Acoustical factors related to pitch precision in choir singing

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Abstract

Choirs seem to exhibit varying proficiency of intonation (meaning the overall degree of precision in pitch) under differing acoustic conditions. If so, which conditions are the most conducive to correct intonation? Amateur male choir singers were asked to sing (one at a time) just intervals from a synthetic vowel tone whose spectrum and vibrato content were varied. The standard deviation in fundamental frequency over the ensemble of singers was adopted as a measure of the difficulty of intonation for a given stimulus.

Spectrum variations such as change of vowel did in some cases cause significant changes in the ease of intonation. Absence of vibrato, presence of common partials and presence of high partials were found to facilitate intonation. Standard deviations of 10-15 cent were found to be typical of a musically acceptable performance under normal rehearsal conditions, whereas values up to 2-3 times greater resulted from stimulus tone manipulation. Skilled choir singers were less influenced by stimulus variations than unskilled ones.

Introduction

Although choir singing is a very widespread activity, research in choir acoustics has been very scarce. Therefore, many questions which are important to a great number of people have remained unanswered. We report here results from a first attempt to elucidate acoustical factors of significance to choir intonation; more specifically, factors affecting the precision with which the choir singers choose their fundamental frequencies.

An important requirement for a choir singer to meet is to sing "in tune", i.e., with correct fundamental frequencies. In order to achieve this, the singer must be in good control of the fundamental frequency of his/her voice. Also needed is a clear concept of what the correct pitch is. However, it is well known that the ability of the choir members to meet these demands is influenced by acoustic conditions, such as room acoustics and choir formation. This leads to the question: what are the properties of the choral sound, which facilitate or complicate the singer's choice of fundamental frequency? In the present investigations, three hypotheses regarding such sound properties have been tested.
Hypotheses

An interval between two tones is said to be just, if the ratio of their frequencies can be expressed by small integers. If a just interval is formed by two tones with harmonic spectra, then some of the partials from the two tones will coincide in frequency (Fig. 1). Mistuning such an interval slightly has the consequence that partials with nearly equal frequencies will sound together, causing beats. Such beats may serve as a clue to correct intonation. In vowel spectra, these common partials may of course be emphasized by a formant. One of our three hypotheses was that the presence of common partials in a consonant interval facilitates the singer’s intonation.

The vibrato corresponds to a small periodic variation of the fundamental frequency. It will therefore eliminate beats in a slightly mistuned interval. Moreover, a sinusoidal vibrato does not change the perceived pitch of a tone (Sundberg, 1978). Another hypothesis that we have tested is that the absence of vibrato in the stimulus tone facilitates the singer’s intonation.

The masking effect of one’s own voice is greater for low than for high frequencies (Gauffin & Sundberg, 1974). This bias is due partly to the low-pass nature of bone conduction, and partly to the directivity of high frequencies radiated from the mouth. Pitch information, however, is available in all parts of the spectrum. The high partials of the sound from the fellow choir singers may be more useful to the singer than the low ones, since they are less likely to be masked by the singer’s own voice. Accordingly, our third hypothesis was that the presence of high partials makes intonation easier. We arbitrarily defined "high partials" as all partials above the lowest common partial.
Methods

A series of experiments was carried out in order to test the above mentioned three hypotheses. Unless otherwise stated, the experimental procedure was the following. Individual male members of an amateur choir were asked to sing a consonant interval with a stimulus tone which they heard from a loudspeaker, at an SPL of about 75 dB. The stimulus tones were synthesized using a minicomputer and MUSSE (a terminal analogue of the human voice), and recorded on one track of a four track test tape. Each stimulus tone was of ten seconds duration, and was followed by a pause of about ten seconds. The task of the subject was to sing, without prior practice, a sustained tone forming a fifth or a major third (frequency ratios 3:2 and 5:4, respectively) above the stimulus tone, as indicated by a music score. A contact microphone was fastened to the throat below the larynx and the resulting voice signal was recorded in synchronism onto a vacant track of the test tape. The SPL produced by the subject singers was not monitored. For purpose of control, the spectra of the stimulus tones were measured at a position near a subject's ear.

There are several plausible ways of obtaining a measure of the intonation difficulty encountered by the singer in attempting to sing a given interval with a given reference tone. For instance, each singer started his tone with a pitch searching phase of varied duration. One possible measure would be the average duration over subjects of this searching. However, for a given stimulus tone, different singers showed quite different strategies and durations of this searching, as can be seen in Fig. 2. Thus, the duration of the pitch searching phase seems to reflect some characteristic of the singer's pitch control system rather than the difficulty of intonation.
Generally, the fundamental frequency used by the singers deviated more or less from the just intonation value. The average of this error over the group of singers is another candidate for the measure of difficulty. However, it cannot be taken for granted that just intonation is the ideal for the intonation of a consonant interval (Hagerman & Sundberg, 1980). Therefore the average error in fundamental frequency is not a good measure of intonation difficulty.

The standard deviation in fundamental frequency taken over the group reflects the amount of disagreement among the choir singer subjects as to which fundamental frequency should be considered ideal. If the interval is easy to sing, this standard deviation must be small. For this reason, the standard deviation of all singers’ fundamental frequencies produced for a given stimulus was accepted as a measure of the difficulty of intonation. All results given below denote such standard deviations, measured in cent, while the absolute values of the fundamental frequencies will be disregarded.
Experiment I

The order of magnitude of the standard deviation just mentioned was estimated for realistic conditions in the following experiment. The choir sang a conventional cadence in an ordinary rehearsal room a number of times, until the choir leader judged the intonation to be musically acceptable. In the cadence, which was composed for this purpose by one of the authors (ST), each of the eight notes in a major scale occurred only once in the bass part. The intonation was measured in six of the bass singers using the method described above, while the cadence was sung another four times. The resulting standard deviations over the six subjects for each of the eight tones are given in Fig. 3. The eight tones appear to have been about equally difficult. The three largest values (> 20 cent) stem from single, though different, singers making large errors on the order of 50 cent. The overall average of the standard deviations (over 6 singers x 8 tones x 4 repeats = 192 sung tones) was found to be 13 cent, with extremes at 3 and 24 cent. Thus, two thirds of the fundamental frequency values produced by the basses of this choir agreed to within ±13 cent.

Fig. 3. Standard deviations (cent) in F0 over 6 subjects. A cadence of eight notes was sung four times. The three largest values, marked *, were all caused by a single (though not the same) subject making an error of about 50 cent (see the Discussion).
This experiment was made in order to find out whether or not the different acoustic characteristics of the tone reaching a singer's ears have any measurable effect at all on the singer's intonation. In the experiment, four skilled choir singers sang a fifth or a major third above a stimulus tone given to them over a loudspeaker in a sound treated booth. The test tape contained 23 stimulus tones. The stimulus sounds lacked vibrato but were vowel-like in that they all had realistic formant frequencies, which were varied systematically. The fundamental frequencies were chosen so as to have the subjects sing notes over a wide pitch range (B2-D4). The four singer subjects made two test runs, thus yielding 23x4x2 = 184 sung tones. The resulting intervals between the fundamental frequencies of the stimulus tone and the sung tone were determined in cent by means of the VISA computer programme (Askenfelt, 1979).

As there were sound reflections in the booth, which, moreover, were influenced by the subjects themselves, the experimental conditions were realistic rather than well controlled. Still, there were substantial spectral differences between the 23 stimulus tones. If such spectral differences are relevant to the difficulty of intonation, they would cause some variation in the standard deviation of the fundamental frequency produced by the singers. In the opposite case, we would expect a standard deviation on the order of 13 cent no matter what the stimulus tone was, see above. The standard deviations observed were found to range from 3 to 30 cent. In some cases the standard deviation changed by a factor greater than two when the reference tones differed in vowel but not in pitch. This is a statistically significant effect, which implies that there are indeed properties of the vowels which affect the inter-subject scatter of fundamental frequency. Also, this tallies with the opinion of the singer subjects, who reported that a satisfactory intonation was much easier to achieve in some cases than in others.
Experiment III

Method. Experiments I and II showed that some (unknown) stimulus tone characteristics indeed do influence the difficulty of intonation. The next step was to identify some of these factors. The experiment was carried out in an anechoic room. The stimulus tone properties were chosen using a binary paradigm (2^k-test, k=4). They combined in all possible ways the presence and absence of three acoustic characteristics of the stimulus tone, namely (1) vibrato, with a frequency swing of ± 1.5 %; (2) common partials; and (3) all partials higher than the lowest common partial. An additional factor (4) was the musical interval: perfect fifth versus major third. In other words, all sixteen permutations of these stimulus conditions were synthesized and recorded on tape in random order. For duplication, four of the stimulus tones occurred twice, unaltered. Eighteen subjects participated in this experiment. Thus, the recordings from this experiment consisted of 360 sung tones ((16 stimulus tones + 4 duplicates) x 18 subjects). The average fundamental frequency value over the subject singers was measured for each tone the nearest Hz using a low-pass filter and a frequency counter. The fundamental frequencies of the stimulus tones were chosen so as to keep the singers within a small and comfortable pitch range (E₃–A₃ in 30-cent increments).

Results. The standard deviations which resulted from the different stimulus tones are tabulated in Table 1a and 1b. Some of them amount to some 40 cent, which is much larger than the mean of 13 cent which was found for choir intonation under normal conditions in Experiment I. This is not surprising in view of the substantially differing conditions (anechoic room, "strange" stimuli, no practice, and no correcting information from other choir singers). As in Experiment I, the largest standard deviations (exceeding 30 cent) were caused by single subjects making large errors on the order of 100 cent. This happened four times, all for supposedly difficult stimulus tones; but no one subject was in such sizable error more than once.

The agreement in the responses for the four duplicated stimuli was remarkably good, as can be seen in Table 1a. This allows the conclusion that the experimental conditions remained essentially constant during the experiment, so that the variations in the standard deviation between different stimuli are likely to depend on the stimulus characteristics.
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Table Ia: Standard deviations (cent) in fundamental frequency taken over 18 singers.

Table Ib: The data of Table Ia arranged so as to visualize the factor effects. The significant effects (F test), marked with asterisks, are commented in the Discussion. A double ring denotes average value of duplicate stimuli.
We assume that the fundamental frequencies of the sung tones pertaining to a given stimulus tone can be regarded as belonging to a normal distribution. This allows us to use the F test for testing the statistical significance of variance changes associated with changes in stimulus tone characteristics, i.e., the significance of the difference in any pair of values in adjacent corners of the cubes in Table Ib. The changes found to be significant according to this test are identified by asterisks and lower-case letters in the table. Some of them merit individual comments as follows.

Referring to Table Ib, we find it interesting to note that there are good explanations to be found for all the significant effects. Comparison (a) concerns the change in the stimulus tone characteristics from two to three partials, corresponding to the addition of the first common partial. This change makes it easier to sing a fifth. Comparison (b) concerns an identical change, except that, in this case, there is no vibrato. The influence of the third partial becomes even greater in this case, as though the vibrato had had a blurring effect on pitch perception.

Comparisons (c) and (d) show the effect of adding two partials in the case of presence and absence of vibrato; since there are two and four partials below the first common partial in a fifth and in a major third, respectively. The results show clearly lower standard deviations when the stimulus tone contains four partials rather than two, no matter if there is a vibrato or not. Moreover, there is no clear effect of adding the first common partial in the case of the major third interval. A possible interpretation is that adding one partial to two partials (as for fifths) leads to a greater improvement than adding one partial to four partials. It seems that three partials are sufficient for ease of intonation. For the interval of the fifth, adding all non-common partials (e) has very much the same effect as adding the first common (third) partial. However, in the case of the thirds, there is no effect of adding all non-common partials.

Comparison (f) concerns the addition of all common partials to an otherwise complete vowel spectrum lacking vibrato (thirds only). The effect is large. This might be an effect of the difference between various versions of major thirds which occur in music practice (Hagerman & Sundberg, 1980). A major third is 22 cent wider in Pythagorean tuning.
than in just intonation. When common partials are absent, the singers are free to tune the third in just intonation, Pythagorean intonation or equal temperament. If different singers choose different versions of the third, this must result in a large standard deviation of their fundamental frequencies; when common partials are added, only the just intonation will be beat-free. This would increase the agreement in intonation, and hence also narrow the standard deviation. We would then expect a smaller standard deviation. If this explanation is true, we may anticipate a slightly higher mean fundamental frequency in the former case, in which some singers would have chosen wider (i.e., Pythagorean or equally tempered) thirds. This is what in fact happened; the average fundamental frequency was 4.5 cent lower when the stimulus tone contained the common partials than when it did not.

Comparisons (g) and (h) both concern the addition of vibrato for thirds. The result shows that the vibrato represents a complication for the intonation, when there are common partials in the stimulus tone (for thirds). The effect disappears when the common partials are removed. The reason for this could be that there are no beats for the vibrato to eliminate when the common partials are missing. For fifths, this "vibrato blurring" effect is absent, but we do not understand why this is so.

Analysis of variance. It is common practice in $2^k$-experiments to assume that the higher-order interactions are negligible, and then to use their calculated magnitude for an estimate of the variance of the data. Here, however, we find quite large higher-order interactions, as might be expected in view of the structure of the stimulus tone properties (see Discussion). The interactions are too large to be neglected and are therefore not of much use in estimating the variance. We resort instead to the four duplicated stimuli. The mean sum of squares of their pairwise differences gives the variance estimate

$$\bar{\sigma}^2 = \frac{1}{4} \left[ \frac{(21-21)^2}{2} + \frac{(40-40)^2}{2} + \frac{(28-27)^2}{2} + \frac{(22-27)^2}{2} \right] = \frac{13}{4}$$

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Source of variation: are weighted + or −, accumulated horizontally and averaged in the rightmost column.

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V No Vibrato

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Table II: Analysis of variance.
These confidence intervals are used in the analysis of variance (Table II) to single out the significant sources of variation.

Discussion

Applicability of results. The interindividual variability was very great. Occasionally, one or two choir singers would sing at a pitch which was up to about 100 cents away from the group average. Moreover, the statistical significance in all such cases was heavily dependent on the data from these very deviant subjects. Incidentally, these stemmed from subjects who were less experienced choir singers than the majority of the group. We take this to mean that the skilled choir singers are rarely disturbed by variations in the stimuli, whereas the less experienced ones occasionally become confused by difficult stimuli. This is not astonishing; "skill" would designate the ability to perform correctly and reliably even under difficult circumstances. We also infer from this that, in such cases, errors in fundamental frequency of more than 50 cent, or half a semitone, may occur.

Can this intonation behaviour (i. e., most singers being essentially agreed except for one or two "dropouts") be typical of choir singing, or is it due only to the experimental situation? The data collected in ordinary rehearsal (Experiment I) reveal that the largest standard deviations were caused by similar single "dropouts". This similarity lends credence to the practical importance of a few extreme data. It also suggests that poor intonation in choirs may manifest itself in this particular way.

Comments on the factor effects. According to the analysis of variance, the three factors of our three hypotheses were all found to be significant, namely presence of common partials, presence of high partials, and absence of vibrato (Table II).
Given, then, that the presence of common partials does help intonation, we must note that in a choral context the common partials are never completely absent; on the other hand, their amplitudes may be manipulated through a judicious choice of vowels. The results indicate that such manipulation could be worthwhile. An interesting practical application would be to construct choir intonation exercises with the common partials emphasized.

Similarly, "high partials" are never quite absent in practice, but their amplitude is strongly dependent on room acoustics, choir formation, and of course also on the vowel quality. Above, we presumed that a stimulus tone with strong high partials is more likely to be heard by a singer than one with weak high partials, because of the masking effect of the singer's own voice. This applies when the singer hears his own voice as loud compared to the sound he perceives of the rest of the choir. In practice, the opposite also occurs, i.e. that the sound of the ensemble is so loud that the singer cannot hear his own voice. We may therefore anticipate that the SPL difference between the individual singer's voice and the sound of the rest of the choir is important to choral performance. If we assume that all choir members sing at about the same SPL, this ratio is determined by two things: the amount of reverberation in the room, and the spacing between the singers. In a heavily damped room, or if the singers are standing far apart, each singer should hear more of himself and less of the others. The present experiment shows that the high partials are useful to the singer in an anechoic room when the "choir" SPL is about 75 dB; but since the subject SPL was not measured, the SPL differences are not known. It does not follow that the usefulness remains at other levels or in normal rooms. The significance of the SPL difference seems to be a worthwhile thing to investigate in the future.

The reason why the vibrato was found to be important is not hard to realize. The vibrato eliminates beats from mistuned consonant intervals. The result suggests that, in our experiment, reduction of beats was used as a way of achieving the ideal intonation. Whether or not this applies under more realistic choir conditions remains to be shown.

As for the fourth factor, the interval (fifth or third), the result apparently shows that thirds are easier than fifths to sing correctly. This is probably true only under the present experimental conditions;
for out of the stimulus tones which lacked high partials, those intended for thirds consisted of four or five partials, while those intended for fifths consisted of only two or three. The pitch of the stimulus tone should therefore be easier to perceive in the case of the third, which accounts for this result.

**Interactions of the sources of variance.** In table 3 we see that the effects of both common and high partials depend strongly on the interval factor (TxC, TxH and TxCH). Adding common and/or high partials to a "fifths" stimulus tone, which has two or three partials, will help the singer more than the same addition to a "thirds" tone, which already has four or five partials.

**Alienation?** In the main experiment, the variation span for some properties of the stimulus tone was much larger than is possible in choirs. Thus, for some stimuli the amplitude of both the common partials and of the vibrato was zero. Such vowels do of course sound very unnatural; hence we might anticipate an undesired alienation, i.e. that the choir singer’s concentration and thus his intonation ability would be reduced by a surprise effect (confrontation with a very unfamiliar sound). The choir singers’ efforts would then reflect the unnaturalness of the reference vowel rather than the intonation difficulty. The stimulus tones consisting of only a few low partials should sound least natural, since they are most different from the human voice. However, these stimulus tones caused both quite large and quite small standard deviations. The alienation effect, therefore, cannot have dominated over the influence of the stimulus tone properties.

**Future plans.** This investigation is but a first attempt to illuminate factors of importance to choral intonation. On continuing, we will study the effect of the sound pressure level and of the relative amplitudes of the common partials. We hope also to find a method permitting of measurements under more realistic, yet well-controlled conditions.
Summary of conclusions

(1) The precision of a choir singer's intonation depends on, among other things, the acoustic properties of the reference sound reaching his ears from the rest of the choir.

(2) Accurate intonation is facilitated by
- presence of common partials
- presence of high partials
- lack of vibrato

(3) A standard deviation in fundamental frequency of about 13 cent is typical of amateur bass choir singers.

(4) Skilled choir singers are little disturbed by even quite abnormal variations in the reference tone characteristics, whereas less experienced ones may become confused and sing with an error of more than 50 cent. Basically, this seems to apply also in the normal rehearsal situation.

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