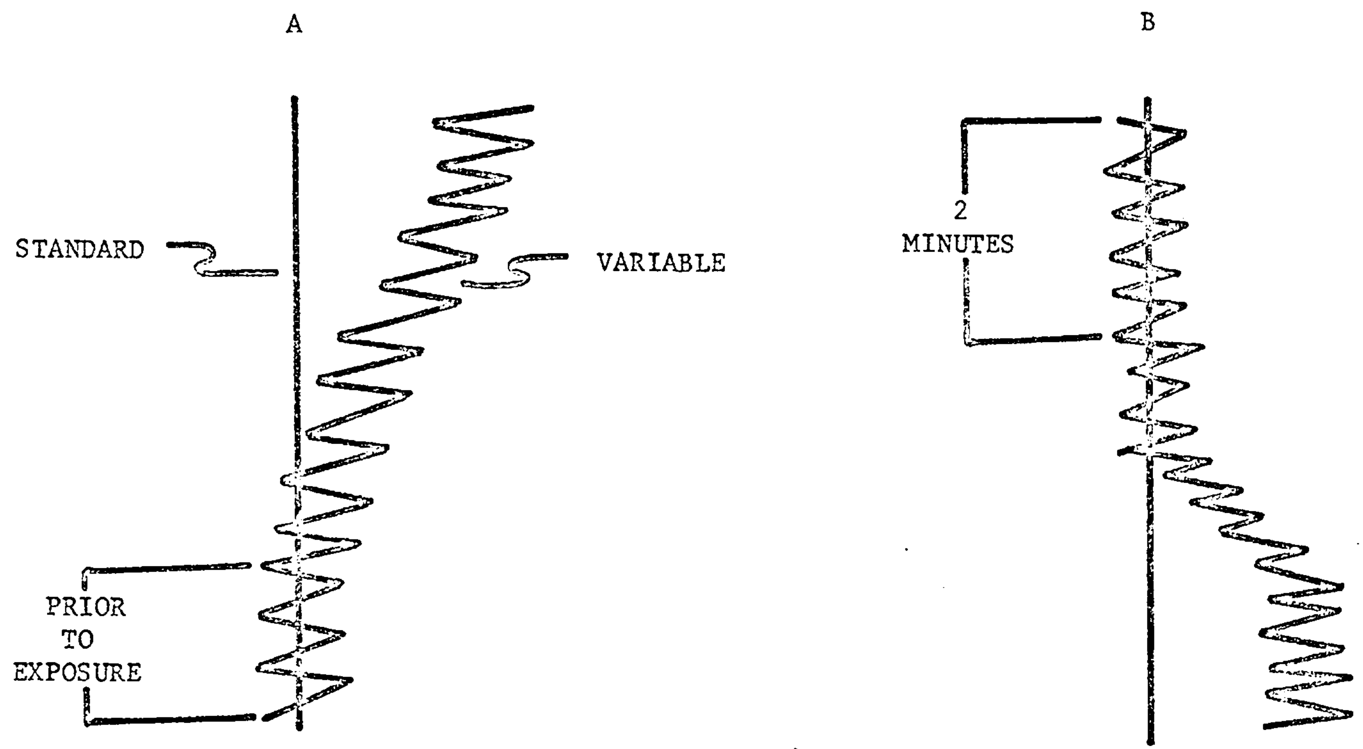


Figure 6. --Postulated Examples of Pitch Shift and Recovery.

A. Pitch Shift. Notice that the JND's have shifted a distance greater than the JND's prior to exposure.
B. Recovery.

bracketing with tones presented at 30 dB SL in each ear. Bracketing continued until the criteria for recovery had been fulfilled.

Experiment III

This experiment questioned if a pitch shift occurred at frequencies adjacent to the standard (fatiguing) frequency. The frequencies 550, 650, 850, and 950 Hz were studied. The standard was 750 Hz under all conditions. Each subject bracketed a pulsed tone for approximately five minutes. This was used as a control condition and was repeated for each frequency. The 750 Hz stimulus was then presented for two minutes at 120 dB SPL. After cessation of the fatiguing stimulus, the subjects bracketed at 85 dB SPL until the criteria for recovery were fulfilled. Pulsed tone bracketing averages were compared to poststimulatory averages to determine if a shift took place.

RESULTS

Control Condition

It was found that JND's with a continuous standard tone were larger at all of the tested frequencies (250, 500, 1500, 2500, and 4500 Hz). On the average, they were 32% larger. At 250 Hz they were 40% larger, 500 Hz 36%, 1500 Hz 27%, 2500 Hz 34%, and 4500 Hz 21%. JND's high and low were equidistant from the standard frequency in both conditions (this was ascertained by direct measurement of the distance of the JND's from the standard frequency on the strip chart recordings), therefore, no pitch shift was apparent. Average distances between JND high and JND low are shown in Table IV.

Table IV. --Average Number of Cycles between Subjects' Judgment of JND High and JND Low.

Frequency	Distance between JND High and JND Low in Hz	
	Steady	Pulsed
250	10	6
500	22	14
1500	51	37
2500	68	45
4500	109	86

Experiment I

No pitch shifts occurred for any of the subjects at any of the tested frequencies at either intensity. At the higher frequencies, some subjects varied from the standard frequency, but none deviated from the JND range prior to exposure. JND's held to the same relationship as reported in the control condition. Point of subjective equality (PSE) and JND range for all subjects are shown in Table V. The averaged data are highly representative of individual subjects.

Table V. --Point of Subjective Equality and JND Range for Experiment I.

	60 dB			90 dB		
Frequency	JND Range High	JND Range Low	PSE	JND Range High	JND Range Low	PSE
250	252	248	250	251	249	250
500	504	498	502	520	492	503
1500	1555	1450	1508	1550	1480	1507
2500	2550	2480	2503	2542	2475	2511
4500	4535	4433	4496	4553	4438	4498

Experiment II

No pitch shift was apparent under poststimulatory conditions at any of the tested frequencies. As shown in Table VI, the average frequency of the brackets was either identical or extremely close to the standard frequency. As in Experiment I, JND relationships held constant for all subjects.

Table VI. --Point of Subjective Equality and JND Range for Experiment II.

Frequency	JND Range High	JND Range Low	PSE
250	252	248	250
500	504	496	500
1500	1509	1489	1498
2500	2504	2493	2499
4500	4540	4475	4509

Experiment III

As seen in Table VII, no shift was apparent at any of the frequencies adjacent to the 750 Hz fatiguing frequency. Control and poststimulatory averages and JND's remained almost identical for all subjects.

Table VII. --Prestimulatory and Poststimulatory Comparisons for Experiment III.

Frequency	Prestimulatory PSE	Poststimulatory PSE	JND Range High	JND Range Low
550	550.0	550.5	554	547
650	649.7	650.9	653	648
850	850.5	851.2	866	843
950	950.2	950.4	967	947

DISCUSSION

Pitch shifts were not apparent in any of the three experiments. These findings are not consistent with the observations of Bekesy, Christman, Ward, and Elliott et al., all of whom reported pitch shifts under conditions somewhat similar to those of the present study. It must be noted, however, that the findings of the previous studies present many discrepancies in addition to those of this study regarding the occurrence, amount, and direction of pitch shift. Several possibilities exist which may have produced these discrepancies.

Psychophysical Measurement

In previous studies the method of adjustment was used to enable the subject to establish separate, independent points of subjective equality; whereas, in the present study the subject continually adjusted JND's above and below his PSE, and only established an actual PSE occasionally. In studies where only PSE's were determined, the subject made pitch matches at various intervals of time after cessation of the fatiguing stimulus. These measures are more susceptible to sporadic error and lack the reliability inherent in tracking techniques which provide continuous observation and monitoring.

Measurement Errors (Context Effects)

It has been observed by Jeffress (1944), Skinner (1963), and Gaeth and Norris (1965) that order of presentation of standard and variable and interstimulus interval can produce differences in the amount and direction of pitch shift. These errors are usually not consistent enough to be predictable but are nevertheless observable.

Motor Speed

Considerable attention has been given to the accuracy of mechanical or electrical control of the variable signal, and to motor speed or attenuation time in studying changes in sensitivity (loudness). The measurement techniques used to study pitch shifts rarely are described sufficiently in studies. The speed of reverse drive motors is of course quite basic to gaining accurate pitch judgments. In using different motor speeds to drive oscillators, marked changes occur in the accuracy of pitch judgments. Since frequency commonly appears on a logarithmic scale on oscillators, small movements of the vernier control at mid and high frequencies produce relatively large changes in frequency which exceed the enlarging width of the pitch JND of the ear. Unless optimum motor speeds are used, this leads to inaccurate judgments by the observer. It was found in our laboratory (with Helwett-Packard 200 series oscillators) that a motor speed of about 1.5 rpm was optimum for permitting accurate judgments. If faster speeds up to 3.3 rpm were used in the mid and high frequencies, the subjects were unable to make accurate judgments.

Size of Pitch Shift

Changes in pitch have been reported as pitch shifts based upon statistically significant differences and yet these differences are often less than the smallest JND's in pitch that are clearly observable to the subject at a given frequency (Egan and Meyer, 1950).

Mechanism of TTS and TPS

Christman (1954) postulated that TPS takes place in an "auditory projection area" of the brain and explained it by the Köhler-Wallach theory of figural after-effects. It is more commonly held that the primary mechanism of TPS and TTS is the hair cells of the Organ of Corti (Bekesy, 1960; Ward, 1963).

Studies of pitch shift, therefore, have been done to evaluate the place theory of hearing. It has been postulated that if place theory is invoked, and if TTS is the result of metabolic changes in the region of the hair cells, then under TTS, temporary pitch shift should also be observed since frequency information should then be provided by adjacent fibers (Galambos and Davis, 1943; Davis *et al.*, 1950).

The inner hair cells have a threshold higher than the outer hair cells (Tasaki, 1954; Davis *et al.*, 1935; Davis *et al.*, 1953). This difference is approximately 40 dB (Davis *et al.*, 1958). Studies of acoustic trauma suggest that there are sensitivity differences among the rows of the outer hair cells (Davis *et al.*, 1935; Davis *et al.*, 1953). Since changes in sensitivity appear to be transversely oriented in the cochlea, and changes in pitch longitudinal (Davis, 1958), TTS would not necessarily produce any change in pitch. One might reason that fatigue of the outer hair cells results in TTS, while higher threshold hair cells continue to provide the same frequency information. In order to fatigue most of the hair cells in a latitudinal plane very high intensity levels are probably required. The orthogonal relationship between pitch and sensitivity on the membrane would then permit a wide range of independence of TTS and TPS.

The foregoing discussion is provided to support the skepticism regarding pitch shifts which was raised in the absence of any observed pitch shifts in the present study, as well as the discrepancies which exist regarding pitch shifts in other studies. It would seem that the subject of TPS requires thorough and exacting study since it remains too controversial for use in evaluating auditory theory.

APPENDIX

Instructions to Subjects

Your task is to adjust the pitch of a pulsed, or interrupted, tone to the pitch of a steady tone. You must continually adjust the pitch of the pulsed tone to where it is just noticeably higher than the pitch of the steady tone, and immediately reverse the pitch of the pulsed tone to where it sounds just noticeably lower. Continue to bracket in this manner.

Occassionally you will be asked to match the two tones in pitch. As soon as the two are matched to your satisfaction, immediately continue with the bracketing.

Determining the pitch sensation of a steady, or constant, tone is a task which requires constant concentration. Focus your attention to the pitch sensation produced by the steady tone and bracket the pulsed tone around it. Be careful not to fall into the habit of merely bracketing by the movements of the switch. Rather, concentrate on the pitch of the steady tone and use this as your only reference for determining pitch judgments. At times the pitch of the steady tone may change. You are, therefore, to be extremely careful to bracket the exact pitch you are hearing at that moment, rather than the pitch you may remember from the start of the session.

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