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THE PERCEPTION OF PITCH IN A WHITE NOISE MASK

by

Alan M. Richards

Bureau of Medicine and Surgery, Navy Department
Research Work Unit MF 12.524.004-9010-D.01

Released by:

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SUBMARINE MEDICAL RESEARCH LABORATORY
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SUMMARY PAGE

PROBLEM:

To determine how pitch is changed in the presence of masking noise.

FINDINGS:

The subjective sensation of pitch, measured in units called mels, has been found to increase in a certain fashion with increases in the physical frequency of a pure tone. The relation between subjective pitch and physical frequency is commonly called the mel scale. A frequency of 1000 cycles per second is arbitrarily assigned the value of 1000 mels, but frequencies of 500 and 2000 cycles per second, for example, do not have values of 500 and 2000 mels respectively. It was found that the shape of the mel scale in quiet was changed dramatically when a background of noise was added. Subjective pitch increased much faster per decibel increase over a noise mask than over threshold. However, as the intensity of a tone of constant frequency increases above masked threshold, its pitch seems to get lower.

APPLICATIONS:

The psychological parameters of pitch perception are now available in order to design sonar equipment with the facilities to equate pitch for a given signal at various intensities when a relatively constant background noise is present.

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Research Work Unit MF12.524 004-9010D—Optimization of Auditory Performance in Submarines. The present report is Report No. 1 on this Work Unit. However, previous work in this area has been reported under a previous Work Unit (MF12 524 004-9004). The manuscript for this report was approved for publication on 10 October 1968 (Clearance No 737, and the report was designated SubMedResLab No. 548.

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ABSTRACT

The mel scale, relating subjective pitch in mels to physical frequency in cycles per second, is now commonly found in texts and handbooks in engineering psychology. It is usually derived from the psychophysical method known as bisection, in which the listener adjusts a variable frequency to sound half as high in pitch as a standard tone. The average subject will not, for example, adjust the variable to 500 for a standard of 1000 cycles per second. In this study mel scales were derived from fractionation data when the standard and variable tones were presented in each of three background noise conditions. The scale for tones in quiet differed in no essential manner from the generally accepted mel scale advanced by Stevens in 1940; however, upon the introduction of a wide-band masking noise, the shape of the mel function became more positively accelerated. In general, when holding the intensity of the masker constant, this acceleration is inversely related to the sensation level of the experimental tones above masked threshold, and is not frequency dependent. Although the relationship is not dependent upon frequency per se, the magnitude of pitch shift increases with frequency.

THE PERCEPTION OF PITCH IN A WHITE NOISE MASK

Alan M. Richards*

I. INTRODUCTION

The relation between subjective pitch of a pure tone and its physical frequency has been incorporated for over 30 years in the so-called "mel" scale. A frequency of 1000 cycles per second is arbitrarily assigned a value of 1000 mels, that frequency adjudged half as high in pitch is assigned a value of 500 mels (this will not be a tone of 500 but perhaps 350 cycles per second), and so on (see Figs. 1-2).

Considering the comparatively few full-scale investigations examining the relation between frequency and its psychological perception, pitch, it is gratifying to find that differences between the obtained pitch, or "mel," scales are not extreme. It would first appear that any reliability would be fortuitous, owing to extreme inter- and intra-subject variability and to the rather insensitive fractionation methods used to extract such functions. However, experimental unanimity indicates that mean pitch can be related to frequency with a fair degree of repeatability, although something is left to be desired should it be used as a predicting instrument for any one individual.

The divorce of pitch from frequency was noted many years ago. However, the earliest systematic studies to quantify the relationship of pitch to frequency was that of Stevens, et al,[1] who used the method of fractionation to develop the first mel scale of pitch perception. Standard frequencies were presented; S adjusted a subsequent variable stimulus to one-half the pitch of the standard. A mel scale can be plotted from such half-pitch functions.

In an attempt to eliminate some biasing factors, Stevens and Volkmann[2] added the method of equal sense-distances. For a repetition of the fractionation method, the procedure used paralleled that of the 1937 paper. However, one important difference was the availability of a knob which controlled the presentation of a 40-Hz tone, representing "zero pitch." Each observer, from time to time, would sound this tone to use as a reference, from which, it was thought, more reliable fractionations could be made. Their method of equal sense-distances used an electronic pure-tone piano. Five standard keys could be tuned from 0.2-6.5 kiloHertz (kHz). The subject was given two end-points and required to adjust the frequency of three intermediate keys until the pitch distance between each adjacent pair of keys appeared equal. In this manner, the four obtained mean pitch distances were presented in the form of a quali half-pitch function (p. 335), and subsequently plotted as a mel scale of pitch. It should also be noted that the same procedure was performed on two other frequency ranges: 40-1000 Hertz and 3-12 kHz.

When plotted along the same coordinates, the results from both the fractionation and equal sense-distance procedures coincided, thereby bolstering the reliability and validity of the mel scale.

Harris[3] investigated the influence of the 40-Hz tone. He observed that the different results found by Stevens in his two investigations could not be accounted for by the introduction of a zero pitch point, but could be due to differences between subjects. He concludes (p. 1576): "It is true that bisection vs fractionation yielded somewhat different curves for Stevens, as his Fig. 3 in the 1940 paper shows, but if one examines the data for the same four Ss who took part in the two experiments, such an overlap is exhibited that some appreciable if not major part of the difference in the Harvard experiments may have been due to individual differences."

Siegel[4] replicated Stevens'[1] study; a rather close correspondence was found up to 4000 Hz. Above this frequency, Siegel's function was exponentially accelerated whereas the 1937 function was somewhat negatively accelerated.

Several studies have investigated the relationship between broadband masking and pitch perception. In general, these studies

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have shown that pitch changes can be effected by masking noise.

In a first attempt to discover the parameters necessary to cause pitch changes, Schubert[5] used a pitch-masking procedure. Initially, each S began by making a loudness balance at a given frequency. Holding intensity constant, the experimenter then tuned the variable tone to the Major Fifth, either higher or lower than the standard tone. S then matched frequencies. Then a noise was introduced with the standard tone only, and S again matched for loudness. E then tuned the variable tone, a Major Fifth, either higher or lower in frequency as before, and S again matched for pitch.

The level of the masking white noise was adjusted to raise threshold of a 1-kHz tone by 35 decibels, while the intensity levels of the standard and variable tones were each 15 dB above masked threshold. The investigation utilized four frequencies: 0.5, 1.2, 2, and 3 kHz. Schubert found that the pitch of the pure tones was raised, increasing as a function of frequency, and decreasing as the intensity of the tone above masked threshold exceeded 20 dB.

Watson and Frazier[6] in a replication indicated that air conduction need not be the only method of introducing pitch changes under masking. Pitch rises were also found to exist with the tone airborne with the noise presented by bone conduction, or vice versa.

Steiner and Small[7] explored Schubert's contention that pitch changes are not present when the intensity of a tone exceeds 20 dB re masked threshold. Pitch matches were used as the experimental technique. Frequencies ranging from 0.25-6 kHz were used, as well as levels of 5, 15, 25, or 35 dB (both re quiet and masked thresholds). The noise shifted threshold at 1 kHz by 35 dB. They supported the earlier finding that pitch shifts above noise increase with frequency, but were not able to support the thesis that pitch shifts only occur at levels below 20 dB sound level.

The present research is an attempt to consolidate several aspects of pitch perception as alluded to in these introductory remarks. Primarily, this research concerns itself with the production of extensive pitch scales under masking conditions, data heretofore not presented. However, subsidiary conditions met by the present study permit a measure of the reliability of previously published mel scales under no-noise conditions, as well as clarify further the intensity parameters necessary to effect pitch changes when tones are heard above noise.

II. METHOD

A. Subjects.

Twelve adults, free from hearing defects, and consisting of graduate assistants, laboratory and Navy personnel, were used as subjects. No attention was paid as to whether the S was naive as regards pitch judgments. The representative age of the group was approximately 22 years.

B. Apparatus and Procedure.

Standard circuitry was used. Grason-Stadler electronic switches and timers presented a standard tone to a monaural Permaflux Model PDR-8 earphone mounted in an MX-41/AR cushion. Following this event a variable comparison tone was sounded. An adjustment period was then allowed for S to adjust the frequency of the variable tone to half-pitch before the next pair of tones. Frequencies were measured with a General Radio Model 1142-A meter, intensities with a vacuum tube volt meter (VTVM). White noise could be mixed independently of the main circuit.

To eliminate extraneous influences, S was placed in a quiet room, where his unused ear was covered by a dummy wooden earphone mounted in an MX-41/AR cushion.

Conventional half pitch functions were determined. S was presented standard frequencies of .2, .3, .4, .7, 1, 2, 5, 8, and 12 kHz at 60 dB SL with no noise. In the two noise conditions, the .2, .3, and 12 kHz standards were not employed.

A wide-band white noise was introduced into the earphone so as to produce a 30 dB threshold shift at each frequency of interest, while the intensities of standard and variable tones were set at either 45 or 15 dB above masked threshold. During a masking condition there was continuous noise, so that both standard and variable stimuli were judged under the same conditions. Also as S turned the variable oscillator to apparent half-pitch, E maintained a constant loudness level of the variable stimuli by adjusting an attenuator to prearranged settings. This procedure was used to eliminate any biasing effects which could have been due to differential loudness across frequency.

A typical test sequence consisted of the presentation of a given frequency/intensity standard (at 60 dB SL in quiet, or at 15 or 45 dB above a 30-dB threshold shift) for 2 sec, followed by 0.25 sec of quiet (or noise), then by a 2-sec variable tone at the same loudness as the standard. At the same time, in order to replicate Stevens'[2] as nearly as possible, an external 40-Hz tone at 25 dB SL could be presented at S's will to indicate zero pitch.

A trial consisted of the presentation of all frequencies in a given noise condition in a random order. Five such trials per subject/condition were obtained yielding sixty half-pitch judgments per frequency/intensity condition.

Half-pitch functions were obtained, best-fitted, and transformed into mel scales.

III. RESULTS AND DISCUSSION

A. Half-Pitch Function and Mel Scale for a No-Noise Condition.

Each entry in Table I indicates the geometric mean of five half-pitch judgments made by S at each of the nine standard frequencies. These data are averaged over Ss and presented as overall mean half-pitch judgments. Figure 1 "A" shows graphically the information presented in Table I.

Figure 1 compares these data with three previous studies.

Upon first impression, a rather broad difference seems to exist between the extreme slopes (.76 and .99). Two sets of nearly equivalent slopes seem to emerge, the present scale and Stevens,'[2] (.76 and .81, respectively), and Harris'[3] and Siegel's[4] (.99 and .96, respectively). However, it seems rather unlikely that these trends are real. Considering the subjective nature of the pitch judgments, as well as the large inter- and intra-subject variability, it seems rather likely that these two small clusters were due to chance, rather than to true differences in function. An ideal half-pitch function would probably fall somewhat intermediate between the two clusters. Indeed, it must be said that considering the abstract task of half-pitch judging, agreement among these four studies appears to be rather good.

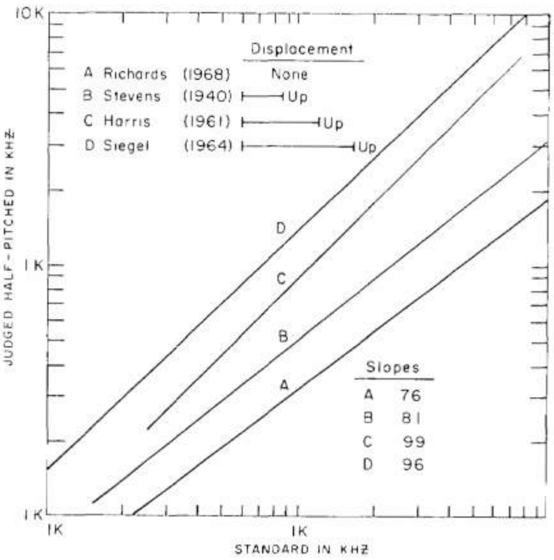

Fig. 1. Half-pitch Functions, Relating the Stimuli Judged One-half Against Their Respective Standards for Four Studies.

In passing, it may be said that the type of transducer used is unrelated to the slope of the obtained half-pitch function. Although they used loudspeakers, Stevens[2] and Siegel[4] obtained markedly different slopes (.81 and .96, respectively). The same is true of earphones: Harris[3] obtained a slope of .99, whereas the present data yielded only .76.

Figure 2A shows Stevens[2] mel scale with the analogous function as derived from the no-noise condition in the present experiment. Agreement between the scales is rather good, but would have been closer had Stevens' half-pitch function been plotted with a linear best fit (as in Fig. 1B).

TABLE I Geometric Means for Half-Pitch Judgments for a No-Noise Condition

SUBJECT	Frequency 200	300	400	700	1000	2000	5000	8000	12000
L.C.	74.3	97.9	138.7	264.2	348.3	527.2	1524	1455	1963
M.S.H.	123.6	148.6	209.9	296.5	448.7	591.6	1156	1919	2773
A.M.R.	135.5	152.1	241.0	270.4	310.5	744.7	1560	2254	3741
J.S.R.	107.6	123.6	145.2	155.6	264.2	663.7	1297	2472	2254
R.R.F.	95.7	115.3	152.1	200.4	191.4	317.7	619.4	1297	1791
C.S.M.	112.7	141.9	152.1	246.6	264.2	578.1	711.2	779.8	1486
S.R.W.	135.5	144.9	195.7	264.2	332.7	727.8	1183	2056	1828
E.L.M.	-	--	141.9	264.2	325.1	605.3	1156	1791	2472
H.J.M.	66.1	83.4	123.6	132.4	356.5	438.5	1358	1791	2365
K.J.S.	--	--	141.9	264.2	364.8	409.3	937.6	1268	2254
T.G.W.	--	--	115.3	252.3	348.3	619.4	1671	2254	3491
C.E.D.	--	--	205.1	317.7	390.8	515.2	959.4	1358	2649
MEAN ½ JUDGMENTS	106	126	164	244	329	562	1178	1725	2422

TABLE II Geometric Means for Half-Pitch Judgments for 45DB Above 30-DB Noise Mask

SUBJECT	Frequency 200	300	400	700	1000	2000	5000	8000	12000
L.C.			97.9	230.7	246.6	981.7	1054	3041	
M.S.H.			209.9	340.4	325.1	539.5	895.4	1327	
A.M.R.			230.1	325.1	418.8	981.7	1560	2472	
J.S.R.			129.4	235.5	399.9	779.8	1156	2888	
R.R.F.			152.1	276.7	310.5	727.8	1358	2710	
C.S.M.			129.4	182.8	310.5	480.8	855.1	1633	
S.R.W.			182.8	373.3	373.3	619.4	1030	1489	
E.L.M.			230.1	310.5	480.8	798.0	1524	3491	
H.J.M.			132.4	241.0	303.4	527.2	1183	1832	
K.J.S.			182.8	310.5	364.8	591.6	937.6	1750	
T.G.W.			120.8	209.9	303.4	679.2	1791	1297	
C.E.D.			170.6	205.1	296.5	428.5	959.4	1560	
MEAN ½ JUDGMENTS			164	270	344	678	1192	1892	

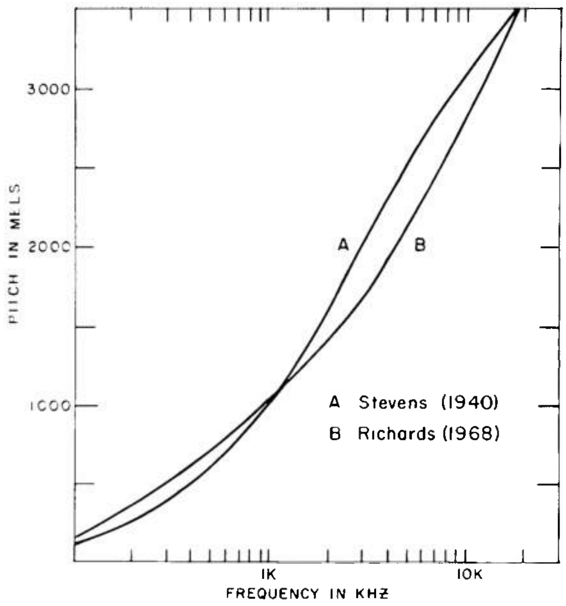

Fig. 2. Mel Scales, "A" as Derived by Stevens (1940), and "B" in the Present Study.

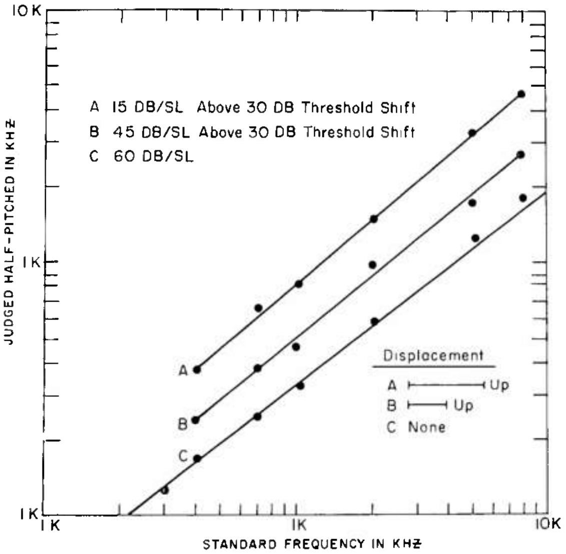

Fig. 3. Half-pitch Functions for ("C") a No-noise Condition, and When All Tones Were ("B") 45-, and ("A") 15-dB Above a 30-dB Threshold Shift Introduced by Noise.

B. Half-Pitch and Mel Scales for Noise Conditions.

Each entry in both Tables II and III represents the geometric mean of five half-pitch judgments for each S at each frequency. Overall group means are also shown in Fig. 3A and B. The most important feature in Fig. 3 is the nearly parallel, upward shifting of function as the sensation level of the tone decreases above noise. Thus, all mean half-pitch judgments across frequency are higher for the 15 dB above masked threshold than for the 45 dB condition above masked threshold, or the no-noise conditions. Analogously, the 45 dB above noise judgments are consistently greater than the 60 dB/SL (no-noise) condition.

To test the significance of the above relationship a triple classification analysis of variance was performed (see McNemar[8]). Table IV indicates these results in the form of an analysis of variance summary table. Perhaps the two most important aspects of the analysis are the significance of the main effect, "Intensity Condition" ($F_{obt} = 5.21$, $F_{\alpha\,05} = 3.44$), and the non-significance of the interaction "Intensity Condition × Frequency" ($F_{obt} = 1.31$, $F_{\alpha\,05} = 1.91$). In short, these two results indicated that the "Intensity Condition" was influential in determining how a tone would be perceived, and that the phenomenon was not frequency dependent (due to the non-significance of the "Intensity Condition × Frequency" interaction). It was not surprising to find that the remaining two interactions of the analysis were significant, since these would be expected on the basis of large inter-subject variability. The main effect, "Frequency," was expected to be significant, and provided information that Ss were truly discriminating.

To ascertain where the significance lay with respect to "Intensity Condition" a Newman-Kuels procedure (see Winer[9]) was used to test between the obtained means. These results are seen in Table V in the form of a summary table. It is seen that the only significance ($\alpha = .05$) lies between the no-noise and 15 dB above noise conditions. The fact that the 45-dB condition is not significantly

TABLE III Geometric Means for Half-Pitch Judgments for 15 DB Above 30-DB Noise Mask

	Frequency								
SUBJECT	200	300	400	700	1000	2000	5000	8000	12000
L.C.			235.5	409.3	578.1	1156	2153	3917	
M.S.H.			224.9	332.7	332.7	875.0	1750	1489	
A.M.R.			241.0	356.5	373.3	875.0	1919	3041	
J.S.R.			178.6	332.7	480.8	1007	1791	3741	
R.R.F.			132.8	303.4	325.1	492.0	1156	2153	
C.S.M.			162.9	219.8	381.9	744.7	1327	1791	
S.R.W.			145.2	252.3	296.5	503.5	695.0	981.7	
E.L.M.			178.6	303.4	448.7	779.8	3412	3412	
H.J.M.			191.4	235.5	289.7	418.8	1211	1963	
K.J.S.			219.8	390.8	448.7	578.1	1422	1791	
T.G.W.			123.6	310.5	438.5	679.2	1390	1390	
C.E.D.			178.6	283.1	340.4	448.7	959.4	1875	
MEAN $\frac{1}{2}$ JUDGMENTS			189	311	395	713	1599	2295	

TABLE IV Analysis of Variance: Intensity, Frequency, Subjects, and Interactions.

SOURCE	SS	df	MS	OBTAINED F	$F_{d.05}$
INTENSITY	.3169	2	.1584	5.21*	3.44
FREQUENCY	29.7800	5	5.956	38.93*	2.37
SUBJECTS	1.030	11	.0936		
INTENSITY X FREQUENCY	.0598	10	.0059	1.31	1.91
INTENSITY X SUBJECTS	.6680	22	.0304	6.75*	1.66
FREQUENCY X SUBJECTS	.8401	55	.0153	3.40*	1.46
FREQ. X Ss INTENSITY	.4942	110	.0045		
TOTAL	33.124	215			

different from either of the other two means, indicates that an intermediate position was achieved.

TABLE V TESTS FOR THE EFFECT OF INTENSITY SIGNIFICANCE OF DIFFERENCES AMONG MEANS BY NEWMAN-KUELS PROCEDURE (WINER[9])

INTENSITIES	NO-NOISE 60 OB	45dB ABOVE 30dB SHIFT	15 dB ABOVE 30 dB SHIFT
Ordered Means (In Logarithmic Terms)	2 683	2.723	2 775
No-Noise	X	040	.092
45 dB SL		X	.052
15 dB SL			X
S_B = .0205	r=	2	3
$q_{.95}(r,22)$		2 95	3 58
$S_B\ q_{95}(r,22)$		060	.073
	No-Noise	45 dB SL	15 dB SL
No-Noise			*
45 dB SL			
15 dB SL			

From the foregoing, it may be said with some assurance that the intensity of a stimulus is influential in determining how that tone is perceived. From the analysis thus far, however, one cannot say whether it is the masking or the intensity level which determines these pitch shifts. It will be left to the next section to determine fully which aspect actually was influential in determining the obtained significance.

Figure 4 presents mel scales for all conditions as derived from Fig. 3. It is clear that a more rapid acceleration under masking conditions occurs than when a no-noise condition is used, and that this acceleration seems to be inversely related to the loudness of a tone above noise.

C. The Role of Pitch Changes Due to Overall Intensity.

One possible explanation accounting for a significant "Intensity Condition" could have been that the changes in pitch were due to differences in sound intensity level. This view, however, has been refuted by several investigations (Schubert,[5] Morgan, et al,[11] Cohen,[10] and Steiner and Small[7]) which indicate that there is little or no change of pitch with differences in intensity.

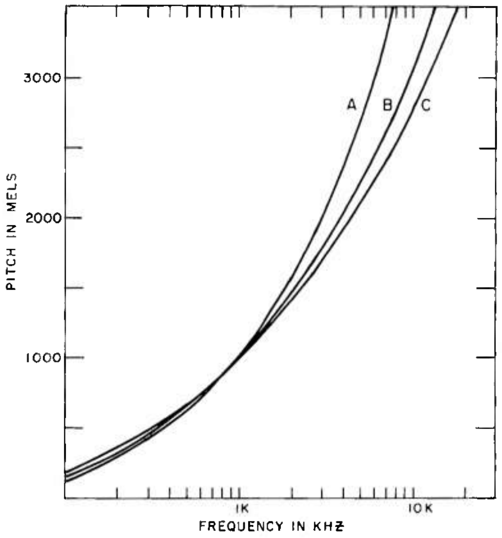

Fig. 4. Mel Scales Derived in ("C") a No-noise Condition, and When All Tones Were ("B") 45-, and ("A") 15-dB Above a 30-dB Threshold Shift Introduced by Noise.

In an effort to validate Stevens'[12] study concerning the relation of pitch to intensity, Cohen[10] conducted two alternate balancing experiments using widely different sound levels (40-100 phons in one case, and 30-90 phons in another) in each ear. Upon looking at these effects across frequency, Cohen concluded (p. 1374): "The findings of experiments I and II provide only minimal support for the predicted replication of the pitch-intensity relationship. First, although increases in loudness level produced pitch changes which were generally in the directions stipulated by the relationship, the average amounts of shift were small and in many instances not statistically different from errors in pitch matching. Second, the observed effects of loudness level upon pitch were not always consistent for the subject group. Last, the low frequency tones did not show the maximum pitch change for 100 cps and progressively smaller changes for still lower frequencies as originally posited."

In an early article, Morgan, Garner and Galambos[11] tested the pitch-intesity relationship posited by Stevens[12]. Their study also commented upon the work of Snow[13] who found more moderate pitch shifts than Stevens.

Using two techniques of alternate pitch balance (an "anchor" method where the standard tone was always 40 dB/SL, and a "Ladder" method in which the standard tone was always 10 dB below the comparison) these authors did not confirm the earlier studies. They concluded: "Perhaps the first thing to note about our results is how little, in general, pitch changes with intensity. The median or typical change never exceeds two per cent. This is far less than Stevens reports for his Subject on many matches, and is somewhat less than Snow reports but is in general agreement with Snow's data. The median or typical situation is, therefore, little or no change of pitch with intensity" (p.662).

From the foregoing, it seems rather unlikely that the significance of "Intensity Condition" was due to the overall levels of the stimuli. Intensity being eliminated as a primary factor influencing the obtained results leaves masking as the only independent variable to which the significant main effect ("Intensity Condition") may be attributable.

Further, and more direct evidence that the changes found in this study were due to masking and not loudness level is to be found in two studies alluded to in the Introductory section of this paper. Schubert[5], in an effort to uncover the correlates of pitch changes under noise, removed the noise from the standard tone, but kept the sound intensity of the standard at the same level at which S would balance loudnesses with noise present. Thus, if the standard tone was originally 15 dB above a 35-dB threshold shift, it was after the removal of noise at 45 dB SL, whereas the comparison tone remained at 15 dB/SL (no noise present).

Schubert[5] found that when the noise was removed, the resulting pitch matches were no different from a condition in which the standard and comparison tones were of equal intensity. On the other hand, as outlined previously, when the masking was present significant pitch changes were present.

Finally, Steiner and Small[7] indicate that their results do not follow the form as outlined by Stevens. That is, with increased sound levels, the pitch of higher frequency tones does not increase, and those of low frequency do not decrease.

IV. CONCLUSIONS

From the evidence available, pitch changes in a moderate noise appear to be primarily influenced by the sensation level of a tone above masked threshold. Generally, an inverse relationship exists whereby a tone of low SL is perceived higher than a tone of the same frequency, but of greater magnitude. The outlined phenomenon has been shown **not** to be frequency dependent, i.e., the relationship will hold at all frequencies of interest. On the other hand, pitch shifts increase with frequency, rather than remain constant across the audible spectrum.

Similarly, pitch, when measured in mels, increases with decreases in SL above noise.

Finally, it is instructive to note that only one level of noise has been utilized in the present work. Perhaps, if this level were to be increased, more pronouced effects might have been encountered. On the other hand, the effect of SL above noise might be negated, had lower noise levels been used.

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13 ABSTRACT

The mel scale, relating subjective pitch in mels to physical frequency in cycles per second, is now commonly found in texts and handbooks in engineering psychology. It is usually derived from the psychophysical method known as bisection, in which the listener adjusts a variable frequency to sound half as high in pitch as a standard tone. The average subject will not, for example, adjust the variable to 500 for a standard of 1000 cycles per second. In this study mel scales were derived from fractionation data when the standard and variable tones were presented in each of three background noise conditions. The scale for tones in quiet differed in no essential manner from the generally accepted mel scale advanced by Stevens in 1940, however, upon the introduction of a wide-band masking noise, the shape of the mel function became more positively accelerated. In general, when holding the intensity of the masker constant, this acceleration is inversely related to the sensation level of the experimental tones above masked threshold, and is not frequency dependent. Although the relationship is not dependent upon frequency per se, the magnitude of pitch shift increases with frequency.

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