ABSOLUTE JUDGMENT OF MUSICALLY-RELATED PURE TONES*

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ABSTRACT

Accuracy of pitch judgment for three sets of 12 sine-wave tones was studied in three experiments. Tone sets differed only in the spacing of stimulus frequencies within the range 175 Hz–2093 Hz. The frequencies for Triad spacing were derived from the (well-tempered) tonic chord with root F_3; for Keyboard Interval spacing, each frequency corresponded to a different musical note; for Arithmetic Interval spacing, frequencies were spaced at predetermined Arithmetic Intervals without specific concern for musical correspondence. Musical listeners showed most accurate judgment and most rapid learning of pitch for Triad spacing, and showed no difference between Keyboard Interval and Arithmetic Interval spacing. Comparison of two interstimulus durations, 3 sec and 8 sec, indicated at the slower rate of presentation a small but significant improvement in judgment of the lower six tones for both Triad and Keyboard Interval spacing, and an increased number of octave errors for the higher six tones for Triad spacing. Non-musical listeners showed no differences between sets or rates of presentation. Some characteristics of decision rules for musical pitch recognition are discussed.

THIS PAPER IS CONCERNED with the effect on absolute judgment of spacing the stimulus tones according to musical temperament. Performance on the task of absolute judgment of pitch is generally limited to accurate recognition of some four or five different tones. Variations in the spacing of the tones along the frequency continuum have been found to produce very little effect on amount of information transmitted, with approximately equal logarithmic units of spacing producing the highest value, 2.3 bits, as opposed to an average of 2.0 bits for partitioned spacing (Pollack, 1952). The effect of assigning stimulus frequencies according to the system of musical temperament has not been studied in detail; considering the stability of the value of channel capacity for unidimensional continua (see Garner, 1962) one would not expect any further manipulations of stimulus spacing to lead to a highly significant improvement in performance. On the other hand, examination of the musical keyboard suggests a reconsideration of the dimensionality of the perception of

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pitch, and, possibly, a reconsideration of previous findings regarding limitations on performance.

The mathematical rules for assigning the fundamental frequencies of musical temperament may be described as a two-dimensional system. In the Western system of equal temperament, the basic unit is the octave, or frequency ratio 2:1. Within a given octave there are 12 tones whose frequencies are determined by dividing the octave into 12 equal logarithmic units; outside the octave each frequency stands in relation of a power of 2 to one of the notes in the reference octave. Thus any musical note may be denoted by its position or nomenclature within the octave and its octave height, e.g. 440 Hz is A_4. Other Western systems, such as mean-tone, or just-tone temperament, may be described as two-dimensional, though restricted to certain keys.

This mathematical analysis does not necessarily mean that the perceptual system for pitch recognition is two-dimensional. The notion that the perceptual system is two-dimensional finds support in classic theory of harmonic structure dating back to von Helmholtz (1862), the two-component theory of Revesz (1953), and the compelling demonstrations of "circular pitch" by Shepard (1964) and Risset (1969). Deutsch (1969) has proposed an organized neural network whereby abstraction of musical intervals, chords, and octaves may be accomplished.

Concerning the absolute judgment of pitch, it is possible that if the frequencies of the stimulus set were assigned so that they were easily classified by the listener along two perceptual dimensions, accuracy of judgment might be as high as that found with bidimensional stimuli (cf. Pollack, 1953). But the octave interval between two notes presented successively is not necessarily a basic unit of melodic pitch distance (Stevens and Volkman, 1937), and it has been argued that recognition of the melodic octave is highly dependent upon degree of cultural training (Lundin, 1967). The extent to which the presence of the interval of an octave between tones of a set would facilitate absolute judgment is therefore not clear. Furthermore, the presence of a facilitatory effect might well be correlated with amount of musical experience and be dependent upon training. Three experiments were designed to consider these issues.

Method

Listeners

Listeners in all experiments were volunteers from Queen's University or a local high school. Except for a control group (Experiment II), who were not music students, all were currently studying music privately, and were preparing at least Grade VIII level of the Royal Conservatory of Music at Toronto. All had had keyboard training, some were also studying instruments. Age range of listeners was 14 to 38 years.

Stimulus sets

The nominal frequencies and musical note-names (where appropriate) of the stimulus sets, each consisting of 12 sine-wave tones, are given in Table I. The three sets have tones no. 1, 5, and 12 in common. The values for the frequencies for Set T (Triad spacing) and for Set KI (Keyboard Interval spacing) were derived from the well-tempered system, rounded to the nearest whole number. The tones of Set T represented the tonic chord pattern F-A-C repeated over four octaves. The tones of Set KI corresponded to 12 different musical notes. The frequencies for Set AI (Arithmetic Interval spacing) were obtained by dividing the range 175 to 440 Hz into four equal arithmetic intervals and the range 440 to 2093 into seven equal arithmetic intervals. The most frequent musical interval between two tones in adjacent ordinal positions was equal to, or in the case of Set AI closest to, the major or minor third (8, 9, and 7 cases for Sets T, KI, and AI respectively, out of a possible 11 adjacent pairs).

Apparatus

Sine-wave tones were produced by applying external voltages to a Hewlett-Packard function generator Model 3300A and were recorded by a Crown tape recorder Model CX 822 on Scotch 202 tape. Automatic programming of stimulus and inter-stimulus durations was accomplished by a digital logic system (Electrocraft LPS 200). Stimulus tones were monitored during recording with a Hewlett-Packard frequency counter Model 3735A and a Tektronix dual beam oscilloscope Type 502A. In order to reduce the efficacy of differential loudness cues, the output voltage of the function generator was first set for each tone so that each recorded tone as reproduced by the tape recorder through an impedance-matched headphone (AKG K-60) appeared equally loud to two trained listeners. For recording the tapes, the output of the generator was varied at random ±5 db about the equal-loudness setting for each tone. At the experimental sessions the tones were reproduced monaurally to listeners at an overall comfortable playback level, about 70 db SPL at 440 Hz.

For Experiments I and III, four test tapes were recorded for each stimulus set; each test tape consisted of each of the 12 tones of the set 3 times each in random

TABLE I

TONES OF THREE STIMULUS SETS IN ASCENDING ORDER OF FREQUENCY

	Set T		Set KI		Set AI
Ordinal Position	Name	Frequency in Hz	Name	Frequency in Hz	Frequency in Hz
1	F_3	175	F_3	175	175
2	A_3	220	$A\sharp_3$	233	242
3	C_4	262	D_4	294	308
4	F_4	349	$F\sharp_4$	370	374
5	A_4	440	A_4	440	440
6	C_5	523	$C\sharp_5$	554	676
7	F_5	698	E_5	659	912
8	A_5	880	G_5	784	1148
9	C_6	1047	B_5	988	1384
10	F_6	1397	$D\sharp_6$	1244	1620
11	A_6	1760	$G\sharp_6$	1661	1856
12	C_7	2093	C_7	2093	2093

order for a total of 36 stimulus presentations per tape. Stimulus duration was always 1 sec; interstimulus duration was 4 sec. Test tapes were similarly constructed for Experiment II with four tapes for Sets T and KI at each of two interstimulus durations, 3 and 8 sec. Eight training tapes, based on the A training method (Cuddy, 1968), were also recorded for each stimulus set. Two tapes of 24 stimulus presentations each were recorded at each of four training levels. At levels 1, 2, 3, and 4, A_4 was presented 9, 6, 3, and 2 times respectively and was repeated after each presentation. The remaining stimulus presentations were chosen at random from the stimulus set, and were not repeated. Stimulus and interstimulus durations were 1 and 4 sec.

Response forms were identical for all sets. Each page of the response booklet consisted of 12 columns of the numbers 1 through 12. Listeners were told that the rows represented the tones of the set, the columns, trials, and for each trial they were to circle the number representing their best judgment of the tone presented. Information regarding the construction of each set, note-names, and stimulus frequencies was provided on a small card which was available throughout the test.

Experiment I

Listeners were individually tested for accuracy of judgment of the tones of three stimulus sets.

Procedure

Twelve listeners, 2 male and 10 female, judged the tones of Sets T, KI, and AI, the order of the three sets being randomized for each listener. Before each test, the listener was presented with the 12 tones of the set in ascending order of frequency, and at least 24 practice trials to ensure that the listener followed instructions correctly. The four tapes for the test were then presented in random order, and the listener recorded a judgment for each trial. No feedback was given.

Results

Mean number of correct responses out of a possible 12 for each stimulus tone, averaged across the 12 listeners, is shown as a function of ordinal position of tone for the three experimental sets in Figure 1. Figure 1 shows that best performance was obtained from Set T (Triad spacing) and that for all Sets the ordinal position effect is skewed with the lower tones of each Set judged more accurately than the higher tones. Analysis of variance indicated the main effect of Set was significant (F (2,22) = 6.80, $p < 0.01$). Orthogonal comparisons showed that overall mean performance on Set T, 7.30 correct responses per tone, was significantly higher than average performance on Sets KI and AI, which had 5.72 and 4.89 correct responses per tone respectively (F (1,22) = 15.14, $p < 0.01$). Sets KI and AI did not differ (F (1,22) = 1.89, $p > 0.10$). The effect of ordinal position of tone was significant (F (11,121) = 20.37,

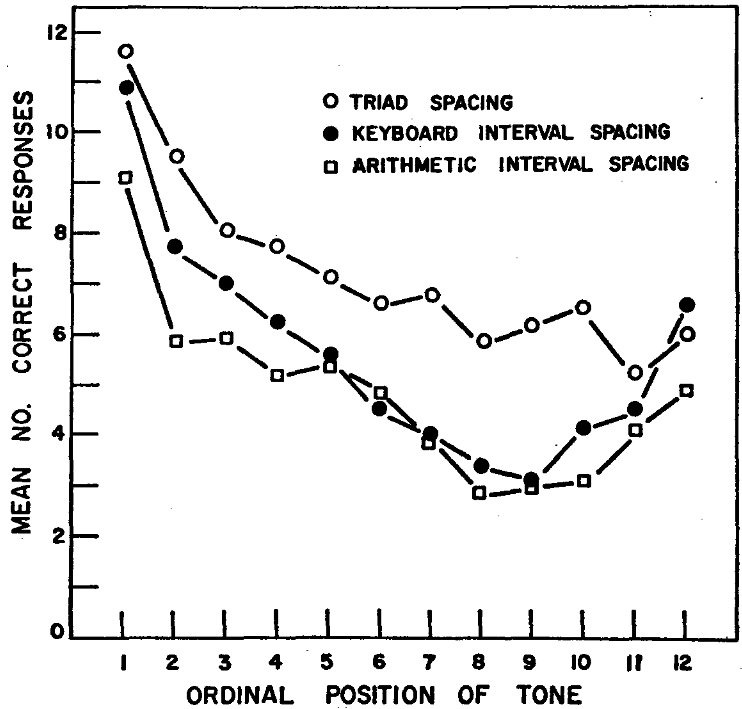

FIGURE 1. Average number of correct responses per tone for Triad spacing, Keyboard Interval spacing, and Arithmetic spacing (Experiment I).

$p < 0.01$) but the interaction between Set and Ordinal Position was not ($F\ (22{,}242) = 1.24, p > 0.10$).

The data for each individual listener were then entered into a stimulus-response matrix in which each cell entry $P\ (R_j|S_i)$ represented for each stimulus tone S_i the proportion of presentations of S_i that the response R_j was given. Error patterns noted in the matrix were summarized as follows: For each S_i, the proportions $P\ (R_{i-1}|S_i)$ and $P\ (R_{i+1}|S_i)$ were averaged (except, of course, for $i = 1$ or 12, in which case only a single proportion was recorded) and were called "Response Proportions at distance $|1|$," where distance refers to number of response categories above or below the correct response. The same procedure was followed for Response Proportions at distance $|2|$ and $|3|$.

The proportions of responses at distances $|1|$, $|2|$, and $|3|$ are shown in Figure 2 as a function of ordinal position of stimulus tone. Data from Sets KI and AI were similar and are averaged together in Figure 2. The top panel represents Response Proportions at distance $|1|$ and shows that for all tones fewer incorrect responses of this type are made to tones of Set T than to tones of Sets KI and AI. For Response Proportions at distance |2|, shown in the middle panel of Figure 1, fewer incorrect responses are made to tones of Set T at 8 ordinal positions, while data points for the two functions overlap at tones 1, 5, 6, and 11. Response Proportions at distance |3|, shown in the lower panel are very low for ordinal positions 1–6 for all Sets, comprising less than 5 per cent of all responses made to each stimulus. However, Response Proportions at distance |3| increase as ordinal position increases from 7 to 12, and are greater in magnitude for Set T than for Sets KI and AI.

The change in the direction of the difference between Sets T and Sets KI and AI for Response Proportions at distances |2| and |3| was noted in the individual data for all listeners. This finding is particularly interesting for present purposes since Response Proportions at distance |3| represent, for Set T only, errors at the octave of the correct response.

Experiment II

Experiment II was a partial replication of Experiment I and measured accuracy of judgment of music students for Triad spacing and Keyboard Interval spacing. To examine the possibility that performance was related to amount of musical training, level of musical training was added to the experimental design. Experiment II also examined the effect of rate of presentation of stimulus tones. If musical listeners compare each tone perceived with the stimulus trace of the preceding tone and judge the musical interval between the two, a short (3-sec) interstimulus duration should lead to more accurate performance than a long (8-sec) duration since more trace information is available following the shorter time duration (Bull, 1968). On the other hand, if judgment is based on a comparison of the sensory representation of the perceived tone with an internal representational structure the additional time allowed for each comparison at the 8-sec duration should lead to better performance.

Procedure

Seven musical listeners who had completed at least Grade X music requirements (Group 1) and seven who had completed Grade VIII or IX (Group 2) of the Royal Conservatory examinations were tested. Median age of Group 1 listeners was 21 years, for Group 2, 17 years. Listeners were tested under each of four experimental conditions – Set T – 3, Set T – 8, Set KI – 3 and Set KI – 8, where the numeral refers to interstimulus interval (ISI) in sec. Conditions were presented in random order; other procedural details were the same as Experiment I.

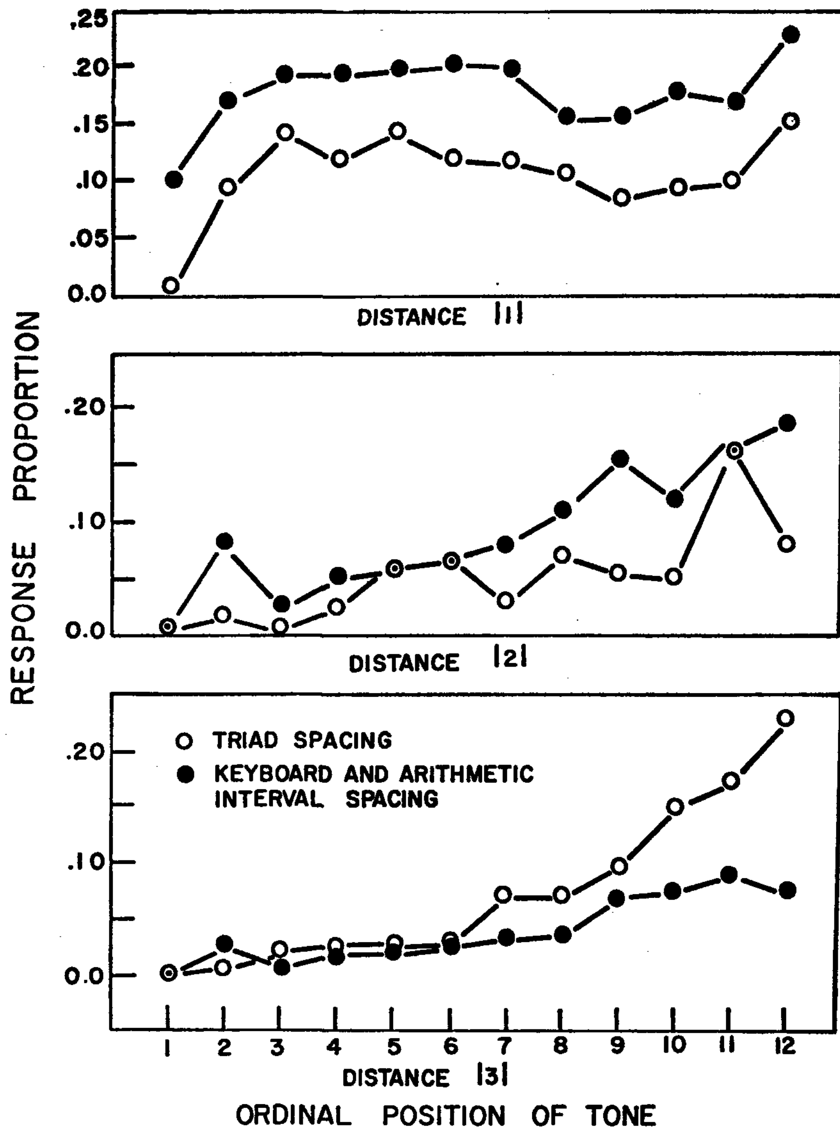

FIGURE 2. Response proportions for distances |1|, |2|, and |3| as a function of ordinal position of tone for Triad spacing, and for Keyboard Interval and Arithmetic Interval spacing averaged (Experiment I).

Experiment II A, run several months after the completion of Experiment II, tested (under the above four conditions) four listeners of college age not engaged in music study. Main results from Experiment II A will be presented with Experiment II for comparison.

Results

Number of correct judgments per tone for each experimental condition was scored (again out of a possible 12 correct) and subjected to an analysis of variance. Mean number of correct responses per tone averaged across conditions for Group 1 was 8.02 and for Group 2 was 5.07. This difference was significant (F (1,12) $= 8.12$, $p < 0.025$), but level of training did not interact significantly with any of the experimental factors. Other significant effects are shown in Figure 3 and Table II; these effects are Sets, Ordinal Position, and the interaction between Rate and Ordinal Position.

The top two curves of Figure 3 show mean no. of correct judgments per tone for Sets T and KI, averaged across levels of training and rate of presentation. Figure 3 shows that the main effects of Experiment I were replicated. The tones of Set T are consistently judged more accurately than the tones of Set KI (for Sets, F (1,12) $= 15.21$, $p < 0.005$) and there is a noticeably skewed Ordinal position effect (for Ordinal Position, F (11,132) $= 15.83$, $p < 0.005$). The interaction between Sets and Ordinal position was again not significant (F (11,132) $= 1.24$, $p > 0.20$). The lowest curve in Figure 3 represents performance by the non-musical listeners in Experiment II A. For the non-musical listeners, data were averaged across Sets and Rate of Presentation, since a separate analysis showed that neither effect achieved significance at the 0.05 level. Ordinal Position of tones was significant (F (11,33) $= 6.18$, $p < 0.001$); Figure 3 shows "anchor effects" at Ordinal Positions 1 and 12.

Table II presents results of varying the rate of presentation. The right hand columns represent mean no. of correct judgments for Sets T and KI averaged across ordinal positions 1–6 and 7–12. Over all conditions, the mean scores for the 3-sec and 8-sec ISI were nearly identical, 6.57 and 6.50 respectively. For Ordinal Positions 1–6 the scores for both Sets are higher for the 8-sec ISI than for the 3-sec ISI, while for Ordinal Positions 7–12, the trend appears to be reversed. This interaction, while much smaller in magnitude than the main effect of Set or Ordinal Position, is nevertheless highly significant (F (11,132) $= 3.06$, $p < 0.005$). Further analyses showed that while the Rate $\times$ Ordinal Position $\times$ Set interaction failed to reach significance (F (11,132) $= 1.70$, $0.10 > p > 0.05$), scores for Ordinal Positions 7–12 for only Set T were lower at the 8-sec ISI. The conservative Scheffé test indicated significance of the difference between presentation rates for ordinal positions 7–12, Set T, beyond the 0.05 level (for the contrast of 2 rates, $F = 18.83$, evaluated against $10F_{.05}$ (11,132)).

The left hand columns of Table II summarize entries in the confusion matrix at distance $|3|$. The 99 per cent confidence interval for zero mean

TABLE II

MEAN NUMBER OF CORRECT JUDGMENTS, AND RESPONSE PROPORTIONS AT DISTANCE |3| FOR SETS T AND KI AT 3-SEC AND 8-SEC INTERSTIMULUS INTERVAL (EXPERIMENT II)

Experimental condition	Mean no. correct per tone	Response proportion distance |3|
Set T, OP 1–6		
3-sec ISI	8.36	0.035
8-sec ISI	8.80	0.024
Set T, OP 7–12		
3-sec ISI	7.26	0.072
8-sec ISI	6.29	0.126
Set KI, OP 1–6		
3-sec ISI	6.66	0.029
8-sec ISI	6.90	0.021
Set KI, OP 7–12		
3-sec ISI	4.02	0.074
8-sec ISI	4.02	0.066

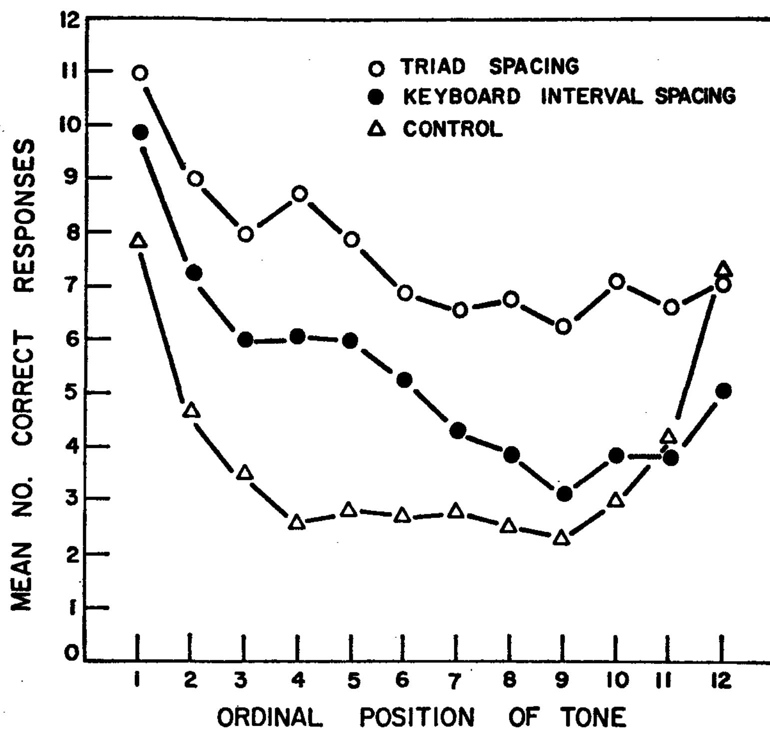

FIGURE 3. Average number of correct responses per tone for Triad spacing and Keyboard Interval spacing for musical listeners, and averaged across Sets for control listeners (Experiment II and IIA).

difference in response proportion is ± 0.036. For both Sets, response proportions at distance |3| were greater for ordinal positions 7–12 than for 1–6. While proportions did not differ between Sets T and KI at the 3-sec ISI, a significantly higher proportion was found for Set T, positions 7–12, than for Set KI, positions 7–12, at the 8-sec ISI. An increase in proportions from positions 1–6 to positions 7–12 was noted in the control group, mean values being 0.035 and 0.071 respectively, but there was again no difference between Sets or Rates.

In summary, the data indicate that judgment of tones 1–6 is enhanced at the slower rate of presentation, but judgment of tones 7–12 is not improved. For Triad spacing, placement of tones 7–12 in the correct octave appears to be more difficult at the slower rate.

Experiment III

In Experiment III, direct training was administered to listeners. The method, A training, is particularly effective for training music students to recognize musical tones (Cuddy, 1968) or tones grouped into frequency categories (Cuddy, 1970). It was concluded that A training is most effective where structural characteristics of a tone set are emphasized. If the musical pattern of Triad spacing is detected by the listener, A training should produce a faster rate of learning on Set T than on Sets KI or AI.

Procedure

Fifteen musical volunteers were randomly divided into 3 groups of 5 listeners each. Each group was given a pre-test and a post-test on one of the stimulus sets, with testing procedures identical to Experiments I and II. Between the pre- and post-tests, listeners were given 8 training sessions. At each training session, listeners heard two A-training tapes, beginning at the first session with level 1 tapes. Listeners were required to judge each tone as "A_4" or "not-A_4"; feedback during training was provided only for tone A_4. If the listener made 3 errors or fewer over both tapes (false alarms or misses), he proceeded to the next level at the next training session. If the listener reached the criterion for level 4 before session 8, practice was continued at level 4, so that all listeners received 8 training sessions. At least 24 hours intervened between each test or training session.

Results

Performance was scored for relative improvement from pre- to post-test, $\Delta X/N - X$, where N is the total number of possible correct responses, X is the pre-test score, and ΔX is the shift in score from pre- to post-test. The average relative improvement for Set T was 0.684, range 0.42 to 0.85, for Set KI, 0.20, range 0.00 to 0.50, and for Set AI, 0.24, range 0.09 to 0.55. The difference between Set T, and Sets KI and AI, was *significant* (F (1,13) = 23.19, $p < 0.001$). Figure 4 plots relative improvement per tone for Set I, and for Sets KI and AI averaged together. Some improvement was noted for tones of Sets KI and AI, especially tones 1 and 2, but relative improvement was greater for all tones of Set T than for Sets KI and AI. All listeners trained on Set T showed a drop in response proportion at distances |1|, |2|, and |3|. For three of the five listeners, the only errors made at the post-test were at distance |3| and these errors comprised only 6 per cent of all responses made to the post-test by the three listeners. A fourth listener showed a slightly higher proportion of total responses made at distance |3|, 0.09, on the post-test than at distance |1|, 0.07. The fifth listener, the lowest scoring of the group, showed error patterns more typical of listeners showing improvement on Sets KI and AI – from pre- to post-test, a drop in total response proportion at distance |1| from 0.34 to 0.25 and at distance |3| from 0.13 to 0.04.

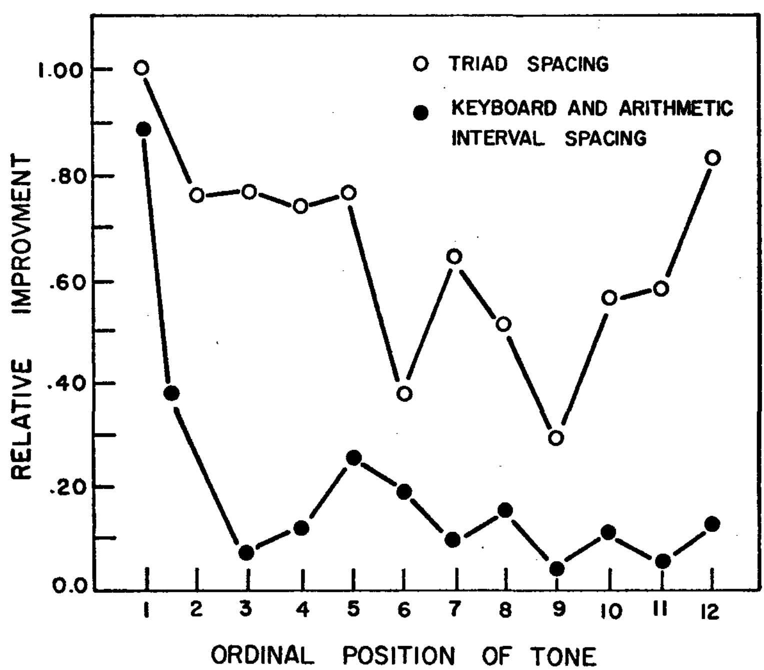

FIGURE 4. Relative improvement per tone following A training for Triad spacing, and for Keyboard Interval and Arithmetic Interval averaged (Experiment III).

Discussion

The experiments indicate that a set of tones based on the F-A-C Triad and its octaves are judged more accurately, and learned more rapidly by music students than sets of tones without simple chord or octave relationships. In terms of information transmitted (T), three listeners achieved the maximum possible value of 3.59 bits with Triad spacing and four more listeners exceeded 3.0 bits. These values are closer to those associated with the bidimensional judgment of pitch and loudness ($T = 3.1$ bits, Pollack, 1953) than to those ordinarily associated with absolute judgment of pitch without feedback (about 2.0 bits).

Because of the critical effect of spacing (or total context of tone set) and rate of presentation for musical listeners, and only for musical listeners, it does not seem likely that the sensory representation of a single tone enters the perceptual processer as a two-valued event. The musical judgment of the pitch of a tone appears dependent not on its absolute value or values as a sensory event but upon the total memory requirement for the task and the amount of practice with these requirements.

The data may be interpreted in terms of the decision-making process. Let us assume two steps or operations for recognition of musical pitch. The first operation analyzes pitch-height. Over all conditions, errors in judgment increase for the upper tones of a tone set if, as is the case in the present experiments, the melodic scalar distance between adjacent tones is decreased. Control listeners (Experiment II A) as well as musical listeners show greater spread of error response proportions for the upper tones.

A decision-theoretic model describing the operation of a linear pitch-height analyzer has been described (Cuddy, 1970). Critical to the model is the assumption that the internal event accompanying each sensory input may be represented by a random variable normally distributed on a subjective continuum and that the response to the event is selected by comparing the value of the random variable with a set of criteria (or response category boundaries) along the continuum. Because of the general limitations on absolute judgment, it may be assumed that the number of relatively stable criteria that can be maintained is very low – about four or five.

The second operation requires the accessible storage of (probably learned) structural rules or patterns. For the trained musician, rules are stored defining the relation of each tone to all others in the major and minor mode, including the recognition and generation of octaves. To achieve perfect performance on Set T all that need be specified are three criteria and the rule for octave transformation. The criteria themselves are partly redundant in that they are generated by another stored pattern or rule, the major Triad – redundancy leads to reduced error. The sensory representation is compared against the criteria either directly or after undergoing octave transformation.

The capacity for octave transformation reduces the memory requirements for accurate recognition, but the data suggest that comparison against musical criteria requires additional processing time and octave transformation is in itself a potential source of error. The basic musical criteria are probably located in that frequency region of a tone set where vocal cues are present and/or early musical training is concentrated (tones 1 to 6). Judgment of tones 1–6 benefits from a slow presentation rate (Experiment II). Judgment of the higher tones (tones 7 to 12) benefits from the presence of structural characteristics (Set T > Set KI or Set AI), but at the slower rate where trace information may not be available and musical processing (including octave transformation) must be relied upon, a greater number of octave errors are present.

The "dimensionality" of melodic pitch recognition is a characteristic of the rules for decision-making. These rules provide a fundamental criterion structure against which a sensory representation of a single tone may be compared. This is not to deny specific sensory events accompanying the presentation of different harmonic intervals. However, patterns of sensory interaction that accompany the presentation of simultaneous stimulus tones are not present in absolute judgment of single tones.

Résumé

Trois expériences sur l'exactitude de la discrimination de la hauteur tonique en trois ensembles de 12 sons sinusoïdaux différant seulement par l'intervalle des fréquences dans une distribution allant de 175 à 2093 Hz. Pour l'ensemble T (espacement par triades), les fréquences stimulus sont dérivées de l'accord tonique (bien tempéré) à partir de FA$_3$, pour l'ensemble KI (espacement par intervalles sur le clavier), chaque fréquence correspond à une note musicale différente; pour l'ensemble AI (espacement par intervalles arithmétiques), les fréquences s'étalent sur des intervalles arithmétiques prédéterminés sans souci particulier de correspondance musicale. Les résultats observés chez des étudiants en musique montrent que la discrimination est plus exacte et l'apprentissage plus rapide pour l'ensemble T, les deux autres ensembles ne donnant lieu à aucune différence. La comparaison de deux durées interstimulus (3s et 8s) indique, pour le rythme de présentation le plus lent, une amélioration faible, mais significative des jugements portés sur les six tons les plus bas, dans le cas des ensembles T et KI, et un accroissement du nombre des erreurs d'octave pour les six tons les plus hauts dans le cas de l'ensemble T. Chez des étudiants non inscrits en musique, on n'observe aucune différence entre les ensembles ni entre les rythmes de présentation. La discussion porte sur certaines des caractéristiques affectant les règles de décision dans la récognition de la hauteur tonique.

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