PITCH CHARACTERISTICS OF SHORT TONES. II. PITCH AS A FUNCTION OF TONAL DURATION *

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INTRODUCTION

In the first experiment of this series (3) our interest lay in determining the shortest duration at which tones of various frequencies still had some pitch character to them. We determined two duration thresholds for pitch, representing the limits of pitch change from a 'click-pitch' to 'tone-pitch.' The 'click-pitch' threshold was the shortest duration at which a click was heard with pitch in it, and the 'tone-pitch' threshold was the point at which the sound became a tone and the pitch character changed little or not at all with further increases in duration. It was concluded that the 'click-pitch' threshold represented the shortest duration with which the ear can be stimulated in order for some pitch identification to be possible and the 'tone-pitch' threshold represented the shortest duration at which reasonably good pitch discrimination should be present.

Having established that pitch is present even in extremely short tones (on the order of four msec. for the middle range of frequencies and 11 msec. for low frequencies around 250 cps), the next step was to investigate whether or not the pitch of a tone changes as its duration is shortened. Certain it is, in view of previously published data on the problem of pitch discrimination as a function of tonal duration, that pitch *discrimination* becomes increasingly less accurate as the duration of a tone is shortened. Less certain, however, is the direction and the magnitude of the pitch change as a function of duration. The available literature presents contradictory reports on this relationship.

Bürck, Kotowski, and Lichte (2), for instance, state that the pitch of high tones is lowered and the pitch of low tones is raised by shortening the duration of the tone. Eckdahl and Stevens, as reported by Stevens and Davis (6, p. 101), on the other hand, conclude that the pitch of all tones (at least from 250 to 8000 cps) is lowered by decreasing their duration. The function for only one frequency, 1000 cps, is reported, however. According to this curve, a tone of 1000 cps lasting 10 msec. sounds equal in

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pitch to a tone of 842 cps lasting 1.5 sec. In other words, the apparent pitch of a 1000 cps tone is lowered considerably by shortening its duration to 10 msec. The data showing this relationship between duration and pitch were obtained from the observations of one *S*. The complete results of this experiment were never published.

Related to the problem with which out study is concerned are several experiments on pitch discrimination as a function of tonal duration. The data published by Békésy (1), based on observations from two *S*s, show that the differential limen for pitch increases as a function of shortening duration. The increase in the limen is gradual down to durations on the order of 100 msec., beyond which the curves rise at a rapidly increasing rate. For instance, in the case of an 800 cps tone, the difference-limen at the duration of 350 msec. is approximately .002, at 100 msec. it is about .004, and at 12 msec. it is about .098.

The problem of pitch discrimination as a function of tonal duration also concerned Turnbull (7). He presented his *S*s with a standard tone of a constant 500 msec. duration followed by another tone of a higher or lower frequency and of a known duration, ranging from 500 msec. to the shortest duration which allowed measurement of the DL. The *S* was required to judge whether the second tone was higher or lower in pitch than the standard tone. By having the *S*s make such judgments for a series of comparison tones of frequencies on either side of the standard, the *E* was able to determine the frequency increment or decrement at which the judgments of the *S*s showed 75 percent high or low respectively. The average of these two DL's, i.e., the least perceptible rise or drop in pitch, was the DL used by Turnbull in plotting his data. He justifies the use of the average DL on the grounds that he found no significant constant errors for pitch as a function of duration. His data agree with those reported in the Békésy study. There is a gradual increase in the DL from durations of 500 on down to 100 msec., beyond which the DL increases at an increasingly rapid rate.

In the cases we have reviewed above, studies aimed directly at the problem of pitch changes as a function of duration have been incomplete. Those dealing with the related problem of pitch discrimination as a function of tonal duration have given no information on the direction and magnitude of pitch changes, when such information should have been available in the data.

In the Turnbull study, it is quite possible that no consistent and reliable trends showed up under the method used, i.e., the method of constants. Our own experience in repeating Turnbull's work would tend to substantiate this to some degree, and a recent investigation by Koester and Schoenfeld (4) supports this possibility. They used a modified method of constants in their study of the effect of context upon judgments of pitch differences. Their results indicate that the degree and direction of pitch change is definitely affected by interaction effects operating in the method of constants. These interaction effects between standard and comparison stimuli might very well obscure the changes in pitch associated with the shortening of a tone's duration. About this more will be said in the discussion.

Purpose.—In the light of the foregoing discussion it is apparent that there was conflicting and incomplete evidence on the relation between tonal duration and pitch. These studies did point to the importance of duration as a variable, however, and our preliminary experiment on the duration thresholds for pitch suggested that reliable data for pitch judgments could be obtained even at extremely short durations.

In view of these considerations, the purpose of our experiment was twofold: (1) To resolve the contradictions found in the literature; and (2) to provide more complete information on the relation between tonal duration and pitch by using a wide range of frequencies and durations.

Experiment A: Method of Constants

Apparatus.—Our first attempt was essentially a repetition of the Turnbull experiment with some changes in apparatus and conditions. In our study, however, we were concerned with pitch changes rather than difference limens as a function of tonal duration. The essential difference in the apparatus was in the timing device. The timer in Experiment A was electronically controlled. The onset of both the standard and comparison tones, their duration, the interval between them and the repetition rate of the sequence of tones were all controlled by a specially designed electronic timing circuit. The timing device in the Turnbull study was mechanical. We feel that this difference did not influence the results. The variable frequencies of the comparison tone were manually controlled in both studies.

Conditions.—The conditions of our experiment differed in some respects from the Turnbull study. Standard frequencies of 250, 1000, and 4000 cps instead of 128, 1024, and 8192 were used. We employed two intensity levels, 90 db and 70 db *re* 0.0002 dyne/cm.^{2}, while Turnbull used a sensation level of 60 db throughout. In his study, the duration of the comparison tone took values from 500 msec. to the shortest duration which allowed measurement of the *S*'s DL; in our experiment the durations of the comparison tone were 6, 12, 25, 50, 100, and 200 msec. for 1000 cycles and 4000 cps and the same for 250 cps with the exception that 6 msec. was omitted.

All other aspects of the two experiments were essentially the same.

Our comparison frequencies for each standard were distributed symmetrically about the standard with one of them being equivalent to the standard. For the shorter durations, the comparison frequencies paired with a standard were spread over a wider range because of the larger difference-limen for pitch at these shorter durations. In most cases 11 comparison frequencies for each standard were selected. Where necessary, however, 13 were used.

Procedure.—In groups of three our *S*s were asked to listen, through earphones, to a series of tones consisting of a standard tone of 500 msec. duration, followed by an interval of silence of 250 msec., followed by the comparison tone of some predetermined duration and frequency. This sequence was repeated every four sec. The *S*s were instructed to write down on their recording sheets whether they thought the comparison tone was higher or lower in pitch than the standard tone, using the letters 'H' for high and 'L' for low. Six *S*s were used altogether.

During any experimental run only one standard was used, and with it each comparison tone was paired ten times. The order of presentation of pairs was randomized. Between each experimental run a short rest period was interpolated. No more than four runs were made during the experimental period of approximately one hour.

All observations were made in a sound-deadened room, and were made binaurally.

Treatment of data.—Using the method of least squares, an average psychometric function for any one set of conditions was determined by fitting a straight line to the combined data of all *S*s obtained under this set of conditions. The point of subjective equality was taken as the 50 percent point. In this way the pitch of 250, 1000 and 4000 cps tones at each of the selected durations was computed for the intensity levels of 90 and 70 db.

In plotting the data, the percentage of pitch loss or gain was used. These percentage values

were computed by substituting in the expression $\Delta f/F$, where Δf is the pitch loss or gain in cycles per second and F is the frequency of the standard tone.

An illustration from the results of this experiment will serve to clarify the reasons for stating that a particular frequency loses or gains a certain percentage of pitch at a particular duration. By computing the point of subjective equality as described above, it was found that a 1007.7 cps tone lasting for six msec. was judged to be equal in pitch to a 1000 cps tone sounding for 500 msec. (Fig. 1, upper 1000 cps curve). It was then assumed that a 1000 cps tone sounding for six msec. would be equivalent in pitch to a 992.3 cps tone lasting for 500 msec., or that it would lose 0.77 percent of its pitch by reducing its duration from 500 msec. to six msec. (Percentage pitch change = $\Delta f/F = -7.7$ cps/1000 cps $= -0.77$ percent.)

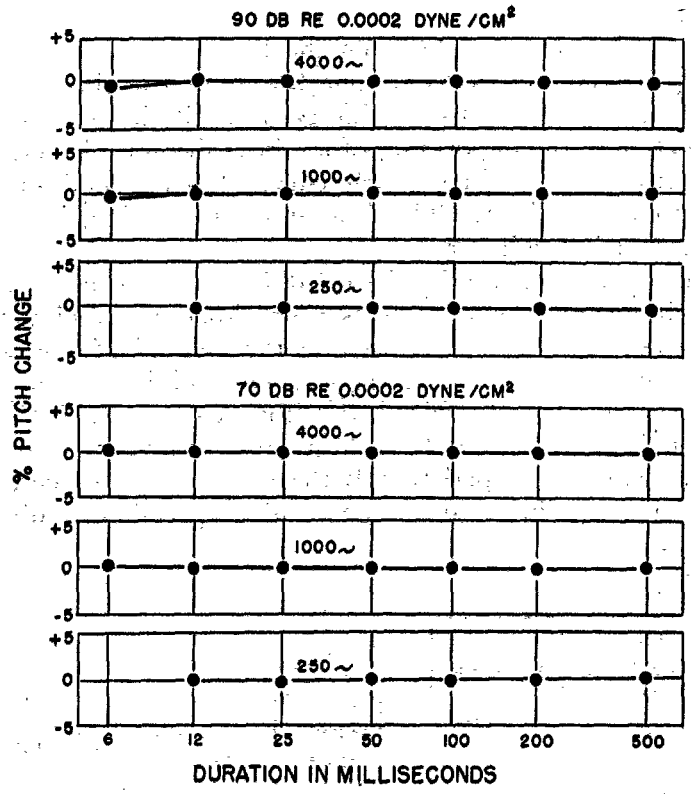

FIG. 1. The relation between tonal duration and changes in apparent pitch, as determined by the method of constants

The three upper curves are at the intensity level of 90 db *re* 0.0002 dyne/cm.² and the three lower curves at the intensity level of 70 db. Each curve is the average function for six Ss.

Results: Method of Constants.—Fig. 1 shows the relation between tonal duration and percentage of pitch change for the intensity levels of 90 and 70 db. The abscissa for each curve shows the durations of the tone; the ordinate shows the percentage of pitch loss or gain for three frequencies of 250, 1000 and 4000. The upper three curves were obtained at an intensity level of 90 db and the lower three curves at an intensity level of 70 db.

Fig. 1 clearly indicates that there is a tendency, although only a slight tendency, for the three upper curves (90 db) to drop with shortened duration, indicating a loss of pitch. This drop is only noticeable at durations shorter than 12 msec. for the frequencies of 1000 and 4000 cps. The largest percentage of pitch loss was recorded for 1000 cps at six msec. This was only on the order of −0.8 percent, or approximately eight cps. This compares with a 15.8 percent drop in pitch recorded by Eckdahl and Stevens for a 1000 cps tone at 10 msec.

Part of the difference between the two sets of results might be explained by the fact that only one *S* was used in the Eckdahl and Stevens experiment, and that a different intensity level was employed. An indication of the importance of the intensity level is evident from a comparison of the three upper curves (90 db) and three lower curves (70 db) in Fig. 1. The drop at short durations in the former is not present in the latter.

Whatever the explanation for the difference, it would appear that if large pitch changes take place as a function of shortening duration, they are not revealed completely by the method of constants employed by us in this experiment and by Turnbull in his study of pitch discrimination. It was decided, therefore, to try a method in which the *S* could match the pitch of short tones to longer standard tones directly. Thus, in Experiment B the method of average error was used and a change in apparatus was made to permit such direct pitch matching.

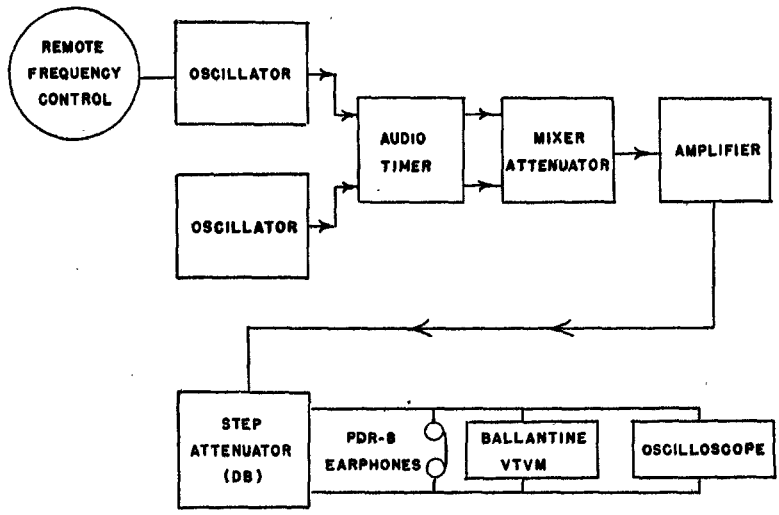

FIG. 2. Block diagram of the apparatus used in Experiment B

Experiment B: Method of Average Error

Apparatus.—Fig. 2 is a block diagram of the apparatus used in Experiment B. The change in apparatus mentioned consisted of installing a remote control which enabled the *S* to control the frequency of the comparison tone. In all other respects the apparatus was the same as that used in Experiment A.

Two oscillators were used: a Hewlett-Packard Audio Oscillator, Model 200A for the generation of the standard tone of 500 msec. duration, and a General Radio beat-frequency oscillator for the generation of the comparison tone.

The outputs of the two oscillators were led into the two channels of the audio timer which allowed for the control of the duration, separation, and repetition rate of the stimuli. From the timer the tones were conducted successively to a mixer attenuator, thence to an amplifier, a step attenuator, and finally into two sets of headphones: one set of Permoflux earphones (type PDR-8) for the *S*; and one set (type ANB-H-1A) for the *E*. These receivers were mounted in doughnut headsets, and binaural listening was used.

Connected in parallel with the earphones for purposes of calibration were a Ballantine Voltmeter and a Dumont (type 208-B) cathode-ray oscillograph.

The earphones which the *S* used had been calibrated by the Permoflux Company for operation into a six cc. coupler and they had a response which was reasonably flat between 100 and 8000 cps. For all calibrations of reference intensity the voltage across the phones was set at a level approximately equal to 110 db re 0.0002 dyne/cm.^{2}, as determined by the calibration curves.

Conditions.—The conditions for Experiment B were as follows: The standard tone of either 250, 1000, or 4000 cps was on for 500 msec., followed by a silent interval of 250 msec., after which the comparison tone of one of six durations—6, 12, 25, 50, 100, or 200 msec.—came on. The frequency of this comparison tone could be varied over a range of 0–20,000 cps by the *S* located in the sound-deadened room. This sequence of stimuli repeated itself every three sec.

Two intensity levels were used—90 and 70 db re 0.0002 dyne/cm.^{2} A small amount of white noise was also introduced to the listener's earphone to prevent the possibility that the *S* could detect weak beats from the slight electrical leakage of the audio timer. This noise was 50 db below the level necessary to mask the steady pure tone.

Procedure.—The same six *S*s used in Experiment A were used in Experiment B. They were all male students between the ages of 22 and 28 years. In most of the experimental sessions at least two *S*s were present. They alternated in making their judgments. They sat in a sound-deadened room, placed the earphones over their ears themselves so that they fitted comfortably, and at a signal from the *E*, who was in another room, proceeded to manipulate the remote control, which allowed them to alter the frequency of the comparison tone over the entire audible range of frequencies, until they had matched the standard and comparison tones in pitch.

Result: Method of Average Error. Effect of duration.—Figs. 3 and 4 show the relation between the duration of a tone and the change in apparent pitch as a function of this duration. So that the results of our two experiments might be more easily compared, Figs. 3 and 4 have been drawn to the same scale and with the same arrangements of variables on the axes as was Fig. 1. The abscissae show the duration of the tone in msec. and the ordinates show the percent of pitch change as determined from the expression $\Delta f/F$. Each point on the graphs in Figs. 3 and 4 represents the average of from 25–30 judgments. (No judgments were obtained at the duration of 500 msec. but it was assumed that no change in pitch occurs at this duration.) From two to five judgments were obtained from each *S* under each condition.

The shaded area around each of the curves represents the variability of the *S*s' judgments as measured by the sigma of the individual judgments above the average.

Fig. 3 represents the changes taking place in the apparent pitch of a tone as the duration is varied with an intensity level of 90 db. It is apparent that considerable pitch change takes place toward the shorter durations. There is a decided tendency for all frequencies, i.e., 250, 1000, and 4000 cps to lose pitch as their durations are reduced to 12 and six msec. The greatest change, on the order of −4.0 percent, takes place at a frequency of 250 cps and a duration of six

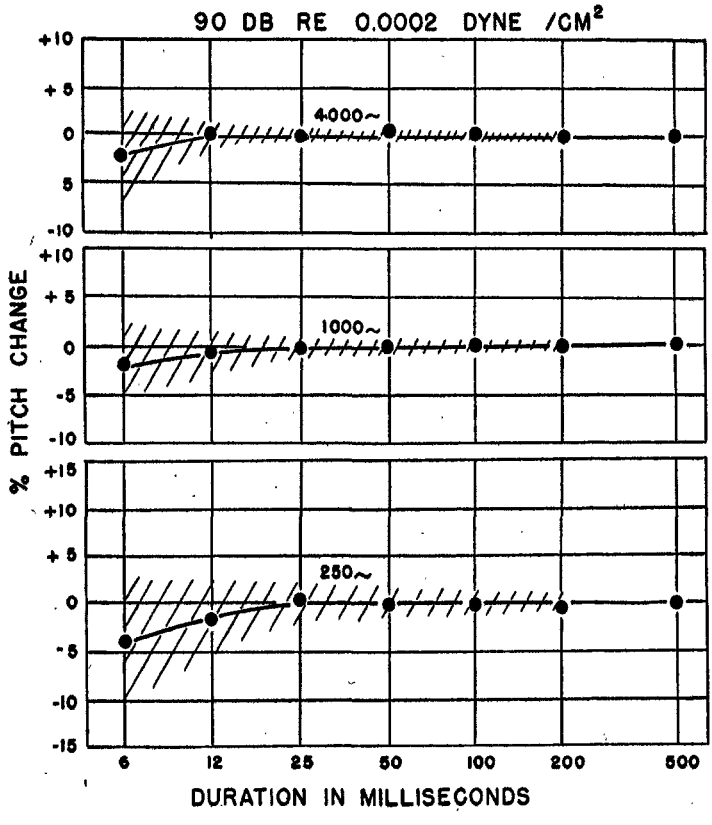

FIG. 3. The relation between tonal duration and changes in apparent pitch, as determined by the method of average error

The intensity level was 90 db *re* 0.0002 dyne/cm.² Each plotted point represents the average of 25–30 observations obtained from six *S*s. The shaded areas represent the sigma of the *S*'s observations about the average.

msec. About the same amount of change and in the same direction is common to both 1000 and 4000 cps. At these frequencies, the percent change is on the order of −2.0 percent at six msec.

These percentages are considerably larger than those reported for Experiment A. The reader will recall that the percentages of loss in that experiment were less than one percent at any frequency.

However, it is to be noted that both sets of data confirm each other in the direction of change. Fig. 1 and Figs. 3 and 4 agree in showing the trend toward a loss in pitch at the shorter durations, at least, in the case of 1000 and 4000 cps.

It is notable that the pitch of a tone remains relatively constant down to durations of 25 msec., being affected seriously only at durations considerably shorter.

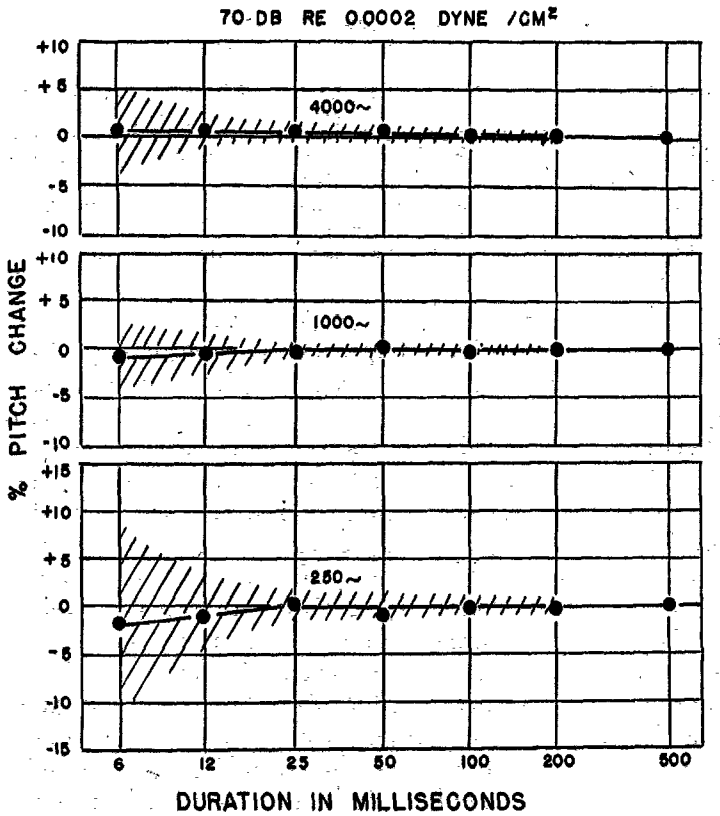

FIG. 4. The relation between tonal duration and changes in apparent pitch, as determined by the method of average error

The intensity level was 70 db *re* 0.0002 dyne/cm.² Each plotted point represents the average of 25–30 observations obtained from six *S*s. The shaded areas represent the sigma of the *S*'s observations about the average.

Effect of intensity.—Fig. 4 shows the results obtained when an intensity of 70 db was used. The striking fact about these curves is that the amount of pitch loss occurring at the extremely short durations is less than that shown at the higher intensity level of 90 db (Fig. 2). This is true for 250 and 1000 cps, and for 4000 cps there is a decided trend toward a gain in pitch as a function of shortening duration.

This same influence of intensity is evident when the three upper and three lower curves of Fig. 1 (Experiment A) are compared.

From these results it is obvious that both frequency and intensity interact in determining the direction and amount of pitch change as a function of tonal duration. For instance, the percentage of pitch loss for a 1000 cps tone at a duration of six msec. at an intensity level of 90 db is 1.8 percent; at 70 db the same tone has a pitch loss of only 0.8 percent. A 4000 cps tone of six msec. duration shows a 2.2 percent loss at 90 db and an 0.8 percent gain at 70 db.

Experiment C: Intensity and Frequency Effects

Apparatus and procedure.—The apparatus and procedure for Experiment C were the same as for Experiment B with the exception that only one *S* was used (not one of the original six).

Conditions.—Five different intensity levels were selected: 110, 90, 70, 50, and 30 db *re* 0.0002 dyne/cm.^{2}, and six different frequencies were used: 250, 500, 1000, 2000, 4000, and 8000 cps. The duration of the comparison tone was kept constant at 12 msec., and the standard tone was again 500 msec. Ten judgments per condition were obtained from this one *S*, to check further the interactions between intensity and frequency.

Results.—Fig. 5 shows what happens to the pitch of a tone of 12 msec. duration and of a given frequency as the intensity of that tone is varied. As the intensity is decreased, pitch change tends, successively, to become less negative (or more positive), to level off, and then to become more negative (or less positive) at very low intensities. This generalization is true for all frequencies with the exception of 4000 and 8000 cps. At these frequencies, the levelling off occurs, but there is no tendency toward negative values at low intensities. Noteworthy about 8000 cps, too, is the fact that at all intensity levels, even at the highest, the pitch change is in the positive direction.

For this particular observer, the pitch change for a 250 cps tone at 12 msec. is contrary to that indicated in our combined data in Figs. 2 and 3. That is, the average of six *Ss*' judgments at 12 msec. for a tone of 250 cps shows a loss of pitch at both 90 and 70 db. The average of this one *Ss*' judgments, shown in Fig. 5, at these intensity levels and at the same tonal duration show a gain in pitch. At all other frequencies, however, the judgments of this one *S* agree quite well with the average judgments of the six *Ss*. We feel, then, that these data are in no real sense atypical. The previous observation about the effect of intensity on the pitch of short tones is confirmed, and the relation somewhat extended by observations from this one *S*.

Discussion

Comparison between Experimental Methods

A comparison between the results obtained with the method of constants (Experiment A) and the method of average error (Experi-

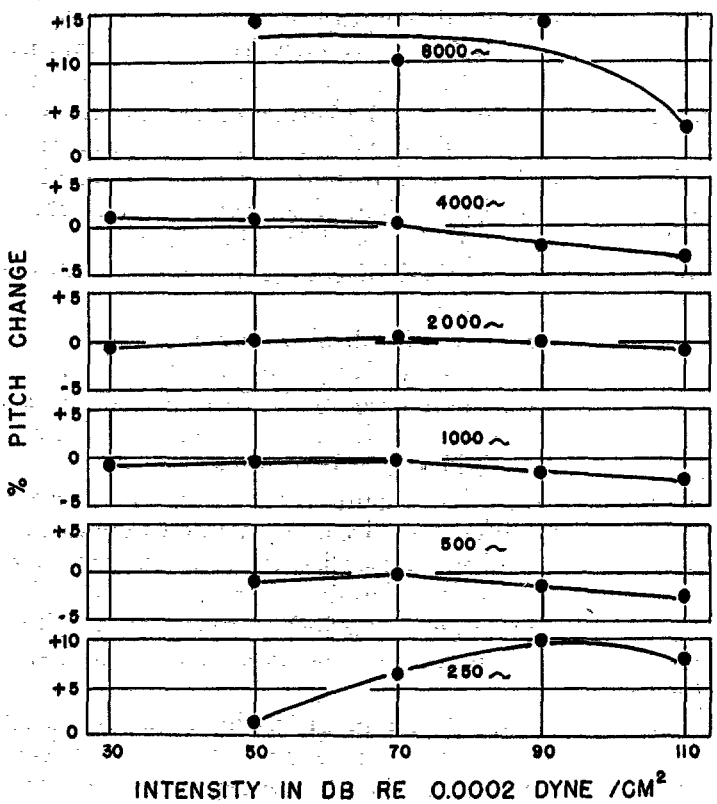

FIG. 5. The relation between intensity and changes in apparent pitch of 12 msec. tones
Each plotted point represents the average of 10 observations obtained from one *S*. The duration of the standard tone was 500 msec.

ment B) shows a difference in the functions representing the relation between tonal duration and pitch. This difference is chiefly in terms of the magnitude of the observed changes. Thus, from Fig. 1 (method of constants) it can be seen that the changes in pitch are never in excess of 1.0 percent at 90 db and that no changes in pitch appear to be present at 70 db. On the other hand, from Fig. 3 (method of average error) it can be seen that changes of between 2.0 and 4.0 percent occur at 90 db and from Fig. 4 (method of average error) that changes of between 1.0 and 2.0 percent are present at 70 db.

That different results can be obtained by using different psychophysical methods in investigating a given problem is nothing new. In a recent study Postman (5), for instance, shows that time-error functions for tonal stimuli obtained by the constants method are quite different from those obtained by a method of average error. The

problem for the experimentalist is to select the set of data, or that method, which gives the better representation of the relationship he is seeking to determine. In this particular case, we feel that the results obtained by the method of average error best represent the relation between tonal duration and pitch for two reasons: (1) The kind of judgment the *S* is asked to make in the method of average error is more relevant to the problem of determining pitch changes, or judgments of subjective equality; and (2) the effect of the stimulus context peculiar to the method of constants tends to obscure the pitch changes which take place.

Kinds of judgments.—In establishing the relationship between tonal duration and pitch qualitatively we wish to determine what frequency of a short duration tone has the same pitch as a longer duration tone with some stated pitch. In other words, we seek to find points of subjective equality. In the method of constants, we determine points of subjective equality inferentially, i.e., we ask the *S* to make judgments of differences (high or low) and then compute the points of subjective equality determining the frequency at which high and low judgments are equal in number. In the method of average error, however, the *S* makes equality judgments directly. The point of subjective equality then becomes the average of a number of such equality judgments.

In terms of the kind of judgment made, then, the method of average error is the more relevant to our problem and we feel, therefore, that the data from this method better represent the relation between pitch and duration.

Effect of stimulus context.—Data of Koester and Schoenfeld (4) suggest that in the method of constants the *S* tends to make his judgments in terms of a standard which is the mean of all the stimuli occurring during the run up to the time of making the judgment. We will point out in a moment how this would tend to obscure the amount of pitch change actually taking place as a function of duration. First, however, let us review the evidence offered by Koester and Schoenfeld to support such an hypothesis.

These authors were primarily interested in the effect of two or more interacting pitch stimuli on the C. E. function in pitch discrimination. Thus, in an experimental run they used several standards with which a number of comparison stimuli were paired. The *S*s were asked to judge whether the comparison tone was higher or lower than the standard with which it was paired (method of constants). An analysis of the data shows pronounced interaction effects. Thus, after stimulation at a high standard level (1100 cps) the judgments with respect to a lower standard level (1000 cps) were preponderantly low, and conversely, after stimulation at a low standard level (1000

cps) the judgments with respect to a higher standard (1100 cps) were preponderantly high. The effect was to force the points of subjective equality for the standards in the experimental run toward a mean of the series of stimuli in the run. In other words, the point of subjective equality for the lower standard tended to be higher and the point of subjective equality for the higher standard tended to be lower. The deduction was, then, that the *S* was making his judgments not with respect to the standard presented at the time but with respect to a standard which is determined by all of the interacting stimuli in the experimental run up to the time of making the judgment.

This information is useful in interpreting the data obtained by us with a method of constants, if we stop to consider the actual procedure used in a method of constants. In our experiment, the *S* heard a tone of 500 msec. duration followed, after a short silent interval, by a short tone. The frequencies of these short comparison tones were selected so that there were as many frequencies above that of the standard as below that of the standard. The mean of all these tones, then, was the frequency of the standard. If there is a constant error, however, these short tones are not symmetrically distributed around the *pitch* of the standard. Since the point of subjective equality tends toward the mean of all stimuli heard, it tends toward the frequency of the standard, not the pitch of the standard.

It might be said that the use of a method of constants, with all comparison tones symmetrically distributed about the frequency of the standard tone, tends to minimize constant errors. On the other hand, the *E* can, by proper selection of the comparison stimuli, determine the magnitude of the constant error. If, for example, all comparison stimuli have a higher frequency than the standard, then the point of subjective equality will be high. If all comparison stimuli are low, then the point of subjective equality will be low.

In a method of average error the *S* usually has complete control over the frequencies of the comparison stimuli. In our experiments he did. The *S* will at various times have the pitch of the comparison tone higher than that of the standard tone, and at other times it will be lower. In general, however, we can expect that the *S* will hear as many tones higher in pitch as lower in pitch with respect to the pitch of the standard tone. In other words, the *S* tends to distribute the tones symmetrically about the pitch of the standard, not its frequency. In fact, all judgments of the *S* must be in terms of the heard pitch, since he has no idea what the actual frequency is. The effect of context will still be present in a method of average error, but the context will be determined in terms of the actual pitch equalities of tones, which is what we are trying to determine. The *S*'s point of subjective equality will in no way be determined by the

arbitrary selection of values for the comparison stimulus which the *E* makes.

Whatever effects may exist, either in a method of constants or average error, due to the fact that all stimuli heard previously affect any single judgment, it is better if the *S* determines what stimuli he hears rather than the *E*. It is, after all, the psychology of the *S* we are concerned with, not the psychology of the *E*. Because of these relations, we again feel that the method of average error provides data which are more representative of the true relation between duration and pitch.

Variability

That the functions in Figs. 3 and 4 are not precise is indicated by the variability in judgments at each of the comparison stimulus durations, especially at the shorter durations. The envelope of shaded area about the line of best fit in Figs. 3 and 4 gives some indication of this variability in terms of the standard deviation of all judgments about the mean. This variability is probably due to a combination of the difficulty of judging pitch at very short durations and the inexperience of the *S*s.

A tone of only six msec. duration has very little pitch character to it. In the case of 1000 or 4000 cps of six msec. duration the tones are just beyond the click-pitch threshold, i.e., they are just beyond the point at which a predominant sensation of click has some pitch to it Since the pitch, in terms of which the *S* makes his judgment, is at a minimum at this duration, we would expect greatest variability at this point. This expectation is borne out by the results.

As the duration of a tone is increased, the pitch becomes more specific. At 12 msec. a 1000 or 4000 cps tone is just beyond the tone-pitch threshold, i.e., beyond the point at which tone is just detectable between the on- and off-clicks. Because there is more pitch in a 12 msec. tone than in a six msec. tone, we would expect that judgments involving pitch would be more stable at the former duration than at the latter. Examination of the envelope of variability in Figs. 3 and 4 shows this to be the case.

It can be seen from these figures that with still further increases in duration, with consequent increase in the amount of pitch, variability decreases—remaining relatively constant beyond 100 msec. This increase in the variability of pitch matching with a decrease in duration is certainly in line with the previously reported measures of differential sensitivity for pitch as a function of duration.

Our data show one condition which presents a paradox. Previously we had shown that the click-pitch threshold for a tone of 250 cps was greater than six msecs. In other words, *S*s had stated that there was no pitch in a six msec. tone at a frequency of 250 cps. In this experiment, regardless of this fact, we asked *S*s to match the pitch of this tone to a tone of longer duration. That they were able to do so with some degree of consistency is indicated in the figures presented. Such a tone contains only one and a half complete cycles, and a pitch match would seem almost impossible.

That *S*s were, nevertheless, able to make a pitch match is the paradox, one which we are unable to explain adequately. The only reasonable explanation at all is that if the *S*s increased the frequency of the six msec. tone, it had a pitch which was distinctly different from that of a 250 cps tone. It is possible, then, that these judgments indicate the highest frequency for the short tone which did not produce a pitch clearly different from that of the 250 cps tone.

Theoretical Interpretations

The physical nature of short tones.—A very short tone is not a pure tone. Many frequencies, adding together in proper phase relations, are required to produce a short tone of any given period of oscillation and duration. The exact nature of the physical spectra of short tones was described in some detail in the previous paper (3), and for our purposes here, the following relations are all that are necessary.

Any short tone is composed of a band of frequencies distributed symmetrically about the frequency of oscillation, and most of the energy is contained in one main band whose frequency limits are defined by $f_0 \pm 1/d$, where f_0 is the frequency of oscillation, and d is the duration of the tone in milliseconds. Within this main band, the maximum energy occurs at the frequency of oscillation, and the rest of the energy is distributed equally on both sides of this central frequency, until no energy occurs at the limits of the main band. The energy in the other bands, farther removed from the central frequency, is very small compared to the energy in the main band and can, for most purposes, be ignored.

When short tones are used, then, the ear is not responding to a pure tone, but rather to a band of frequencies.

Response to the geometric mean.—Differential sensitivity to frequency is a relative matter; that is to say, the difference limen for frequency tends to be constant only if we measure the limen on a logarithmic scale of frequency. Likewise, it has been shown that equal units of subjective pitch are more closely related to equal logarithmic units of frequency than to equal arithmetic units of frequency. For these reasons, then, and the many related facts, we would expect the ear to respond to the geometric mean of a band of frequencies, rather than to the arithmetic mean, since the geometric mean of a ban of frequencies is the mean of those frequencies on a logarithmic scale. We expect this type of response on the assumption that the ear would average pitches rather than frequencies.

There are many ways of computing a geometric mean for bands of frequencies which are continuous and in which all frequencies do not have equal representation on the intensity scale. But regardless of the particular method chosen, the geometric mean is always less than the arithmetic mean. We would, then, expect that the pitch of short

tones would always be less than the pitch of a long tone. The shorter the tone, the wider the band of frequencies involved in that tone, and the lower the geometric mean with respect to the arithmetic mean. Thus, we would also expect that the shorter the tone, the lower the pitch of that tone would be as compared to some tone of longer duration.

It would be interesting to compute geometric means for many of the tones used in these experiments to see if the apparent pitch of the short tone approximates the pitch of the geometric mean of the band of frequencies involved. Such calculations would be, however, rather fruitless since so many arbitrary assumptions must be made in the calculations. For example, what band of frequencies shall we use in our computations? We do not know the effective bandwidth of energy as far as the ear is concerned, and the wider the band of energy we use to compute the geometric mean, the lower it will be. Likewise, should we use a geometric mean in which each frequency component has been weighted according to its amplitude, or simply concern ourselves with the total band of frequencies involved? These problems, for all practical purposes, make it impossible to determine precisely whether the ear is responding to the geometric mean of a band of frequencies. The *general* expectation that the pitch of a short tone should be lower than the pitch of a long tone is confirmed, however.

Differential sensitivity of the ear to frequencies.—Another factor which enters into the problem of the pitch of short tones is the fact that the ear is not equally sensitive to all frequencies in the audio spectrum. At any given intensity, frequencies in the middle range will appear to be louder than either higher or lower frequencies. Thus, we can not concern ourselves entirely with the physical spectrum of short tones: we must be concerned as well with the psychological spectrum, and with the concept of a psychological geometric mean. Under certain conditions, for example, some of the frequency components in a short tone may be completely inaudible, while others will be quite loud. Such differential sensitivity will certainly affect the apparent pitch of a tone. Once again we can not make precise predictions, but we can make a general sort of prediction which checks with our data within limits.

At low frequencies, the higher frequencies in any given band will be louder than the lower frequencies in that band. At high frequencies, on the other hand, the ear is more sensitive to the lower frequencies of any given band than to the higher frequencies. We would predict, then, that the pitch of short tones at the low frequencies would be relatively higher than the pitch of short tones at high frequencies.

As an illustration, we have computed the geometric means for tones lasting six msec. at 250 and 4000 cps. We have arbitrarily computed these as the geometric midpoint of a band of frequencies defined by $1/d$. In the case of 250 cps, this band was 167–333 cps. and in the case of 4000 cps, the band was 3917–4083. The geometric mean in the former case is 236 cps, and in the latter case 3999 cps. In percentage terms, the pitch of these tones should then be -5.6 percent for 250 cps, and -0.025 percent for 4000 cps. If, however, the sensitivity of the ear has its effect, then the pitch should be relatively higher for the lower frequency, and relatively lower for the higher frequency. Reference to Fig. 3 will show that this expectation is confirmed: at 250 cps, the pitch drop is only 4 percent, and is 2.2 percent at 4000 cps.

There are other deductions which can be made with this line of reasoning. One of these is that the pitch of short tones at lower frequencies should become relatively more positive at lower intensities, since equal loudness contours become steeper at lower intensities. This expectation is likewise confirmed. At 4000 cps, however, pitch tends to become positive at a lower intensity, which is exactly opposite to what would be expected. In general, however, it seems as though the ear is responding to some psychological geometric mean. A better way of phrasing this statement, perhaps, is to say that the ear seems to respond to the midpoint of the total range of the psychological stimulus.

Summary and Conclusions

The purpose of these experiments was to determine the direction and magnitude of pitch changes as a function of duration over a wide range of durations, frequencies, and intensities. Both a method of constants and a method of average error were used, and the major difference between the methods was in terms of the magnitude of the effect. This problem is discussed, and results obtained by the method of average error are accepted as being more valid. Further results and discussion indicate:

1. As the duration of tones is decreased, there is a tendency for all tones to lose pitch.

2. The amount of pitch loss is related to intensity and frequency:

a. Pitch loss is greatest for high intensities, and is somewhat less for lower intensities.

b. Low frequencies show the greatest amount of pitch loss.

c. High frequencies at low intensities show actual pitch gain at short durations.

3. Many of the relationships found can be explained in terms of the ear's responding to the geometric mean of all the frequency components involved in a short tone.

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